M.Sc. Engg. (CSE) Thesis

A PEER-TO-PEER ENERGY TRADING FRAMEWORK FOR SMART GRIDS USING GAME THEORY APPROACHES

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Candidate's Declaration

I, do, hereby, certify that the work presented in this thesis, titled, "A PEER-TO-PEER ENERGY TRADING FRAMEWORK FOR SMART GRIDS USING GAME THEORY APPROACHES", is the outcome of the investigation and research carried out by me under the supervision of Dr. Rifat Shahriyar, Associate Professor, Department of CSE, BUET.

I also declare that neither this thesis nor any part thereof has been submitted anywhere else for the award of any degree, diploma or other qualifications.

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The thesis titled "**A PEER-TO-PEER ENERGY TRADING FRAMEWORK FOR SMART GRIDS USING GAME THEORY APPROACHES**", submitted by Mehjabin Rahman, Student ID 1014052056, Session October 2014, to the Department of Computer Science and Engineering, Bangladesh University of Engineering and Technology, has been accepted as satisfactory in partial fulfilment of the requirements for the degree of Master of Science in Computer Science and Engineering and approved as to its style and contents on November 22, 2020.

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Abstract

The concept of a peer-to-peer (P2P) energy trading system is becoming popular. Individuals will be capable of both consuming and producing energy without the need for centralized power plants. However, the integration of renewable energy in today's power grid remains challenging. The emerging smart grid technology will have to be built on mathematical tools such as game theory. The benefit of peer-to-peer energy trading to the distribution grid needs to be considered. If demand goes below the load demand of the grid, then how does the grid decide on its price lower than the P2P price that enables it to sell its energy to the prosumers is another issue. Another challenge is that the negotiation process can become more complicated for the scenario where a higher number of end users are involved, as both the seller and the buyer are unaware of each other's requirements and priorities. So we have proposed a new model where end users can trade surplus energy with other consumers and the grid using the grid-connected distribution network, which ensures a collective minimization of energy cost and potentially maximizes profits. The grid can impose some constraints to decide when the end-user can participate in P2P energy trading. We have proposed a hybrid framework, including a cooperative coalition formation game and the Stackelberg game. The choice of the price is made by the grid, prosumers, and consumers in the coalition formation game and participate in P2P energy trading with the neighboring peers of the same coalition. We have added a non-cooperative pregame in which coalitions are formed and then simultaneously energy trading occurs both cooperatively and non-cooperatively based on the calculation of the maximum utility and minimum cost. We have analyzed various properties of the resulting game. In particular, it is shown that, due to the strategy-proof property of the formed coalitions' stability, the proposed game possesses a unique Stackelberg equilibrium. We derive a closed-form pricing function for the grid and propose an algorithm that the grid and prosumers can use to solve it. Further, using numerical simulation, we demonstrate the beneficial properties of the proposed scheme.

Chapter 1

Introduction

Prosumer is an important element in the smart grid. Prosumers are the consumers who can also produce and sell the energy. Integrating the prosumers will result in selling the surplus of energy to the grid or other consumers This is known as peer-to-peer energy trading. However, the interactions between prosumers and the grid need to be defined in order to maximize the profit of each stakeholder. This thesis addresses the challenges and opportunities of peer-to-peer (P2P) energy trading to deliver unprecedented economic benefits and improve grid reliability and asset efficiency. This thesis introduces a framework which is a combination of cooperative and non-cooperative game theory platforms.

1.1 Problem Statement

The smart grid is a power network composed of intelligent nodes that can operate, communicate, and interact autonomously to deliver power and electricity to their consumers efficiently. On the other hand, peer-to-peer energy trading is a next-generation energy management mechanism for the smart grid that enables customers to participate in energy trading with other prosumers and the grid independently [1]. Prosumer is an individual who not only consumes but also produces his own energy through renewable energy sources. This advancement changes residential consumers into prosumers. An entity that can produce, consume, and possibly also has demand response capacities is known as prosumer [2]. P2P energy trading's potential benefits include renewable energy usage maximization, electricity cost reduction, peak load shaving, prosumer empowerment, and network operation and investment cost minimization. It also provides a solution for individuals whose homes are unsuitable for solar with rooftops that are shaded, small, has an ill-suited orientation, or require re-roofing. The main objective of P2P sharing is to break the centralized infrastructure of the electricity grid by allowing the direct communication and supply of energy between various prosumers with DERs (distributed energy resources) within the energy system. This enables interested consumers to buy renewable energy at a cheaper rate from a peer with excess renewable energy, thus reducing its dependency on the grid or central supplier [3].

Instead of merely depending on the grid, a smart home can generate its energy via solar panels, wind turbines, and other renewable energy sources. This shift towards solar is being complemented by an increase in the adoption of residential energy storage systems [4]. One or multiple storage devices accumulate cheap and excessive energy to support future energy requirements, avoiding the need to acquire expensive energy from the grid during periods of high prices (for example, peak hours) [5]. Photo-voltaic (PV) or solar panels will eventually be at parity with natural gas and coal, but that does not mean there will not be any coal or natural gas generators after that. Because the sun shines only during daylight hours, and the wind is most prevalent at night, both are variable. We can not be entirely dependent on renewable in the foreseeable future. Besides, more than 20 percent of solar and wind would require significant investments in transmission lines. Not only transmission lines are expensive, but also they are hard to permit because of the NIMBY (not-in-my-back-yard) factor. Transmission lines also require three to four years to build versus solar or wind plants, which can be quickly constructed in two years. One possible way is integrating the P2P energy trading mechanism into the current energy policy.

However, the integration of renewable energy in today's power grid remains challenging. Conventionally, power is generated centrally and flows unidirectionally to passive consumers who pay a fixed price according to contractual agreements with the utility company. Since the energy is consumed directly from its production, balancing supply and demand during high demand periods is necessary to guarantee stable operation. Utility companies often have to respond with costly fast energy generation via peak spinning reserves [6,7]. We claim that with a proper understanding of its behavior and different key design points, a prosumer-centric and consumer-centric P2P energy trading can produce optimal scheduling for smart grids with minimal load curtailment.

1.2 Motivation

Peer-to-Peer energy trading enables everyone to engage in energy exchange and brings profit to small scale energy producers and consumers. Peer-to-peer energy trading can also reduce power outages by providing alternative local energy sources during a power outage from the central utility provider. So, P2P trading has various beneficiary aspects. P2P trading can be done for both grid-connected and islanded microgrid systems. As participants in an islanded microgrid should have enough generation capacity to ensure an appropriate security level and reliability in supplying energy, it is better to choose the hybrid option. The hybrid option means we can think of peer-to-peer energy trading in a grid-connected infrastructure. Now, in a grid-connected system, a prosumer may need to deal with both regulated and deregulated P2P markets. Hence, how to integrate both of them in a single paradigm remains a challenge.

Moreover, most researches have focused on to bring profit for either prosumer or consumer or both. However, no one has considerd the benefit of the grid. However, if the grid is not benefitted, it will not incorporate grid-connected peer trading.

Due to the interactive nature of the energy trading process, game-theoretic approaches are used to develop the P2P trading scheme. Game theory is a mathematical tool that analyzes strategies of competitive situations where the outcome of a player's action depends on the actions of other players . Game theory can be broadly divided into two types: non-cooperative game and cooperative game. A non-cooperative game deals with the strategic decision-making process of a number of independent players that have totally or partially conflicting interest over the outcome of a decision that is affected by their choice of actions. A cooperative game focuses on how one can provide incentives to independent decision-makers so that they act together as one entity in order to improve their position (or utility) in the game.

Now, if the only non-cooperative game theory is used, it will increase the computational complexity for large-scale network trading. Moreover, in real-world scenarios and situations require decision making, and strategy buildings are often messier, more dynamic, and less easy to control. Also, real-life scenarios, gains, and losses are not always as clear cut and easily quantifiable.

Moreover, it is hard for cooperative game theory to encourage all the participants in a large group. Considering all the challenges mentioned above, we have proposed a framework which will mitigate all these issues.

1.3 Scope and Contributions

This research focuses on the energy source, storage, and load scheduling in end users and the grid to increase energy efficiency and minimize energy costs. Researchers have proposed many ideas to improve the implementation of P2P energy trading platforms. However, all these studies have some limitations. Most prior studies assume a static demand model with physical constraints as different houses have different solar energy requirements.

Further, P2P trading algorithms need to be simulated for a large-scale realistic power system models to observe the impact of computational complexity on the conduct of trading in such an extensive system. Our model deals with real-time market experience to avoid overloading electric load-lines. Also, our model is suitable for a large system.

Compared to competitive game theory, where players act to maximize the benefit for themselves, a cooperative game is one where the group's direct actions maximize the group's overall benefit. But it is not possible to force everyone to behave cooperatively. Our proposed framework utilize the combination of both game theory approaches.

Most prior researches have not directly simulated peer-to-peer energy trading—moreover, those who simulate use only one seller and multi-buyer. And previous works are considered only off-grid microgrids. However, our model has been simulated using a multi-seller, multi-buyer, and the grid. The consumer-centricity of peer-to-peer trading has been well established in recent literature [8–10].

However, the benefit of peer-to-peer energy trading to the distribution grid also needs to be demonstrated. Further, the grid should also have the provision to participate in P2P trading either as a generator or service provider, if necessary. And while we use the infrastructure of the grid for peer-to-peer energy exchange, we have to rethink the way we attribute costs of prosumers, consumers, and the grid's utility. Our proposed model is beneficial for all the players, including prosumers, consumers, and the grid.

1.4 Objectives and Outcomes

The objectives of this thesis are as follows:

1. To design a hybrid cooperative and non-cooperative game-theoretic model that makes the users interact with the grid in such a way that fulfills both sides' demands.
2. To develop utility functions during energy trading, the cost function, and a set of theorems for the proof of equilibrium.
3. To simulate our model to ensure stable operation in both peak and non-peak hours and analyze with numerical case studies to show that our model is beneficial.

The possible outcomes of this thesis are as follows:

1. A Stackelberg game theory algorithm for peer-to-peer energy trading with a price, set by the Coalition algorithm is beneficial for all entities- grid, sellers, and buyers.
2. A proof of the equilibrium using the designed utility and cost functions.
3. An open-source implementation of our algorithm that can be used in real-world peer-to-peer energy trading scenarios for smart grids.

1.5 Thesis Outline

The body of this thesis is structured around the three critical contributions outlined above. Chapter 2 provides an overview and surveys of different grid types, including smart grid, off-grid, and hybrid grid. It gives a more detailed background on previous works on peer-to-peer energy trading. Chapter 3 discusses our experimental methodology, discusses various properties of our peer-to-peer energy trading model and also provides proof of these properties. And it also includes the algorithms we have designed. Chapter 4 presents the simulation results of the model, and Chapter 5 concludes the thesis, describing how the contributions have been identified, quantified, and addressed the challenges of achieving high performance in peer-to-peer energy trading. It further identifies vital future directions for research.

Chapter 2

Literature Review

This chapter provides background information on the smart grid and P2P energy trading basics, cooperative and non-cooperative game theory to place the research contributions in context. This chapter starts with a brief introduction to grid and energy trading. Section 2.1 outlines the grid and P2P energy trading terminology. Section 2.2 outlines the critical components of game theory. Section 2.3 provides detailed background on studies of P2P energy trading in terms of game-theoretic approaches.

2.1 Terminology

2.1.1 Traditional grid Vs Smart grid

The traditional power grids [11] (Figure2.1) are generally used to carry power from a few central generators to many users or customers.

A smart grid (Figure:2.2) differs from the traditional grid in that it allows two-way communication of electricity data, rather than a one-way flow. Smart grids enable real-time data collection concerning electricity supply and demand during the transmission and distribution

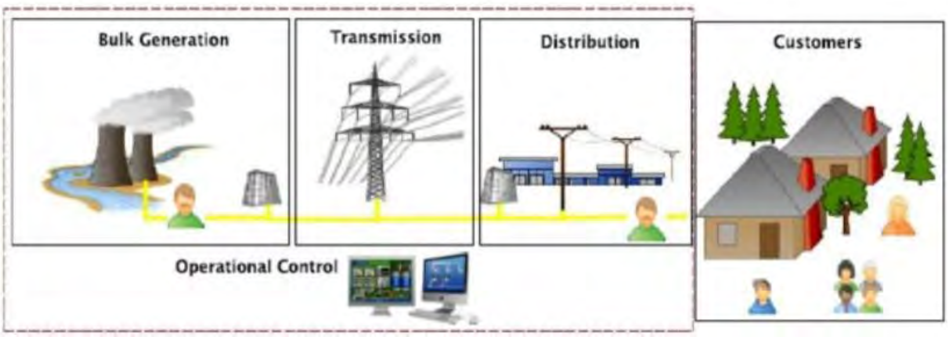

Figure 2.1: Traditional Energy Trading System.

Figure 2.2: Smart grid energy trading system.

process, making monitoring, generation, consumption, and maintenance more efficient. Smart grid involves innovative products and services in conjunction with intelligent monitoring, control, communication, and self-healing technologies. The following attributes can be associated with Smart grid:

- Allows consumers to play a role in the optimization and operation of the system and provides consumers with more significant information and choice of supply.
- Demand response and demand-side management are enabled through the integration of smart meters, smart appliances and consumer loads, micro-generation, and electricity storage (electric vehicles) and by providing customers with information related to energy use and pricing.
- Dynamic energy pricing allows consumers to adjust when and how high-load devices are operated, ultimately lowering energy bills and reducing the demand spikes, leading to power outages.
- Facilitates the integration of all renewable energy sources, distributed generation, and residential micro-generation, which is inherently unpredictable. This includes the integration of storage options, e.g., plug-in electric vehicles.
- Efficiently operates assets by intelligent operation of the delivery system (rerouting power, working autonomously) and pursuing efficient asset management. This includes utilizing assets depending on what is needed and when it is needed.
- Increased physical, operational, and cyber-security attributes which will improve resilience to attacks and natural disasters.
- Improved reliability and security of supply by anticipating and responding in a self-healing manner Quality of supply is generally improved thus more aligned with that required by sensitive digital equipment.

2.1.2 Non Renewable and Renewable energy sources

Traditionally, non-renewable energy sources such as coal, oil, and natural gas have been the primary sources of energy. However, non-renewable energy sources are being depleted and becoming more expensive from time to time, which indicates that the energy from these sources will not support the increasing demand caused by a growing population. Moreover, non-renewable energy sources are not environmentally friendly as they cause a high level of carbon emissions. All these factors have motivated the emergence of various kinds of renewable energy sources(RES) such as solar panels and wind turbines. RES cause less pollution and are also more economical than their counterparts as they reduce transmission cost. Also, renewable energy sources help reduce the burden imposed on the primary grid by supplying a proportion of the demand through locally produced and consumed energy. While renewable energy systems can power houses and small businesses without any connection to the electricity grid, many people prefer the advantages that grid-connection offers. So there are various types of connections between the grid and the renewable energy sources.

2.1.3 Grid Tied

The first one is grid-tied. As its name implies, a grid-tied renewable energy source(e.g., solar system) is one that's still connected to the local power grid. If at any given time our panels are not producing enough energy to meet our home's power needs, then that energy is supplemented with electricity from the local power company. This system is shown in the Figure2.3.

2.1.4 Off-grid

If we are off-grid, then our home is disconnected from the local power supply. For this, we must have to be completely self-sufficient, generating enough power on our own to meet all of our energy needs. During peak sunlight hours, any extra electricity generated is used to charge a solar battery. That battery then powers our home at night, or at any other time when our energy

Figure 2.3: Grid tied solar system.

Figure 2.4: Off grid solar system.

usage exceeds the amount of power our panels are currently generating. This system is shown in the Figure2.4.

2.1.5 Hybrid

Just because we have supplemental energy storage does not mean we have to go off-grid. We can have a hybrid system, which draws electricity from both the power grid and from one or more solar batteries, as needed. If we use more energy than our battery's capacity allows for, then we will draw power from the grid to provide the rest. It is particularly common when electricity usage is at its peak, depending on where we live. The advantage of this system is, during the night, when our system does not produce the electricity, we can draw our power from the grid, and our electricity meter measures our consumption. With a solar battery, we can eliminate our electricity bill entirely and not rely on our local power company for anything. The drawback is, solar batteries are expensive. They can range anywhere from 6,000 dollars to over 8,000 dollars, on top of what we pay to install the actual solar panels.

Additionally, even with a battery backup, our energy needs can sometimes exceed our supply. If we choose to go off-grid, we have nothing to fall back on when running out of power. So, the hybrid solar panel system is the feasible one.

2.1.6 Peer-to-peer energy trading

The expansion of renewable energy resources opened the door for competitive P2P energy trading. The peer-to-peer (P2P) network is a widely used model for resource sharing in the field of computer science where resources are located in and provided by computers (i.e., peers) at the edge of the network. Similarly, P2P energy trading is flexible between peers, where excess energy from various small-scale DERs (Distributed energy resources) is traded locally. Current research intensively evaluates the power grid's alternative architectures to allow easy integration of renewable energy sources and eliminate significant issues of the conventional system [6,12]. A successful Peer-to-Peer (P2P) electricity trading within a microgrid requires a P2P electricity trading price and strategy that enable both energy prosumers and consumers to obtain profits. This is also a challenging issue of p2p energy trading [13].

2.1.7 Game theory

Various technical challenges arise while adopting new energy trading schemes at different levels, such as design, control, and implementation. For example, in P2P trading, it is expected that prosumers will trade their energy with one another with a very low (or not any) influence from a central controller, which makes P2P platforms a trust-less system. Hence, it is a challenging task to encourage prosumers to cooperate in such a trust-less environment. Further, in an energy system with many users, it is not easy to model the decision making process for various energy trading parameters. Furthermore, electricity exchange is different from any other exchange of goods as it's hard technical constraints on energy exchange. How to trade energy in the P2P network without compromising the network's security and how different stakeholders' priorities should define are also challenging tasks.

Game theory becomes a robust framework in the design and analysis of energy trading for the smart grid. Game theory is a mathematical framework. Game-theoretic approaches are widely used in energy trading research in future smart grid, such as auction mechanism and non-cooperative game. The main object of employing an auction mechanism in the energy market is optimally matching energy demand and supply to minimize the costs [14,15].

Non-cooperative game theory can be used to analyze players' strategic decision-making processes, which have partially or conflicting interests over the outcome of a decision process that is affected by their actions. A particular non-cooperative game that has extensively been used to design P2P trading in the literature is the Stackelberg game [16]. A Stackelberg game is essentially a strategic game in which at least one player is defined as the leader who makes its decision first and commits a strategy before other players. On the other hand, other players act as followers in the game, who optimize their strategies in response to the leader's action. The solution concept of a Stackelberg game is the Stackelberg equilibrium. Followers participate in a non-cooperative Nash game and reach a Nash equilibrium in response to the Leader's decision. At the Stackelberg equilibrium, neither the leader nor any follower has any incentive to deviate from its chosen strategy.

Cooperative games allow the investigation of how one can provide incentives for independent decision-makers to act together as one entity to improve their position in the game. The most common form of the coalitional game is the characteristic form [17], where the coalition's value is determined by the coalition members irrespective of the structure of the coalition. Now,

- Canonical coalition game: In canonical coalition games, forming a grand coalition with all players is never detrimental to any game participant. Consequently, such a game's main objectives are to determine whether or not a grand coalition can be formed, investigate if the grand coalition is stable, and formulate a fair revenue distribution scheme for distributing the gains of coalition among the players. The most commonly considered solution concept of a canonical coalition game is the core [17]. Meanwhile, the most popular methods for revenue distribution include the Shapley value, the Kernel, the nucleolus, and the strong epsilon-core.

- Coalition formation game: The objective of a static coalition formation game is to study the coalitional network structure. In a dynamic coalitional game, the game is subject to environmental changes, including a change in the number of players or variations in the network topology. Therefore, this type of dynamic game's main objective is to study the formation of a coalitional structure through players' interactions and inquire about the structure's properties and its adaptability to environmental variations [1].

- Coalitional graph game: Coalition graph games deal with the connectivity of communications between players of the game. The main objectives are to derive low complexity distributed algorithms for players who want to build network graphs and study the graphs [17].

2.2 Prior studies on P2P energy trading

In the smart grid context, energy management research has received considerable attention recently, as seen from a large amount of work reviewed in [18]. They have explored three major systems: namely the smart infrastructure system, the smart management system, and the smart protection system. They have also proposed possible future directions in each system. Their survey divided the energy subsystem into power generation, transmission grid, and distribution grid. The power generation section said that a critical power generation paradigm enabled by the smart grid would be distributed (DG). DG takes advantage of distributed energy resource (DER) systems (e.g., solar panels and small wind turbines), which are often small-scale power generators (typically in the range of 3 kW to 10,000 kW), in order to improve power quality and reliability. According to NIST (National Institute of Standards and Technology), they divide the smart grid into seven domains. Each domain encompasses one or more smart grid actors, including devices, systems, or programs that make decisions and exchange information necessary for performing applications. The brief descriptions of the domains and actors are given in Table2.1. Refer to the appendix of the NIST report [19] for more detailed descriptions. In our work, we have also defined our stakeholders according to this standard.

Table 2.1: Domains and Actors in the NIST SG Conceptual Model

Domain	Actors in the Domain
Customers	The end users of electricity. May also generate, store, and manage the use of energy.
Markets	The operators and participants in electricity markets.
Service Providers	The organizations providing services to electrical customers and utilities.
Operations	The managers of the movement of electricity.
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

The microgrid is regarded as the preferred way to promote the integration of distributed PV systems. PV system's power could be maximally consumed within the microgrid, which reduces the impact on the utility grid [20]. In paper [21], the focus was on the energy sharing problem inside P2P PV prosumers' microgrid. They proposed an energy sharing structure to integrate the autonomous PV prosumers into an energy sharing zone, and a virtual entity named energy sharing provider (ESP) to coordinate the sharing activities. They proposed a energy sharing structure to integrate the autonomous PV prosumers into an energy sharing zone, and a virtual entity named energy sharing provider (ESP) to coordinate the sharing activities. They also proposed a dynamical internal pricing model for the energy sharing zone's operation, which was defined based on the supply and demand ratio (SDR) of shared PV energy, and the feed-in tariff was considered the price bound. As the internal prices are adjusted with the SDR change, participants' autonomous demand response was integrated into energy sharing. They have not considered the power loss during energy sharing. Furthermore, the microgrid with the islanded capability and the internal pricing model has not been designed according to the marginal cost of controllable distributed energy resources and battery energy storage systems. Recently, peer-to-peer energy trading between mini-grids has started a pilot project in Bangladesh named SOLshare. SOLshare [22] has created a revolutionary new approach to bring affordable solar electricity to everyone in Bangladesh and beyond. The researchers of the SOlShare have proposed and implemented step by step electrification approach for off-grid rural areas. The main activities of

SOLshare are the design and management of DC nanogrids. Their current economic model is based on selling its solutions for connectivity SOLbox and SOLcontrol.

As grid development proceeds, it is necessary to realize that smart grid benefits should be the final energy consumption recipient. In the long term, we need to address how to build a smart grid that is both consumer-centric and capable of balancing multiple-attributes. However, one of the critical challenges for successful energy management in smart grids is to motivate consumers to actively and voluntarily participate in such management programs. If the consumers are not interested in actively taking part in energy management, the smart grid's benefits will not be fully realized [23]. In reference [23], aspects of grid modernization that affect consumer-end activities are addressed, categorized into information and infrastructure, instrument and technology, and intelligence and automation. Also, in [9], consumer-centric energy management schemes for smart grids have been studied where utility and cost models have been proposed, and a Stackelberg game has been formulated to solve the optimization problem. Their proposed technique is for a consumer-to-grid system. They have considered a smart grid network that consists of a CPS (central power station) and multiple ECs (energy consumers). The CPS refers to a power generating unit that is connected to the ECs of the network using power lines, and ECs are the energy entities such as electric vehicles (EVs), solar and wind farms, smart homes, and biogas plants, which have energy storage devices (batteries) and communication devices such as smart meters for communicating with the CPS [24]. The block diagram of such a power distribution system is shown in Figure2.5.

To decide on energy trading parameters, a single-leader multiple-follower Stackelberg game is proposed to study the interaction between the CPS and the ECs. They aim to offer an energy unit price that matches each prosumers' constraints. One limitation was that they ignore that a predominant source of demand-side flexibility stems from the inter-temporal elasticity of substitution. Paper [8] has introduced an energy management scheme for a smart community consisting of multiple residential units (RUs) with distributed energy resources (DERs). They share facilities to the RUs public services, such as maintenance of lifts in community apartments. They have considered the case in which the shared facility controller (SFC) has a storage device

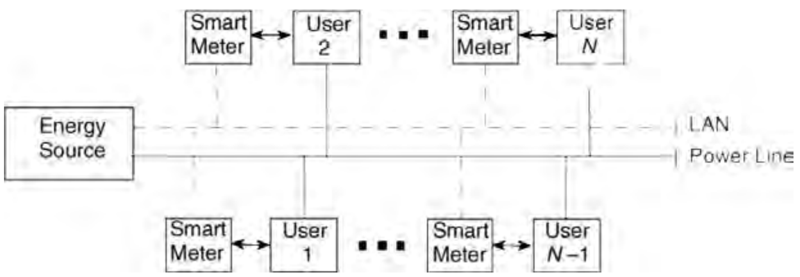

Figure 2.5: Block diagram of smart grid system composed of an energy source, users, a distribution power line, and a local area communication network

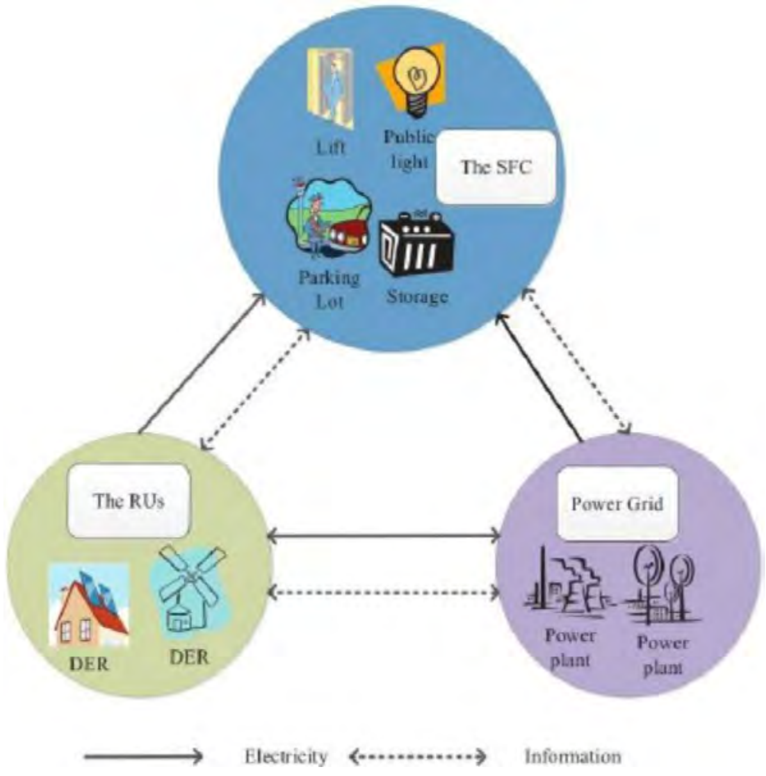

Figure 2.6: Energy management between RU, main grid and SFC

(SD) with a charging and discharging scheme based on the grid's price. The SFC does not have any electricity generation capability. On the other hand, each RU is assumed to have a DER without any storage device. They considered the residential unit as a single unit or group of units. These units connected to the primary grid using power and communication lines, as shown in Figure2.6. They assume that each RU can decide on the amount of electricity that it wants to consume, and hence the excess energy can sell to the SFC or primary grid for making revenue. It has been shown to have considerable influence on the cost incurred by the SFC. They have not considered the impact of discriminate pricing among the RUs on the outcome of the scheme. They also ignore the way of setting the threshold on the grid's price. Furthermore, quantifying the inconvenience between SFC and RUs have also been ignored.

In line with the above works on P2P energy trading, many researchers have researched demand response management (DRM), energy sharing management, and real-time pricing using various game-theoretical approaches in [25], [26–28]. Paper [25] has introduced a contribution concept where each micro-grid has a historical contribution value indicating how much electricity it has provided to this energy trading microgrid society. Besides, there is a weight factor of the contribution that serves to measure the importance of the system's contribution. They assume that each microgrid can be an energy provider or a consumer according to their energy generation and local demand in each fixed time interval. Under the trading mechanism, a

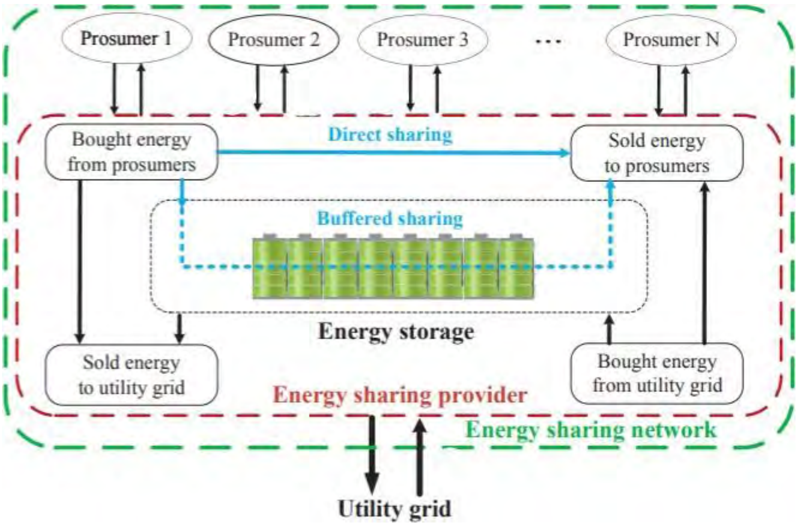

Figure 2.7: Basic structure of the energy sharing

distributor gathers the surplus energy from providers and distributes it to the consumers based on the consumers' historical contribution level. This trading mechanism's economic benefits are studied by analyzing the decision-making procedures of consumers and a distributor. They formulated the problem as a non-cooperative energy competition game among the consumers. The existence and uniqueness of Nash Equilibrium (NE) have shown that the NE solution has been a closed-form.

In [26] paper, the primary focus is to study the energy sharing of multiple PV prosumers with the assistance of public shared Energy Storage (ES). Considering the mismatched power profiles are generally exist between prosumers, the ES could act as a buffer to facilitate energy sharing. They assume that the involving parties in the energy sharing are PV prosumers, Energy Sharing Provider(ESP), and the utility grid. Rational prosumers are willing to share the PV energy with other prosumers when their self-produced energy is surplus or deficit, which is better with more profit or less cost than independent operation. The ESP can be seen as an agent among the prosumers and the utility grid. If the selling and buying energy can be directly matched, energy sharing is defined as direct sharing; otherwise, energy sharing can be facilitated by the equipped ES system of ESP, which is defined as buffered sharing. Generally, the ESP should invest the ES and accordingly pay the investment and maintaining cost.

Therefore, during the sharing process, the ESP should have the rationality to maximize the operating profit. Then, an energy sharing network (ESN) is formed by an ESP and several prosumers. All the components and energy flows are shown in Figure2.7. They have formulated a hybrid approach which consists of day-ahead ES scheduling and real-time internal pricing. In the day-ahead ES scheduling, they have transformed the original profit maximization of ESP to minimize the utility grid's exchanging energy and considered the uncertainty factors through the conditional value-at-risk(CVaR).

Moreover, they have built a Stackelberg game-based DR model for the prosumers with dual characters, importing, and exporting roles in real-time pricing. This method is mainly suitable for large PV prosumers, such as industrial and commercial users. For small residential PV owners, the utility function and the energy consumption adjustment would be different as the number of participants could be huge, not included in their study.

In [27], they have proposed a fully distributed energy trading mechanism. Under their approach, the sellers lead the competition by independently deciding the amount of energy for sale subject to a trade-off between the attained satisfaction from the received revenue and that from the stored energy. The buyers follow the sellers' actions by independently submitting a unit price bid to the sellers. Proportional sharing applies to both sides of the competition where the energy is allocated to the buyers in proportion to their bids. The revenue is allocated to the sellers in proportion to their sales. To study the economic benefits of such a distributed energy trading mechanism with a hierarchical decision-making structure, they have analyzed it using the Stackelberg games' framework. Through rigorous game-theoretic analysis, they have proved that the proposed approach converges to a unique equilibrium solution and shows that distributing the energy based on a well-defined utility function can maximize the payoff for all participating microgrids the equilibrium of the game. This provides an incentive for energy trading among microgrids in the future power grid.

In paper [28], they have formulated an MG energy trading game with the MG energy trading decision based on battery level, local demand, renewable energy generation model, and energy trading history. They have provided the conditions under which an NE exists, showing how an MG can satisfy its local demand by the local smart grid's renewable energy generation. They have proposed a DQN-based MG energy trading scheme in the dynamic game to reduce the dependence on power plants and increase the MG utility compared with the benchmark algorithm. Their proposed DQN-based energy trading scheme uses CNN as a nonlinear function approximator to estimate each feasible energy trading policy's quality or value and compress the MG's state space.

To assess the feasibility of P2P energy trading, where local electricity demand and supply balancing is desired, a so-called P2P index was developed in paper [29]. By clustering the historical smart metering data using the k-means method, customers were categorized by their electricity consumption patterns, and representative demand profiles of low voltage electrical distribution networks were produced. A linear programming optimization was carried out to find the optimal capacity of different DERs to maximize the local demand and supply balancing. PV systems and combined heat and power units were considered as renewable resources. This work provides network planners with guidelines of fair shares of DERs for better constructing their future networks and facilitates a P2P energy trading market paradigm.

In [30], three different representative market paradigms were proposed for P2P energy trading.

The first one is the bill sharing method, a cost-sharing method that each household pays for their individual electricity use. However, this payment is in the form of a cost-share of a single electricity bill of the overall community microgrid recorded by the utility meter at the connection point between the community microgrid and the main grid. This cost is shared according to individual customer's total energy consumption and export. Every customer pays at the same price for each kWh of energy consumption and receives payment at another price for each kWh of export. The second proposed method was the mid-market rate(MMR). The energy exchange price within the neighborhood is taken as a value mid-way between the electricity buying price and selling price. The MMR method assumes that the exchange price is the middle of these two prices. The third one is Auction-based Pricing Strategy (APS). APS is a method that utilizes an auction market for local demand and generation. Each household plays an active role in providing bids or offers of their demand or generation. These offers and bids are put together and managed using pre-defined rules to allocate and define the price strategy. For each of these market paradigms, business models were specified, local energy exchange prices were defined, and P2P energy trading's feasibility to reduce consumer energy costs and increase income for DER producers was assessed.

Paper [31] proposed an energy sharing model with a price-based DR for microgrids of P2P prosumers. They proposed an energy sharing structure to integrate the autonomous PV prosumers into an energy sharing zone. A virtual entity named energy sharing provider (ESP) is defined to coordinate the sharing activities. They also proposed a dynamical internal pricing model for the energy sharing zone's operation, which is defined based on the supply and demand ratio (SDR) of shared PV energy. The feed-in tariff is considered the price bound. As the internal prices are adjusted with the change of SDR, participants' autonomous demand response is integrated into the energy sharing, and the implementation method is also designed.

In [25,26,29 –31], a separate entity acted as an energy trading coordinator and was responsible for executing energy trading. There was no direct communication between buyers and sellers. However, since prosumers in a community are proactive, it is possible to perform P2P energy trading in a community with less energy coordinator involvement.

In [10], they have proposed P2P energy trading using direct interactions between buyers and sellers in a community microgrid. Their proposed P2P energy trading method is carried out as the following steps. First, Prosumers register into a P2P market as a seller or a buyer based on their GDR(generation-to-demand ratio). After grouping prosumers as a seller or a buyer, P2PMO(P2P market operator) assigns a unique and encrypted identity to each buyer and seller, which maintains seller's and buyers' anonymity, ensuring privacy. The P2PMO sends uniquely assigned buyers identities to all sellers and sellers identities to all buyers. This establishes direct communication between sellers and buyers. Each anonymous seller and each anonymous buyer participate in a P2P energy trading game to obtain a stable state. Finally, P2PMO receives information about the final price and amount of energy traded anonymously by different prosumers to settle the financial transactions. Their proposed method is applied to a small community microgrid with PV and energy storage systems. They did not consider the P2P network of several community microgrids and the stochastic nature of prosumers.

Current research intensively evaluates the power grid's alternative architectures to allow easy integration of renewable energy sources and eliminate the conventional system [6,12]. Much literature has been discussed on demand-side management (DSM) coordinated with peer-to-peer (P2P) energy trading using game theory. The majority of the works above are done on large-scale generators to consumers over long distances and non-cooperative game theory, not the P2P energy trading within a local geographical area. In the conventional peer-to-grid (P2G) trading, the prosumer's excess PV energy is used to charge the battery until the battery is fully charged, and the remaining is fed back to the grid. The stored energy is used to meet the demand when the PV generation is lower than the demand. The prosumer buys energy from the grid when there is insufficient energy from the PV and battery system.

In paper [32], they proposed a comprehensive analytical framework of a dynamic price-based P2P energy trading scheme that can help the CPS reduce its energy production cost and supply to the prosumers at the peak demand period. They proposed a cooperative Stackelberg game that comprises a CPS as the leader and the prosumers as followers. At the peak hour, the CPS strategically chooses the selling price per unit of energy such that the supply of energy to prosumers reduces to zero. In response to the choice of price made by the CPS, prosumers, as followers of the game, use the double auction to participate in a coalition formation game. The followers' objective is to form suitable coalitions, based on their submitted bids, and participate in P2P energy trading with the neighboring peers of the same coalition to meet the demand of energy without interacting with the CPS. They have analyzed that due to the strategy-proof property of the formed coalitions' auction and stability, the proposed game possesses a unique cooperative Stackelberg equilibrium. Under the cooperative theoretical scheme, the profit allocation is directly linked to each player's contribution to the coalitions, measured by how much a player's energy behavior can offset the coalitional energy usage [33]. Therefore, they have considered grouping customers with similar load patterns into joint players to limit the number of possible coalitions, thus reducing the required number of linear optimization problems.

Paper [34] proposed a local energy coalition among prosumers, where ES systems operate collaboratively under a centralized control to minimize the joint coalitional energy cost. Cooperative game theory is used to develop a profit-sharing scheme, which ensures that all participants are financially rewarded and discourages participants from deviating from the expected cooperation.

Paper [32–34] formulated cooperative games to show a stable coalition structure. All these researchers have done on a smaller group. A fundamental limitation of all these papers is the computational complexity, which increases exponentially with the number of prosumers. So, an overview of these challenges is also illustrated in Table2.2.

Table 2.2: Findings of different review papers

Author	Identified challenges
C. Zhang [35]	No discussion on local markets.
	No discussion on control system.
	Communication before exchange was ignored.
J. Abdella [36]	No discussion on security and privacy with respect to P2P DET.
	the trading takes place only between local PEVs.
T. Sousa [37]	Investment and maintenance with ICT infrastructure in case of scalability to all system.
	Potential slow convergence to obtain a consensus in the final delivery of energy.
	Guarantee of safety and high-quality energy delivery.
	Reaching the preferences of energy use for all community members at all time.
	Energy poverty for some group of consumers have been ignored.
	No discussion on security and privacy with data.
W. Tushar [38]	P2P trading algorithms need to be simulated for large-scale realistic power system model to observe the impact of computational complexity on the conduct of trading in such a large system.
	the benefit of peer-to-peer energy trading to the distribution grid needs to be demonstrated.
	the way of charging electricity bills needs to be researched and revised for billing under a peer-to-peer trading paradigm.
	investigating how coalitions can help to provide ancillary services to the grid such as with virtual power plants.
	Prioritizing stakeholders.

2.3 General Review and remaining challenges of Related Works

The critical challenges of previous works are as follows, which will be overcome by our proposed framework.

- Previously primary researches have been done on non-cooperative situation.
- However, there was no proper clarification about the player's domain.
- No constraints were imposed on the players.

- Previous works were either prosumer-centric or consumer-centric.
- Some recent energy-trading models and pilot projects have been discontinued as consumers did not accept them. To avoid this, the users' interests and benefits must be taken into consideration.
- The grid's association was ignored.
- Recently some works have been done using cooperative game theory.
- Here, also no proper explanation of area limitation as most of the studies are based on energy trading within the same premises.
- Previously proposed games only addresses one consumer, which seems to be impractical, as, in reality, P2P accommodates more than one consumer.
- The previous research only focuses on prosumers and consumers' interaction, either in cooperative or non- cooperative games.
- In all the bidding strategies and pricing mechanism, there is a high probability that some prosumer or consumer may face an exit situation, either because of not getting matched entities or not getting the expected price from the market. This may lead to a monopolized market, in which not all players can trade fairly, leading to uncertainties and contract instabilities.
- No explanation of these players who will not participate in coalition formation.

To address these gaps, we have proposed a peer-to-peer energy trading framework for Smart grids, a hybrid combination of cooperative and non-cooperative game theory approaches.

Chapter 3

Proposed Hybrid System

This section presents our proposed system's architecture, methodologies, utility function and cost function, and algorithms that we use in this thesis. We have also described some properties of our coalition formation game and the non-cooperative game.

3.1 Problem Formulation

To formulate the problem, we assume an energy network consisting of a grid and many customers. Among the customers, N is a set of prosumers. In this paper, customers refer to energy entities in the network that buy energy from the grid. On the other hand, prosumers have energy producing capability and can participate in P2P energy trading and sell its energy to the grid or other end users. Each prosumer nsN is a rational individual equipped with a rooftop solar panel with or without a battery in a grid-connected system.

The grid always needs to meet the total demand $D(t)$ of its customers at the time t. Suppose the customers' total demand $D(t)$ is very high, for example, during peak hours. In that case, the network could be overloaded, and the grid might need to start a new generation unit or always maintain a reserve to meet the extra demand of its customers. This increases the cost of the grid significantly [39]. To this end, the grid permits end users (EUs) to participate in P2P trading and also acts as a buyer and buy energy at peak hours from prosumers if the total demand is higher than a threshold value, E_{Thresh}.

To ensure this constraint, the grid encourages end users to buy energy from other prosumers rather than the grid by lowering grid's buying price. And when demand goes down the base load the grid lower its selling price. In this work, the main objective is to show from P2P trading how all the parties get benefited, including the grid, customers, and prosumers. Now, we formulate the system model in the following section.

3.2 System Model

The flow diagram of the system is shown in Figure3.1. Our research considers peer-to-peer energy management for peak demand and off-peak demand during peak hours among the grid, prosumers, and consumers. Our framework is designed in such a way so that all the players can get benefitted.

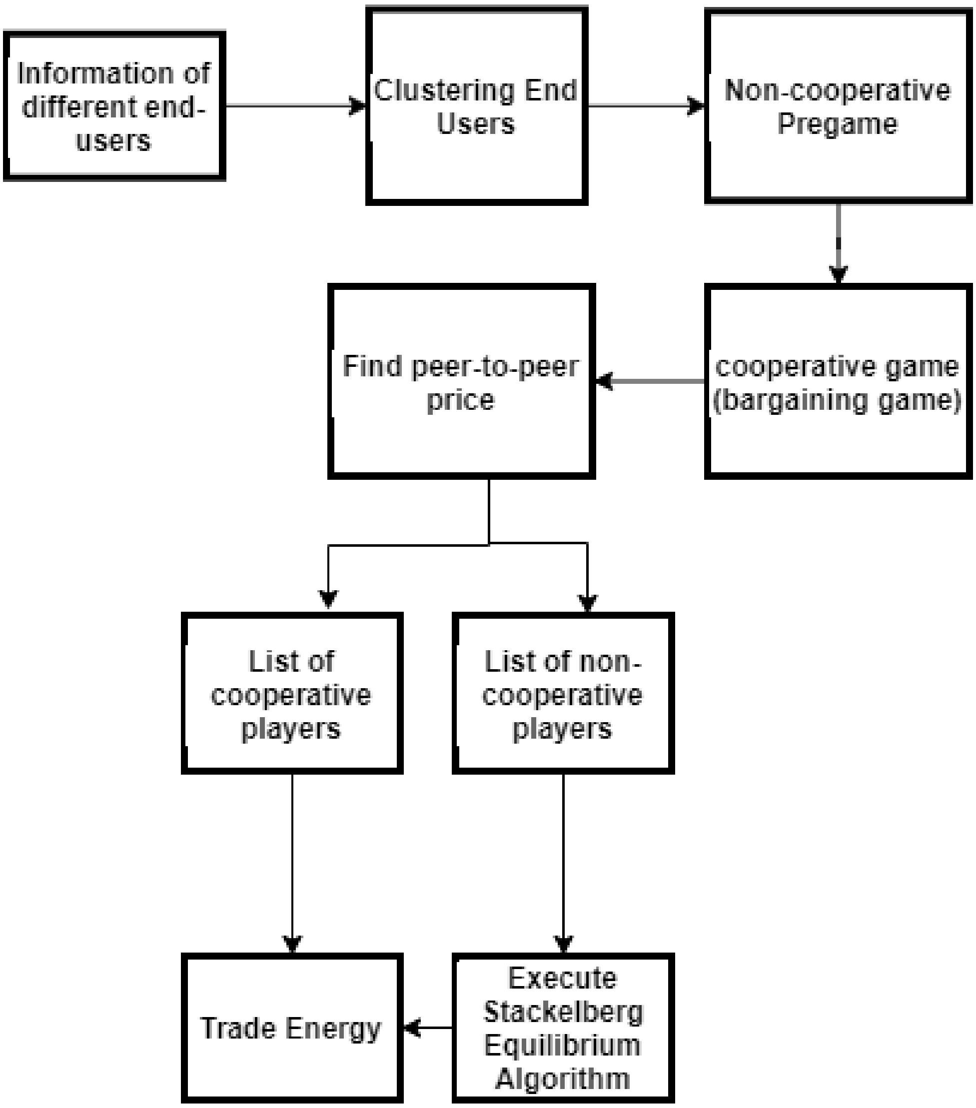

Figure 3.1: Flow Diagram of the Proposed System Model.

- Let us consider, there is a set of N end users (EUs) and the grid. $D_i(t)$ is the demand of energy for a user i at any time t. Here, in smart grid networks, the demand $D_i(t)$ is considered as being random [40] since it depends on many unpredictable factors such as consumption level, consumer behavior, among others. E_{Thresh} is a specific threshold value, which is the capacity of the grid's supply at that moment. So, the condition for peer-to-peer energy trading to be initiated is,

$\sum D_i(t) > E_{Thresh}$

- In general, the buying price P_{BG} set by the grid is considerably lower than its selling price P_{SG}. So, the users suffer a loss. On the other hand, if peer-to-peer price P_{p2p} is always lower than the P_{SG}, then the grid will suffer a massive loss as the users will always transfer energy bypassing the grid.

- Another problem is that the computational complexity increases exponentially with the number of participants [41].

- To overcome the problems mentioned above, we first design a coalition formation game to decide their strategies and peer-to-peer price P_{p2p}.

- We consider the case when peer-to-peer energy trading is enabled. That time we group the end-users into two groups: buyer and seller. Both groups can include the grid, prosumers, and consumers according to the demand of energy. When generated energy of the ith prosumer Gen_i is sufficient and the minimum energy need for i th prosumer is $Need_i$ is less, then the surplus energy of i th prosumer is, $S_i = Gen_i - Need_i$. At that time, they act as the seller group. They can contribute to other users who are in demand for energy.

  A suitable utility function for the prosumer and the grid's cost function is defined in the following subsections.

3.2.1 Utility function

Utility function of seller who participate in P2P energy trading,

$$U_i = k + D_{avgj} * P_{p2p} + max(0, S_i - D_{avgj}) * P_{BG} \tag{3.1}$$

In Equation3.1, k is a preference parameter [16,42] which vary from prosumer to prosumer and may also vary along with time and $k = ln(1 + max(0, S_i))$. In Equation3.1, U_i is the utility of a Prosumer i with respect to a buyer j. Here, $S_i = Gen_i - Need_i$. D_{avgj} is the weighted demand of the j th buyer. Here, we have used logarithmic utility instead of linear utility. As if there is no upper bound of the possible wealth, then the linear utility meets with mathematical obstacles. The other parts of the equation3.1are the revenue that the EU receives from selling D_{avgj} energy at P_{p2p} price and if any surplus energy remain then that will be sold to the grid at P_{BG} price.

3.2.2 Cost function

Energy cost is comprised of three primary components:

- Generation (the production of energy by power plants)

- Transmission (the bulk transfer of energy over long distances at high voltages via interconnected lines that form a network, or the grid)
- Distribution (lines, poles, and transformers owned by utility companies or independent entities that distribute energy over shorter distances, from regional transmission operators to homes and businesses).

We define a net cost function to capture the total cost of the grid. It has three components. When the grid takes over (when demand goes below the threshold), it will lower its selling price P_{SG} to compete with the seller groups. P_{NEU} is the new price of the seller group that will activate when D_{avgi} is greater than surplus energy and higher than E_{Thresh}. At that time, they will limit their own usage and give it to others. But they will not consider selling unless they have profit. If the exchange price between end users is always lower than P_{SG}, then the users will always transfer energy bypassing the grid. So, in our proposed model, we introduce a new price P'_{SG} which hold the following condition,

$$P'_{SG} < P_{NEU} < P_{SG} \tag{3.2}$$

Equation3.3is the cost function. It has a revenue component and a cost component. Here the first part is the utility of the grid at peak hour. The Second part will activate for the above situation. D_{i1} is the demand which cannot be supplied by the prosumers. Generation cost (GC) includes the cost of energy production or an additional generator to meet the excess demand.

$$\begin{aligned} C_G = max(0, \sum D_i - \sum S_i) * P_{SG} + \sum D_{i1} * P'_{SG} \\ -max(0, \sum S_i - \sum D_i) * P_{BG} - GC - TC \end{aligned} \tag{3.3}$$

Here, TC is the transmission cost.

The grid can optimize its price in a centralized fashion to minimize its total cost of purchasing energy from the EUs by determining the parameters P_{P2P} and S_i. To this end, we propose a scheme based on a cooperative coalition game and a non-cooperative Stackelberg game in the following sections.

3.2.3 Cooperative Coalition Game

A coalition is simply a subset of the set of players which forms in order to coordinate strategies and to agree on how the total payoff is to be divided among the members.

To formulate different players' collaboration as a cooperative game, we need to answer three key questions: 1) how do players collaborate, 2) how do we quantify the value of this collaboration, and 3) how do we allocate the benefit gained through collaboration to each player. The following subsections provide detailed discussions on these questions.

Coalition Algorithm for coalition formation

In Algorithm1, we show how to formulate the coalition. Here, C is the grand coalition. It consists of all the participating players. Based on distances, we use the K-means clustering algorithm to divide it into smaller clusters. Moreover, we use re-clustering to make a much smaller group so that the coalition formation can be much more effective and cost savings. As we use the grid's infrastructure for energy trading, we have to think of sharing costs related to the use of common infrastructure and services. Here, we have used a zonal cost allocation policy [43]. If anyone wants to trade outside of any cluster, then he has to pay a unique cluster fee, which will increase the cost of the prosumer or consumer and decrease the utility. So, this constraint encourages end users to trade inside the cluster. Following equation3.4represent the network cost,

$$N_{eui,euj} = \frac{U_{cluster} N_{cluster}}{NU} \tag{3.4}$$

Here,

$N_{eui,euj}$ =Network charges of end user i's trade with end users j.

$U_{cluster}$ = unique cluster fee.

$N_{cluster}$ = number of crossed cluster for trade.

NU = total number of end users.

This second clustering will be done when there are still many more end-users in the first clustering means end users are not uniformly distributed. Based on battery capacity and PV roof area, we divide the coalition members into buyer set B and seller set S.

Before this cooperative game, we have considered a non-cooperative pregame where the grid is the leader, and end-users are followers. So the grid will select its buying price. And in the case of the selling price, we have used a mix of static and dynamic prices. At first, the selling price is static for peak and off-peak hours. Based on the price selected by the grid, within the group, each seller $n \in S$ submits its reservation price (P_{nS}) and energy (E_{nS}) that it is interested in selling at each time slot. Similarly, each buyer $n \in B$ submits its price (P_{nB}) and energy (E_{nB}) that it interested in buying. Then the algorithm arranges the selling prices in ascending order and the buying prices in descending order without the loss of generality as,

$$P_{1S} < P_{2S} < \ldots.. < P_{nS} \quad and \quad P_{1B} > P_{2B} > \ldots.. > P_{nB} \tag{3.5}$$

Then, we generate the aggregated supply and demand curves using equation3.5to determine the intersection point of the two curves. The price at the intersection curves refers to the peer-to-peer price P_{p2p}. Once the coalition algorithm is formed following Algorithm1, the prosumer trades their energy within each respective coalition.

Value of Coalition

We will quantify the above coalition's value by calculating individual prosumers' energy costs if they form coalition and behave cooperatively.. Moreover, we compare these two values. This process evaluates all the financial benefits for all the possible coalitions (groups of prosumers). The net load of individual players (including the player's batteries) and the electricity prices for trading with the supplier are the inputs for calculating the coalition. The value of the coalition is shown in the following function (where RG= clustered group (it can be re-clustered group also if any)), but we assume that inter cluster group is not possible. If anyone wants to trade energy with other cluster's player then they have to behave non-cooeratively.

$$value_{coalition} = \sum_{i \in RG} Cost_i^{noCollaborate} - Cost(RG) \tag{3.6}$$

So, this cooperative coalition game can be defined as following,

Definition 1. A n-person coalition game is represented by (N, v), here N = 1,2. . . N is the set of players and v is the function which refer the value of coalition. The value of coalition function must satisfy two conditions,

- $v(\emptyset) = 0$
- if S and T are two separate entities ($S \cap T = \emptyset$), then $v(S) + v(T) \leq v(S \cup T)$

The first condition states that the value of an empty coalition is zero. The second condition states that the value of two different entities should be more significant when they join than the value obtained when they do not form a coalition.

Allocation of benefit gained through collaboration

Here we design a method to allocate the energy bill or income of individual customers. This allocation is conducted by considering the marginal contributions of individual prosumers.

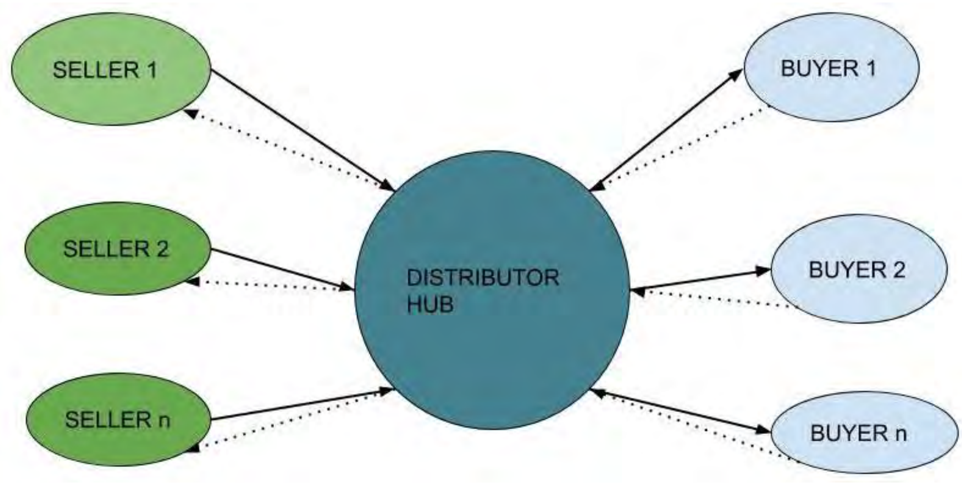

Figure 3.2: Allocation of benefit.

Figure3.2shows the allocation of benefit mechanisms. All the players connect with a central distributor hub. The incoming arrow refers to the seller, and the outgoing arrow refers to the buyer. The dotted line refers to the cash flow. Each buyer will pay the bill according to the percentage of his consumption and each seller will get the monetary award according to his percentage of contribution. Distributor hub charge is the network charge. So, following equations define the value of contribution,

$$S_p = pc_S * P_{p2p} - hub_{cost} \tag{3.7}$$

Here, pc_S is the percentage of contribution of seller and S_p is the utility of seller p.

$$B_p = pc_B * P_{p2p} + hub_{cost} \tag{3.8}$$

pc_B is the percentage of consumption of buyer and B_p is the cost of buyer p.

3.2.4 Non-cooperative Stackelberg Game

Our cooperative game theory explores collaboration strategies that execute an agreed-upon interference mitigating policy. Here, some participants may bid a price for selling energy, and if the intersection price is lower than that, it will not participate. Without that player, the trading will be continued. However, if most of the players fall after the intersection point, several iterations will occur to balance supply and demand. As if supply becomes less due to insufficient prosumers, buyers will be notified and increase their buying price for the next iteration.

However, players cannot be forced into such collaboration, and a small number of players can always keep themselves out of this coalition formation due to their high expectations. So, we involve a mix of cooperative and non-cooperative players. From Algorithm1, we have decided on the seller group, buyer group, and peer-to-peer energy trading price P_{p2p}. For non-cooperative players, we design the Stackelberg game Γ.

$$\Gamma = \{(N \cup G), \{D_n\}_{n \in N}, \{U_i\}_{i \in N}, C_G, P_{BG}\} \tag{3.9}$$

which contains the following components:

- The end-users in set N act as the followers in the game and respond to the price set by the grid(G).
- The D_n is the set of strategies of each EU n $\in$ N from which it selects its strategy.
- U_i is the utility function of each EU n as explained in equation3.1that captures the EU's profit from consuming energy ($Need_i$) and selling a minimum of D_{avgi} and S_i energy at P_{p2p} price to the buyer group and surplus energy to the grid at P_{BG} price.
- P_{BG} is the price set by the grid to buy from the EU'S.
- The cost function C(G) for the grid (leader of the game), which captures the total cost required by the grid for trading energy with EUs.

As discussed previously, each EU and the grid's objectives are to maximize the utility in equation3.1and to minimize the cost in equation3.3respectively by their chosen strategies.
For this purpose, one solution can be the Stackelberg equilibrium (SE) of the proposed. At this equilibrium, neither the grid nor any end-user can benefit, in terms of total cost and utility, if they change their strategy.

Definition 2. Consider the game Γ defined in3.9, where U_i and C_G are determined by3.1and 3.3respectively. A set of strategies ($Need_i^*$,P_{P2P}) constitutes a SE of the proposed Γ, if

$$U_i(Need_i^*, P_{P2P}) \geq U_i(Need_i, P_{P2P}) \tag{3.10}$$

and

$$C_G(Need_i^*, P_{P2P}) \leq C_G(Need_i^*, P_{BG}) \tag{3.11}$$

Therefore, when all the players in (N $\cup$ G) are at SE, the grid cannot reduce its cost by reducing its price from the SE price P_{P2P}, and similarly, no EU n can improve their utility by choosing a different energy to $Need_i^*$ for consumption.

3.2.5 Stackelberg Equilibrium Algorithm

To attain the Stackelberg Equilibrium, the grid needs to communicate with end-users (EUs). We propose an algorithm that all the EUs and the grid can implement in a distributed fashion to reach the unique SE. In each iteration, a coalition will be formed according to Algorithm1.Prosumer i chooses its best energy consumption amount $Need_i$ in response to the price set the grid P_{BG} and peer-to-peer price P_{p2p} from equation3.12.

$$\begin{aligned} P_{P\,2P} = average(P_{nS}, P_{nB}) \\ where,\ P_{nB} > P_{BG} \end{aligned} \tag{3.12}$$

Then, the grid decides on its best price that minimizes its total demand load and encourage prosumers and consumers to cooperate in peer-to-peer energy trading. The interaction continues until the condition in equation3.10and equation3.11are satisfied, and therefore the Stackelberg game reaches the SE. Details are given in Algorithm2. Now, as the algorithm is designed, in response to the P_{p2p} and P_{BG}, prosumer i chooses its strategy to choose $Need_i$ from the bounded range $[Gen_i, D_{avgi}]$ to maximize its concave utility function U_i. Hence, due to the bounded strategy set and the continuity of the utility function U_i with respect to $Need_i$, each EU i also reaches a fixed point at which its utility is maximized for given price P_{p2p} and P_{BG}. As a consequence, the proposed algorithm is always guaranteed to converge to unique SE of the game.

3.3 Algorithms

3.3.1 Coalition Algorithm

Algorithm 1 Coalition formation algorithm

thresholdvalue α, grandcoalition C, seller S, buyer B, areaFactor β
Apply K-means algorithm to divide the C according to euclidian distance.
if $noofhousesinanycluster > \beta$ **then**
  recluster
end if
for i = 0 and $i < noofhouses$ **do**
  if $surplusenergy[i] > 0$ or $storagecapacity[i] > 0$ **then**
    for $j = i$ to $j < no_of_houses$ **do**
      if $storagecapacity[i] > storagecapacity[j]$ **then**
        $S \leftarrow enduser_i$
      else
        $S \leftarrow enduser_j$
      end if
    end for
  else
    $B \leftarrow enduser_i$
  end if
end for
each seller $n \in S$ submits it's reservation price (P^t_{nS}) and energy (E^t_{nS}) that it interested to sell.
each buyer $n \in B$ submits it's price (P^t_{nB}) and energy (E^t_{nB}) that it interested to buy.
sort all the selling price in ascending order and buying price in descending order.
generate the aggregated supply and demand curves.
The intersection point of these two curves reveals the stable price P_{p2p} and players who agree to collaborate.

3.3.2 Stackelberg Equilibrium Algorithm

Algorithm 2 Stackelberg Equilibrium algorithm

Require: initialization: P=0, $C_G^* = max(0, \sum D - \sum S) * P_{S_G} - max(0, \sum S - \sum D) * P_{B_G} - GenerationCost$

for Buying pricing P_{P2P} from P_{BG} to P_{SG} **do**

  for each EU $n \in N$ **do**

    EU n adjusts its energy consumption $Need_i$ according to,

    if $D_{avgi} \leq S_i$ **then**

      $Need_i^* = argmax[k + D_{avgi} * P_{p2p} + max(0, S_i - D_{avgi}) * P_{BG}]$

    else

      if $D_{avgi} \geq E_{Threshi}$ **then**

        $Need_i^* = D_{avgi} * P_{NEU} * ln(1 + \sum D_i - \sum S_i)$

      else

        Grid will stop $P2P$ trading

      end if

    end if

  end for The Grid computes the cost according to, C_G=max(0, $\sum D_i - \sum S_i$)*P_{SG}+D_{i1}*P'_{SG}- max(0, $\sum S_i - \sum D_i$)* P_{BG} -Generation Cost

  if $C_G \leq C_G^*$ **then**

    The Grid records the optimal price and minimum cost $P = P_{P2P}$, $C_G^* = C_G$

  end if

end for The SE ($Need_i^*$, P_{P2P}) is achieved.

3.4 Properties of the Peer-to-peer Energy Trading

Following sections are the study of the properties of the proposed coalition game and Stackelberg game.

Definition 3. A coalition mechanism is said to be strategy-proof, if the participants reveal their true strategies during the group formation process and do not cheat and deviate from their chosen strategies during the trading.

Theorem 1. The proposed P_{p2p} price selection mechanism followed by the prosumers to decide on their respective coalition and subsequent peer-to-peer trading is strategy-proof.

Proof. Let us assume that the energy amount that each prosumer n reveal to trade via price selection is E_{nS}^t and E_{nB}^t for a seller and buyer respectively. Now, if the total available supply and demand are $\sum E_{nS}^t$ and $\sum E_{nB}^t$ respectively, the burden shared by each participating seller $n \in S$ is ,

$$burdershare = 1/S(\sum_{n=1}^{S} E_{nS}^t - \sum_{n=1}^{B} E_{nB}^t) \quad (3.13)$$

Now, let us assume that one prosumer i, which is a seller, cheats during the energy trading and trades $E^{t'}_{nS}$ instead of E^{t}_{nS}. Then, the burden is,

$$burdershare = 1/S\left(\sum_{n\in S, n\neq i} E^{t}_{nS} + E^{t'}_{i\in S} - \sum E^{t}_{nB}\right) \quad (3.14)$$

Which is not possible. This is due to the fact that, as the scheme is proposed, the burden, which is shared equally by all seller prosumers only possess the value *burdershare* only if all the seller stick to E^{t}_{nS}, for trading. Every member obtains at least the same utility as if they told the truth. Similarly, by considering that one buyer j, chooses to buy $E^{t'}_{nB}$ instead of E^{t}_{nB}. Then it affect other seller or buyer, which will not be permitted by the grid. Because buyer, seller, coalition form all will be done and fixed before energy trading .Hence, no prosumer would cheat and deviate from their chosen strategies without affecting others, and this subsequently proves the strategy-proof property of the proposed scheme.

Definition 4. A group of coalitions is said to be stable, if no prosumer has an interest to perform a merge-and-split operation in order to form another new coalition for better payoff in a selected time slot. This is known as stable.

Definition 5.. A partition refers to the Pareto optimal network structure if it exhibits the property of stability with the following characteristics:

- The partition is stable.
- The resultant partition is the unique outcome of any round of merge-and-split operation.
- The partition maximizes the social welfare (sum utilities of the participants).

Theorem 2. At any given time slot t, the network structure or partitions resulting from the proposed coalition game is stable and Pareto optimal.

Proof. : According to Algorithm1and2we note that any time slot *t*, prosumers and consumers participate in p2p trading when utility is maximum and cost is minimum. And hence, they cannot be better paid off by choosing alternate coalition. Consequently, it will have no incentive to split from its current coalition and merge to a new one for better payoff. So, the structure is stable and also Pareto optimal (according to definition 4, and definition 5). Here, the strategy state is Pareto optimality in terms of energy consumption among residential users and minimizing energy cost.

Definition 6. A P2P energy trading scheme is defined to be prosumer-centric and consumer-centric if

- The coalition structure formed in is stable.
- The utility received by each participant, satisfies the rational economic, elaboration likelihood and positive reinforcement models of motivational psychology [44].

We note that from Theorem 2 the proposed coalition formation game possesses stability. We also note that,

- A prosumer and a consumer decide to participate in coalition based on the utility function3.1. The utility is influenced by the P_{p2p} price. In this context, clearly, economic benefit plays a key role for both prosumers and consumers to choose a stable coalition to perform P2P trading. Thus, the proposed scheme satisfies the rational-economic model.

•From Theorem 2, the proposed coalition formation game possesses stability.

- A positive reinforcement refers to the case when a human response to a circumstance is followed by a reinforcing stimulus that increases the potential of having the same response from the human when a similar situation arises [45].

  For example, by always receiving a better utility by cooperating with other peers within a P2P energy network is likely to encourage the users cooperate with its peers for energy trading again in the future.

  Thus, the proposed social cooperation based P2P trading satisfies all three considered motivational psychology models and thus exhibits the properties of a prosumer-centric and consumer-centric scheme.

Theorem 3. A unique Stackelberg Equilibrium always exists in the proposed Stackelberg game between the grid and end users.

Proof: For each end user , the utility function3.1is concave while taking the second partial derivative of S_i (where, $S_i = Gen_i - Need_i$) , since,

$$\frac{\partial^2 U_n}{\partial S_i^2} = -\frac{1}{S_i^2} \tag{3.15}$$

From equation3.15, we can say, $\frac{\partial^2 U_n}{\partial S_i^2} < 0$. So, utility function3.1is strictly concave. and hence for any price $P_{p2p} > 0$, each end user n will have a unique S_i for $Need_i$, chosen from a bounded range, that maximizes utility.

We also note that the game reaches the Stackelberg Equilibrium when all the players in the game, including each participating end user and the grid, have their optimized payoff and cost respectively, considering the strategies chosen by all players in the game.

Thereby, it is evident that the proposed game reaches an SE as soon as the end user is able to find an optimized price, unique energy. Now from equation3.3, given the choices of energy by each end user n in the network, the cost function is convex with respect to price. Hence, the grid would be able to find an optimal unique per-unit price for buying its energy from the prosumers based on their strategies. Therefore, there exists a unique SE in the proposed game, and thus Theorem 4 is proved.

Chapter 4

Simulation Results

In this section, we have analyzed the proposed method from various aspects to evaluate its performance. At first, all the parameters are defined. Then the simulation process is described. And then, analysis and evaluation are described.

4.1 Market Parameter

In our simulation, the energy trading market is modeled as a 24-hour game, which repeats daily. We split the time into $|t| = 60$ minutes consecutive time intervals. This means we split the time into 1 hour. During an interval t_k, each consumer buys energy on the market according to his private demand curve, modeled as a sum of fixed and variable components. The fixed component includes a morning and an evening peak between 7 am to 2 pm and 4 to 8 pm [46]. Each consumer has his habits, and thus, the peaks are generated at random within the typical times, which are shown in Figure4.1. We have used the Australian distribution network dataset [47], and the variable part is sampled from a normal distribution. Consumers are interested in buying cheap energy to meet their demands. We assume that consumer demand varies between 100 and 500 KWh. It is important to note that all chosen parameter values are particular to this study only and may vary according to the availability, and number of end user, requirements of the grid and buyers, trading policy, time of the day/ year and the country.

prosumers extend consumer function with generation capabilities. Each prosumer has several solar power panels capable of generating between 245 and 345 KWh. The value of k is selected based on the first part of the equation3.1. For our proposed system, we have considered preference is 1 when $k > 0$ otherwise 0. PV output curves of typical day are shown in Figure4.2. Sample PV output of five houses are shown in Figure4.3.

As power load varies between end users, all the parties, including the grid, prosumer, and consumer, need to participate in peer-to-peer energy trading.

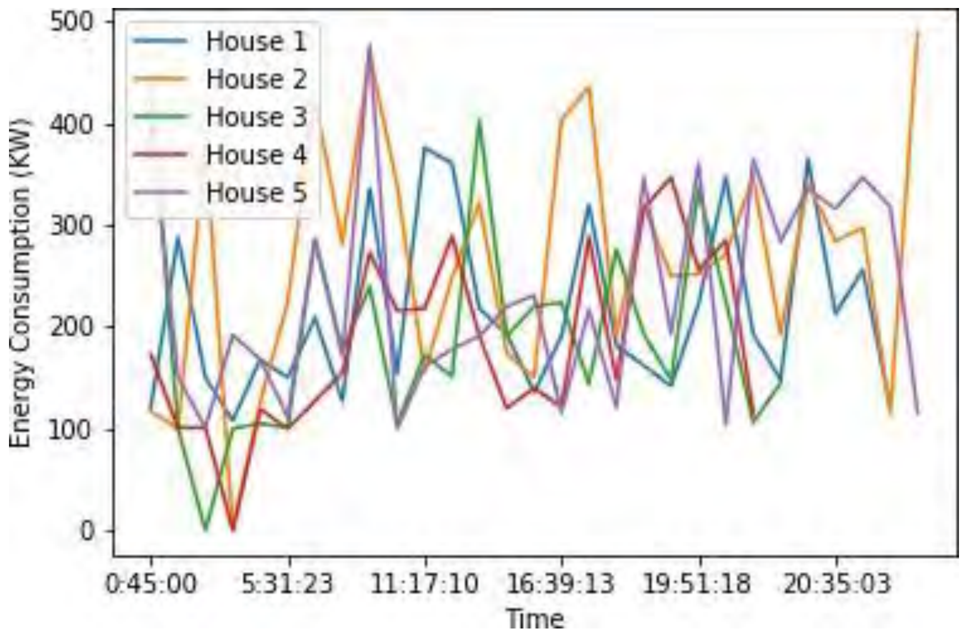

Figure 4.1: Energy Consumption of different houses.

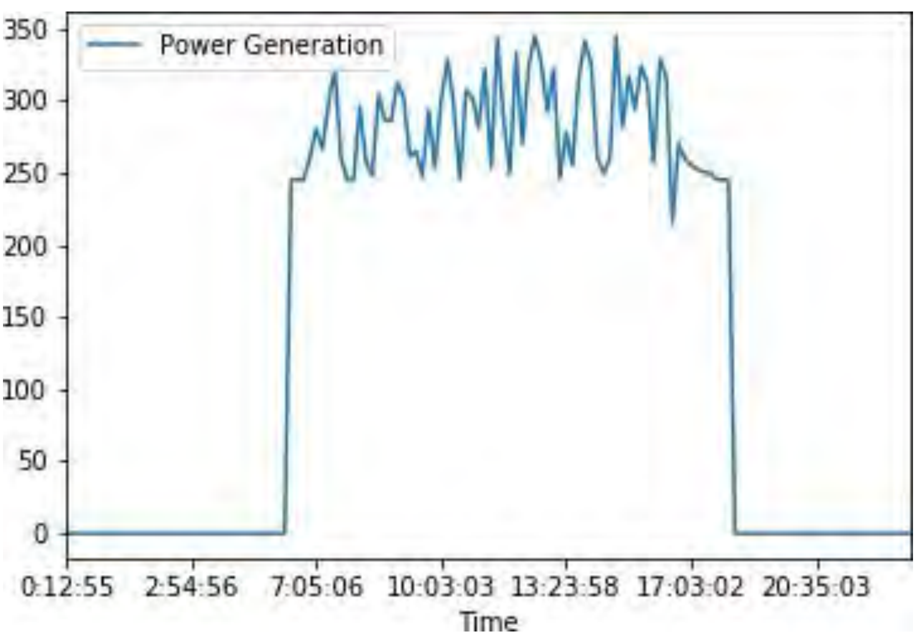

Figure 4.2: PV output of all prosumers.

4.2 Simulation process

The simulation have done in two part. Firstly, we show the solution process of the proposed algorithms and secondly, analysis the perspective of economic, incentive and efficiency.

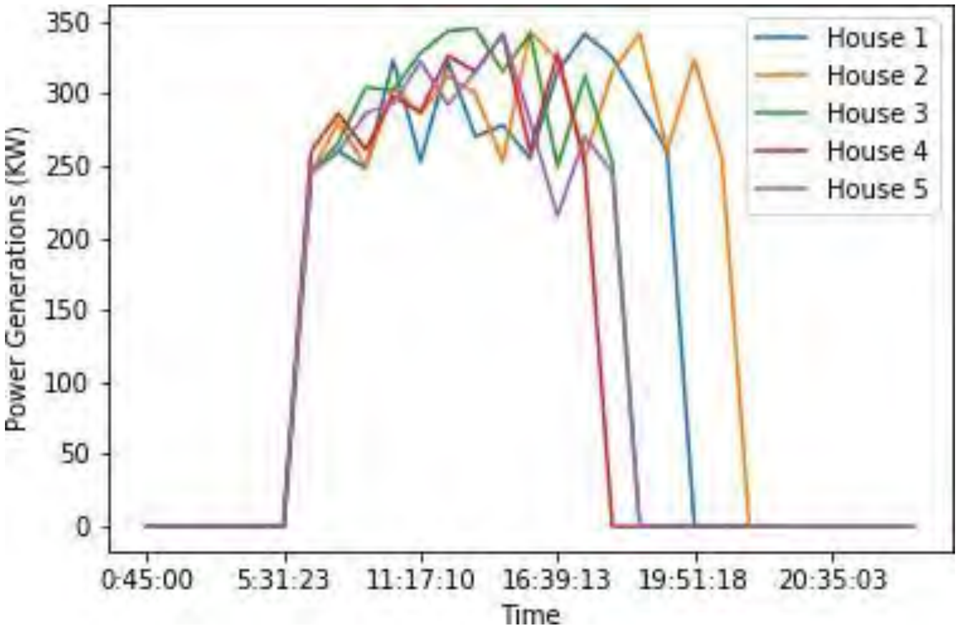

Figure 4.3: PV output of different houses

Throughout the simulation, end users are randomly generated in an area of 50 km x 50 km. A sample of this is shown in Figure4.4. Then we run K-means algorithm to cluster End users, assuming to be connected with electric lines and are capable to trade power Figure4.5. Each cluster represents a grand coalition.

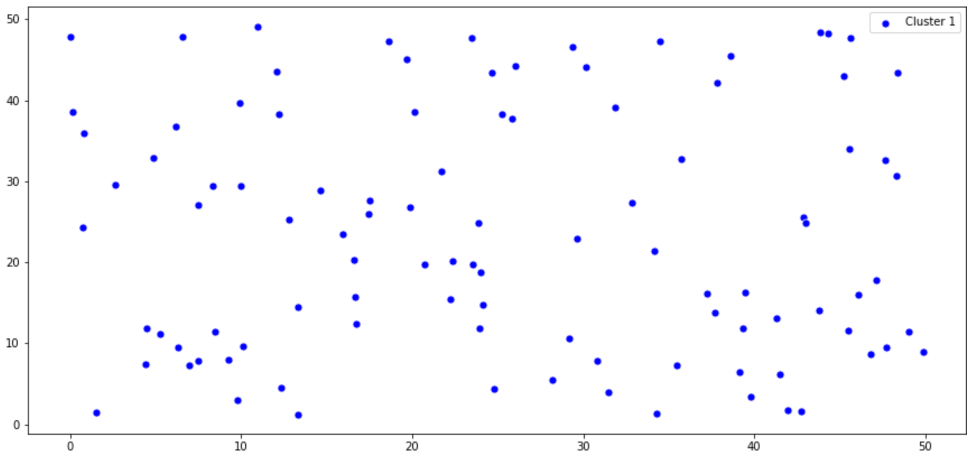

Figure 4.4: Scatter graph of different houses

Now, various clusters contain different houses and each house has their own energy load, power generation capabilities and battery storage which is shown in Table4.1. So, according to our

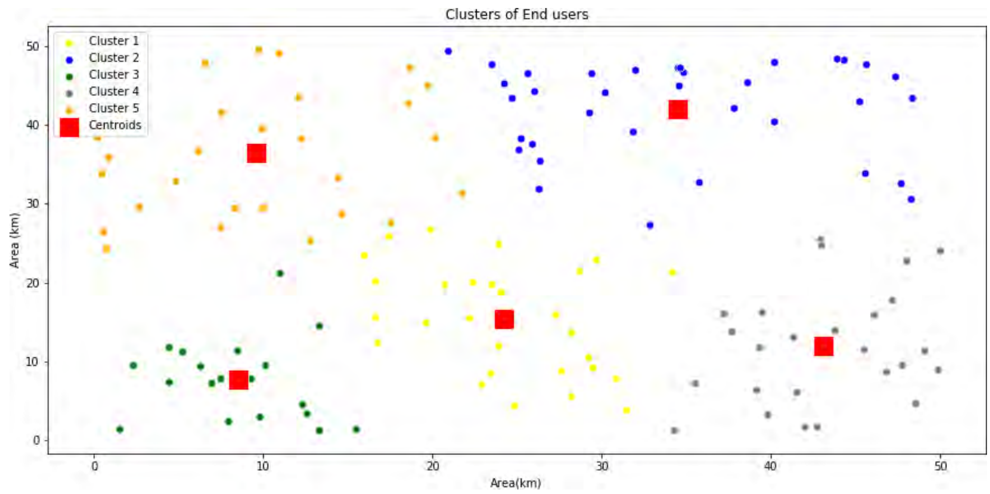

Figure 4.5: Cluster houses using K-means algorithm

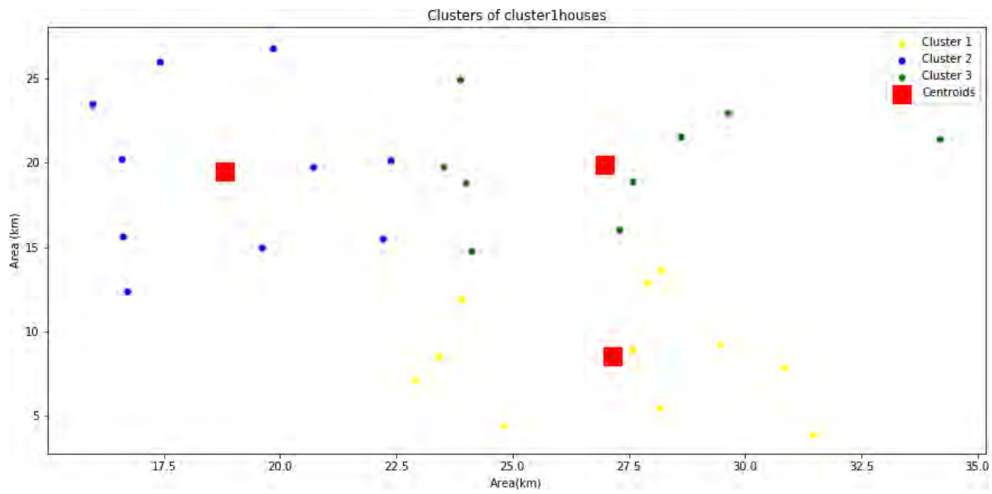

Figure 4.6: Re-cluster of cluster 1 houses using K-means algorithm

proposed coalition algorithm1we again divide it into smaller groups. Figure4.6shows the re-cluster of cluster one houses. Then we group these end users into sellers and buyers based on their features. A sample of sellers and buyers among clustered houses are shown in Figure4.7, 4.8, and4.9. Here, blue circle represents seller and red star represents buyer.

Based on the export and import electricity price of Australia, the buying price of electricity from the grid is taken as 39 cents/kWh. The minimum selling price to the grid is assumed 2 cents/kWh.

To trade the energy at each time slot, the prosumers choose their bidding from the range [10, 30](cents). When the total demand of all End users is below threshold of that selected time slot, the grid sells its energy to the end users at the general standard off peak rate of 20 cents

Table 4.1: Features of different houses of one cluster

house no.	Energy consumption(KWh)	Power generation(KWh)	Inverter quantity
1	437	0	0
2	173	0	0
3	288	0	0
4	101	215	2
5	108	245	1
6	126	245	3
7	105	0	2
8	248	312	2
9	476	253	1
10	280	307	1
11	397	302	1
12	303	333	1
13	403	323	1
14	289	326	1
15	478	292	1
16	191	315	1
17	320	341	1
18	140	260	1
19	416	215	3
20	142	260	1
21	488	250	3
22	121	245	1
23	469	0	3
24	242	0	0
25	104	0	0
26	316	0	1
27	213	0	0
28	298	0	0
29	126	300	3
30	226	0	0

per kWh. However, as soon as the total demand becomes greater than the threshold, the grid allow prosumers to contribute in energy trading. The bidding process will continue for some iteration until it reaches equilibrium. For example, buyer's buying price and prosumer's selling price for a particular time slot is shown in Table4.2. Here, we do not show all the prices as all the prosumers and consumers will submit their trading prices in this way. And according to the algorithm1, we produce two curves as Figure4.10. Form this we determine the intersection point of two curves which will refer the highest reservation price. If the price does not match, then the process will iterate multiple times with the changed prices of sellers and buyers.

Based on the selected trading price lists of cooperative and non-cooperative players are selected.

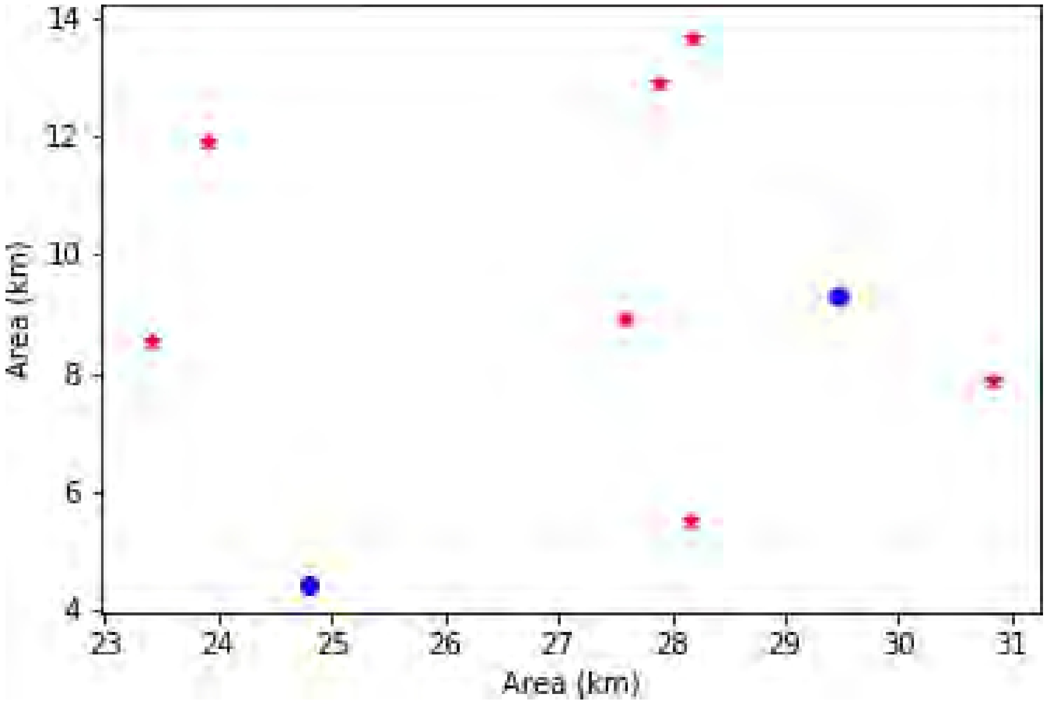

Figure 4.7: Seller and buyer among cluster 1 houses

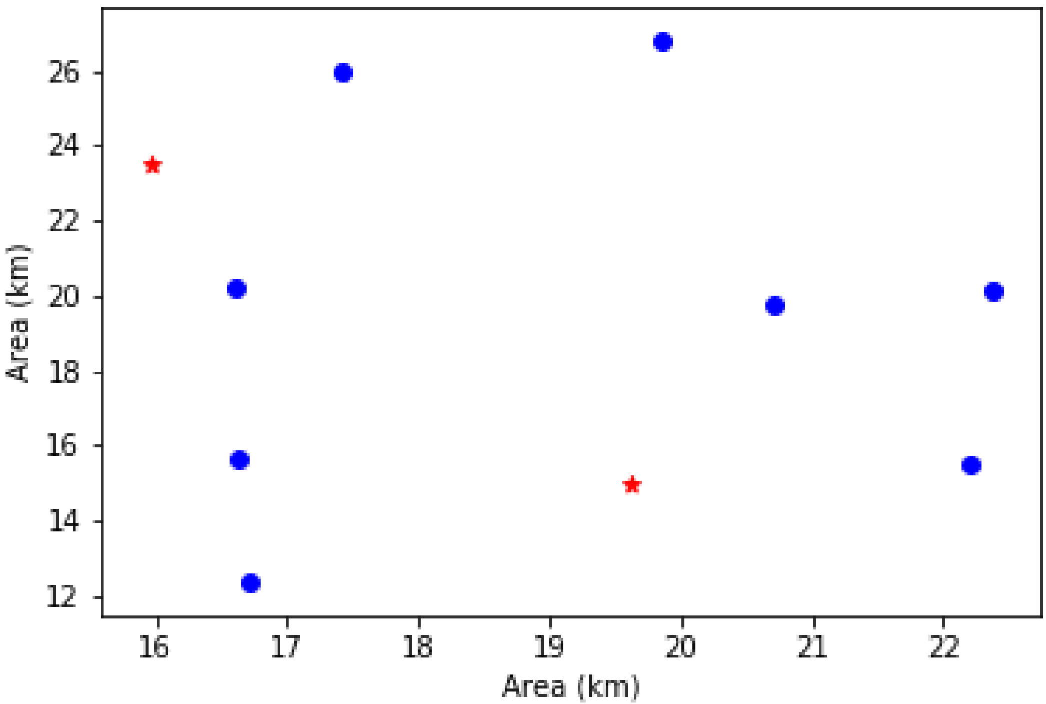

Figure 4.8: Seller and buyer among cluster 2 houses

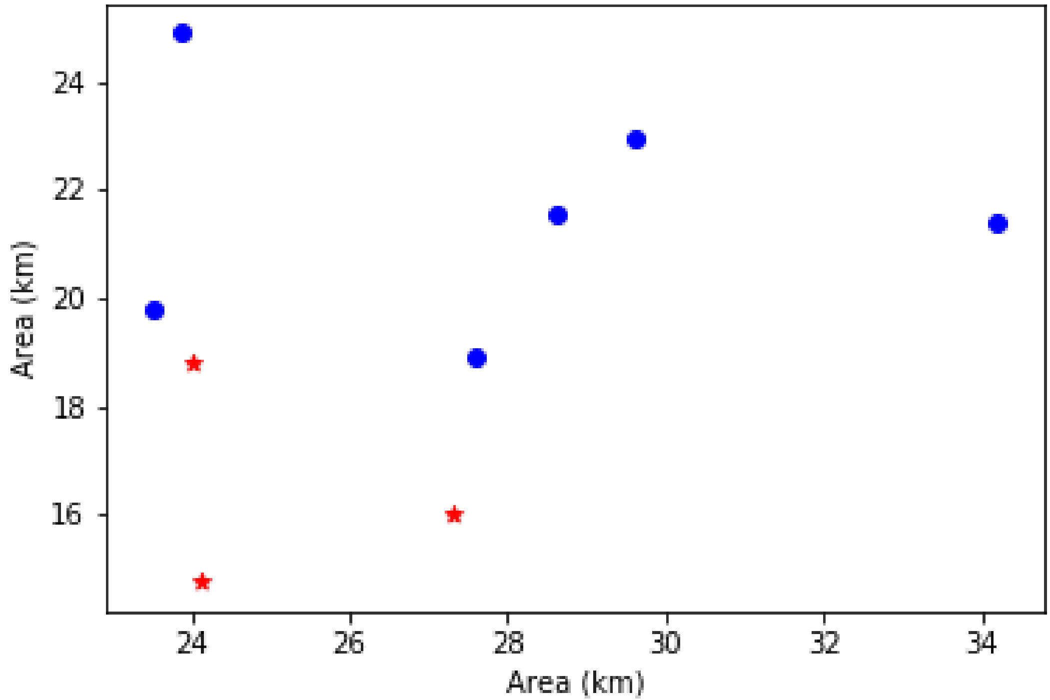

Figure 4.9: Seller and buyer among cluster 3 houses

Table 4.2: selling prices of prosumers and buyers buying price of one cluster

iteration no	Buyers buying price	prosumer's selling price
1	27	26
2	21	25
3	21	13
4	29	25
5	25	11
6	15	23
7	24	29
8	10	13
9	12	19

Cooperative players will form a coalition and trade energy among them. And simultaneously, non-cooperative players have to select their demand and consumption of energy to attain the Stackelberg equilibrium. Here, when the demand goes lower than the threshold, the grid's selling price mechanism will be dynamic and lower its selling price, so that buyers will choose the grid to buy energy.

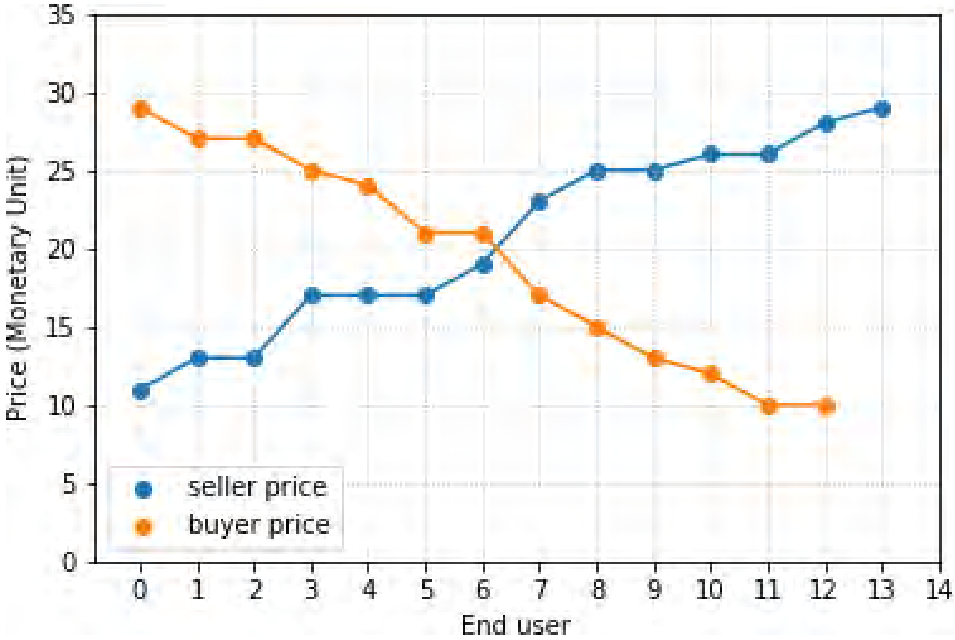

Figure 4.10: A demonstration of how the P2P price is selected in the proposed model.

4.3 Analysis and comparison of results

To test the effectiveness of our proposed model, we have analyzed and compared the results of proposed method with state of art from various aspects. At first, we have considered our model for stochastic situation where demand of each end user is fixed and compared the result for different number of electricity generation. When grid permits peer-to-peer energy trading, its cost of buying energy from other companies and the cost of the new generation will reduce to zero if prosumers have sufficient surplus energy.

Table 4.3: Cost from grid perspective (base on when demand is greater than the generation)

Generation (Kilowatt)	Without our model (Monetary unit)	with our model (Monetary unit)
828.869	5198.4029	323.25891
883.47	3909.2733	344.5533
974.23539	1766.30244	379.952
984.2057	1530.9034	383.84

Table4.3shows the cost reduction of the grid, switching from traditional to our proposed p2p framework. Here, for the same demand, the grid will analyze its cost and found that when it generates 828.869-kilowatt energy at that time, its cost is minimum. So, it will stick to this generation and reduce its buying price so that more prosumer and consumer will encourage to participate in cooperative trading by adjusting their price.

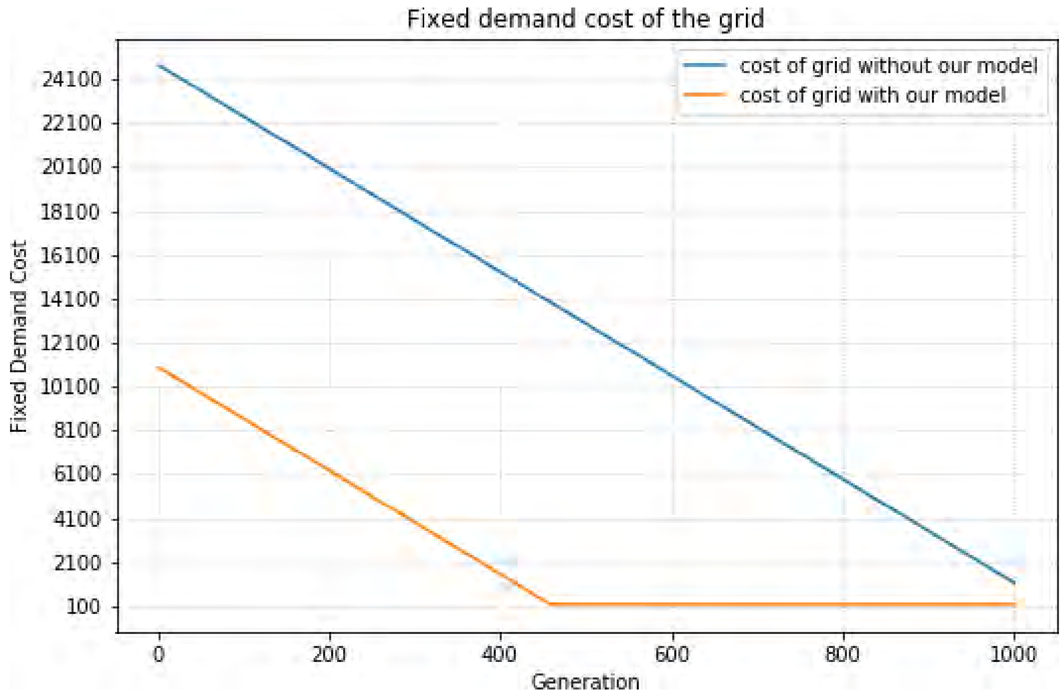

Figure 4.11: Fixed Demand cost of the grid

When there is a sufficient generation grid, apply the constraint according to our algorithm, which will not allow P2P energy trading. Moreover, to make this constraint a more robust, grid will drop down its selling price according to equation3.2. So, when demand goes below the load demand end-user will buy energy from the grid rather than prosumers. So, it is proved that the proposed framework is beneficial for the grid. We have experimented with our model with different numbers of generations for the same demand and found that our model reduces the extra cost of the grid. This is shown in Figure4.11. We can see that our proposed model reduces the burden of the extra cost of the grid. The grid can generate around 450 KwH and permit peer-to-peer energy to minimize the cost.

Our proposed model also reduce the demand load on the grid, as shown in Figure4.12.

Comparison between cost of buyer using our proposed model and traditional model is shown in Figure4.13. From our experiment we have seen that when there are less end users in any coalition then cost is not that much significant but when more users participate in the coalition process then cost is reduced on average 21%. However, in our proposed model, prosumers can limit their consumption or reschedule their consumption and activate the P2P trading with a new price P_{NEU} , which is less than the buying price from the grid. That's why the buyer can get more benefit in our proposed hybrid P2P energy trading approach.

In a recent work [32], a dynamic price mechanism has been proposed. But if we considered that then consumer's cost will be so high if they buy energy from the grid at peak hour. In a real

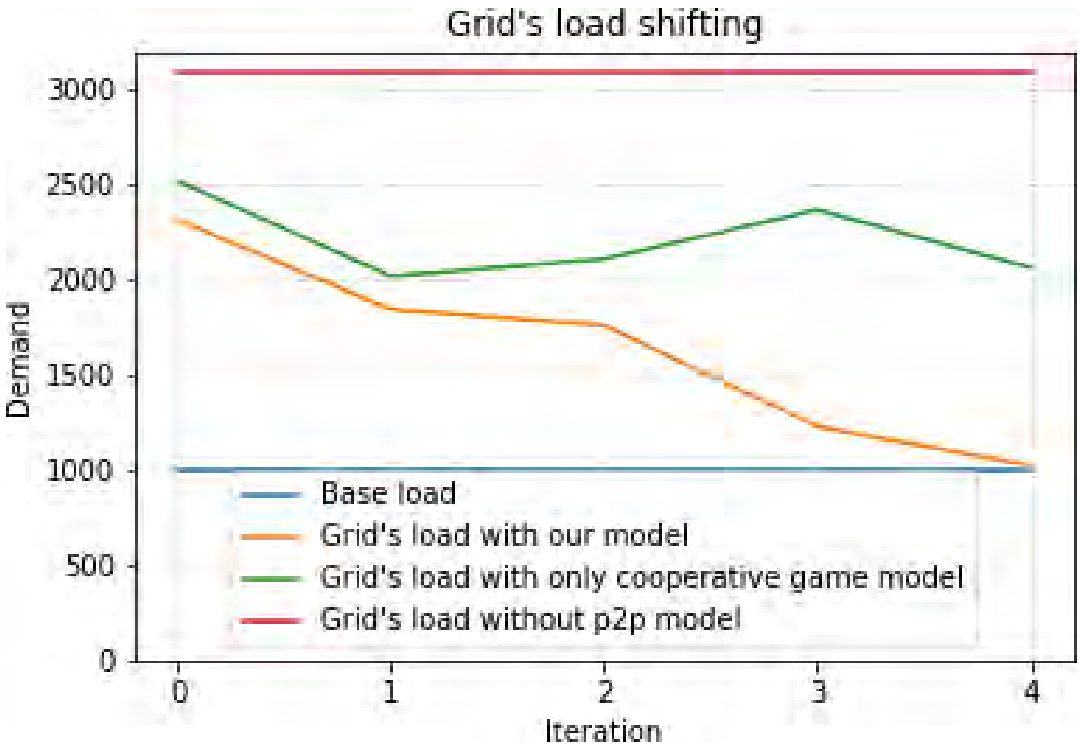

Figure 4.12: grid's load shifting

Figure 4.13: Comparison between cost of Buyer

scenario, it is possible that prosumers surplus energy cannot serve all the demand. So, some consumers might have to buy energy from the grid at a really high price. But in our proposed

Figure 4.14: Comparison between cost of Buyer while dynamic price of the grid is used and not used

framework, we have used the grids regular price and when the demand goes below the load demand at peak hour at that time it decreases its selling price. So, consumers are more benefited in our proposed system. This scenario is shown in Figure4.14. Here, for the dynamic price mechanism, we use the grids price is 12.5 times higher than the usual price at peak hour. In our proposed hybrid model not only cooperative prosumers are benefited but non cooperative players also benefited. Table4.4, shows the utility of non-cooperative prosumers. In perspective of prosumer the higher utility is better. In Figure4.15, we have shown that non-cooperative

Table 4.4: Sample prosumers utility

prosumer	Peer consumer	Profit	Extra Energy	Total profit
0	5	1767.5	19	1805.5
2	1	3806	42	3890
3	7	2394	1	2396
4	2	4899	8	4915

prosumers are more benefited if it uses our proposed hybrid model. As for only using mid-market value, it's surplus energy will be wastage. And if it sells to the grid only then it's revenue will be so less. Here, more prosumers could not deviate from the cooperative game as at that time they will be less benefit. If players increase in non-cooperative game than there is a high risk that they could not find the consumer to trade. On the other hand, if he cooperates then his profit is fixed.

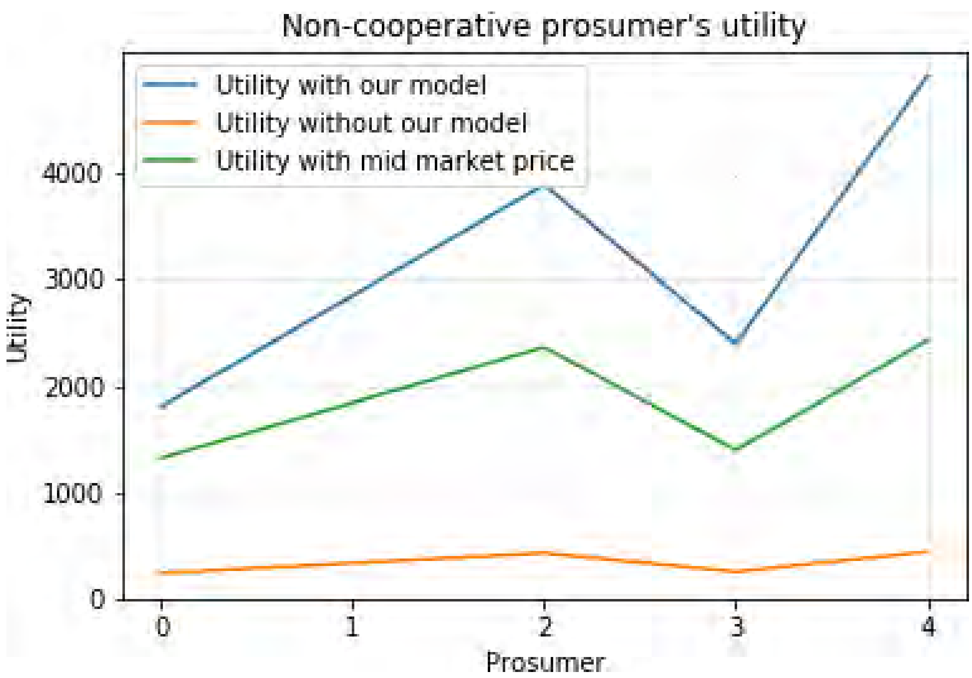

Figure 4.15: Comparison between prosumer's utility based on various model.

Most of the studies include the simulation of a smaller group of participants. So, if the participants are smaller in number, then according to Figure3.2the connection process, electricity distribution, and bill allocation will be straightforward. If we only use the non-cooperative Stackelberg game, then all the end-users need to be connected, as Figure4.16. However, in reality, the scenario is not that simple. There is a massive number of end-users in a limited number of areas. So, the computational complexity will be increased exponentially with the number of participants. In the grand coalition case, we have seen that if there are 50 end users, then customer 1 has to find prosumer 1. The system first makes a temporary contract between them, after observing that they get high priority with customer 2. Then the system finds that customer 1 moves to prosumer 3, but there is a temporary contract between consumer 4 and prosumer 3, so customer 1 will be rejected. So, this scenario continues for all the end-users in the system.

And most studies are considered either a single leader, single follower or single leader, and multiple followers and all the works are done considering off-grid connection. That's why they did not think about the grid. But our proposed model is built considering the grid is connected and we will use the already established framework. That's why the grid is the leader in our approach. And there are two types of followers- buyers and sellers. And we consider both of them are large in numbers. So, considering all these things, we have re-cluster our model. And assume that in each cluster there is a connection between all the end-users. This connection is static. Players can select peers within their clusters.

Our process of re-clustering keep the process simple and efficient for a huge number of

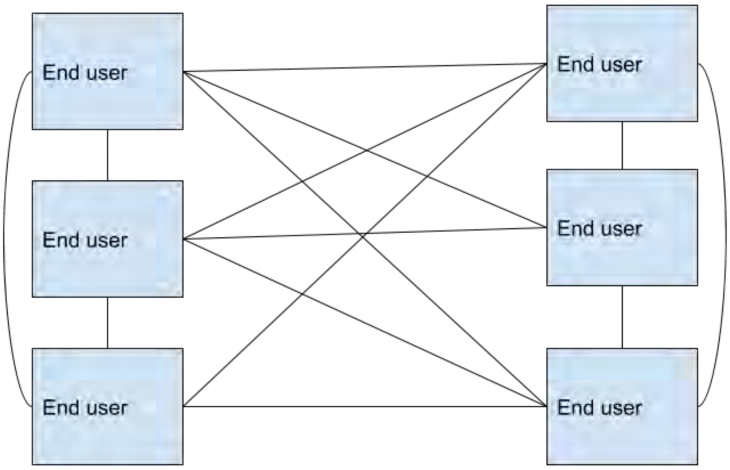

Figure 4.16: Connection between all end users.

participants.

We use elbow method to find the optimal number of clustering. So, our process split the huge end user into smaller cluster as shown in Table4.5and trade energy using peer-to-peer framework within the cluster without any complexity.

Table 4.5: Optimal number of clustering based on number of users

Cluster no.	End user no.
3	10
6	30
15	100

From Table4.5, we see that if there are 100 end users in a particular area, our framework will split it into 15 clusters. So each cluster, on average, includes 6 to 10 end-user. Moreover, after re-clustering it into more 3 clusters, a group of 5 to 6 people will participate in energy trading. Our simulation shows that if there are more than 30 end-users in any cluster, more consumers will be deprived of surplus energy within that group. Moreover, they have to search for surplus energy with another prosumer in non-cooperative way. At that time, if we divide them again in clusters, then complexity reduces slightly. Moreover, it is much easier to identify the seller and buyer within a small group and process their bidding, billing. Whereas, if we do not use the clustering method, all the above process will be complex exponentially with the increase

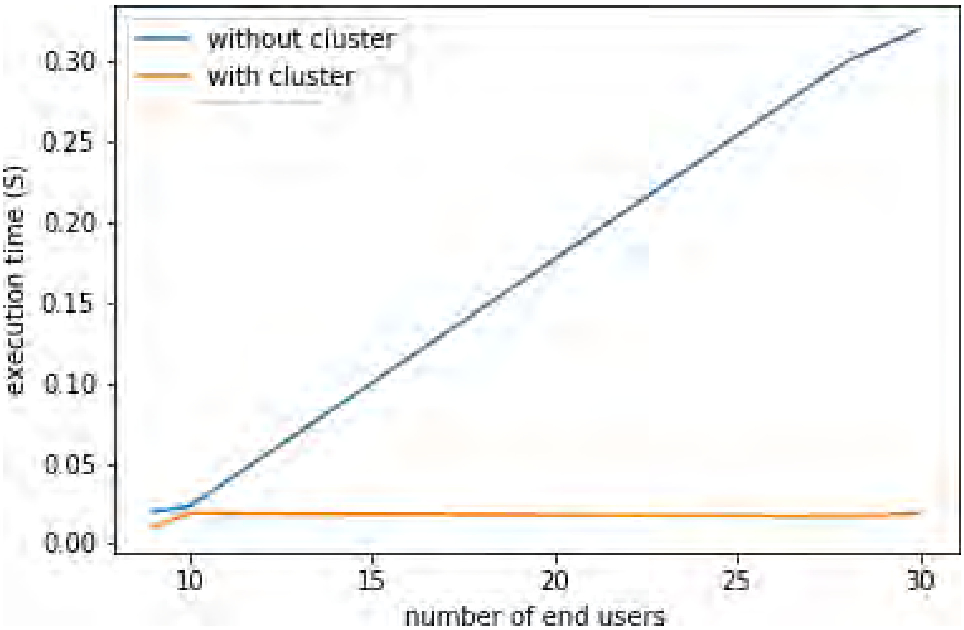

Figure 4.17: Comparison of selecting seller and buyer using our framework and not using it.

number of participants (sample execution time of seller and buyer selecting and bidding process are shown in Figure4.17). In Figure4.18, we see that execution time increase if there are more than 30 end user and consumer is much more than prosumer in a cluster. So, we use re clustering method.

4.4 Performance evaluation

Moreover, prior works do not consider network charges. But as we use the grid's infrastructure for peer-to-peer energy, we need to pay the infrastructure cost. And for this also we need to cluster all the end users. This constraints will encourage end-users to trade within their cluster. As if they want to trade with other cluster they need to pay the higher network charges.

Our proposed framework is tested on the IEEE-14 bus system with eight producers and 11 consumers(Figure4.19). The most common approach to analyzing power system stability is through computer modeling and simulation. Due to the vast size and inaccessibility of transmission systems, real-time testing can prove difficult. IEEE-14 bus system provides a realistic case to simulate P2P market designs [48].

From Figure4.19, it can be seen that IEEE 14 bus system can connect and disconnect from the primary grid through Bus-1 so that in case of imbalance between demand and supply, energy from the grid can be imported or exported. The IEEE 14 bus system has its own distributed generation. The energy data of consumers' demand, producers' surplus, and the primary grid

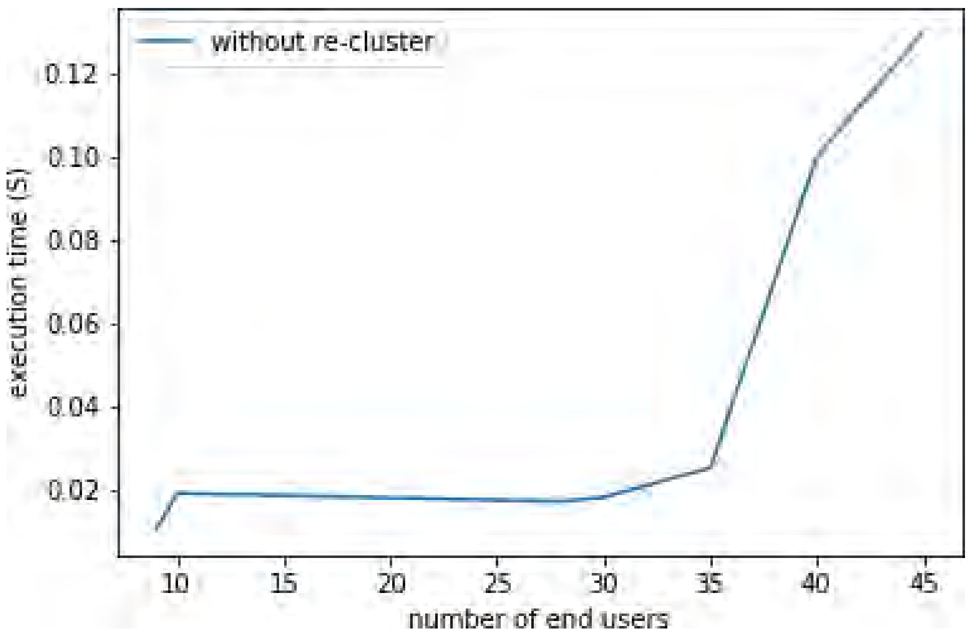

Figure 4.18: Execution time without re-cluster

import and export energy rate are used in [49]. As in IEEE 14 bus there is very little number of end users, we have not apply cluster here. At time t consumer's demands and prosumers surplus energy is as follow (Table4.6), From Figure4.20, we can see that using our framework, prosumers can be benefited more. And from Moreover, according to our model, when demand is less than the generation, the grid can hold peer-to-peer energy trading by lowering its selling price. So, eventually, the grid and consumer will also be benefited.

As we have used a hybrid approach, more consumers are benefited from peer-to-peer energy trading.

4.5 Discussion

Trading electricity is different from the exchange of other goods. The integration of the peer-to-peer energy trading model into the grid's infrastructure is also challenging. Previous works are done considering off-grid peer-to-peer energy trading with a minimal number of players to the best of our knowledge. That is the reason why we cannot directly compare our work with state of the art. No work is done considering the grid, prosumers, and consumers in a non-cooperative game model. Moreover, in the non-cooperative game model, players act rationally and selfishly to maximize their individual utility. To find the equilibrium among many players, we need to efficiently predict demand, price, and energy generation, which is not a feasible solution. So, we use non-cooperative pregame, and after clustering and coalition formation, we have used that

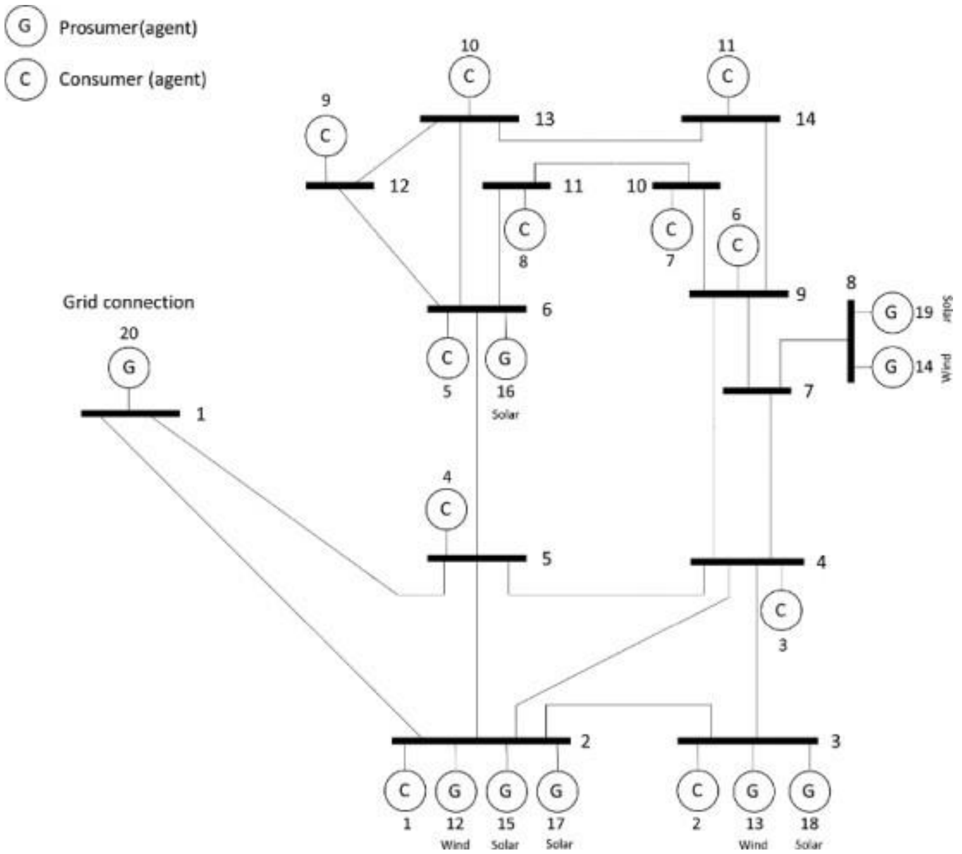

Figure 4.19: IEEE-14 bus system

non-cooperative game for a small number of players. So, our hybrid model is scalable for any number of end-users.

In this thesis, we have presented a game-theoretic model for real-time P2P energy trading. In our proposed model, prosumers and buyers will fix a price based on the grid's price. If followers do not want to cooperate, then they can participate in a non-cooperative game. But at that time, they have to submit a probable amount of their required energy. If prosumer's surplus energy matches with the consumer, then they will trade energy. And as we consider real-time demand, extra surplus energy prosumer can sell to the grid. And as the grid is the leader, he can change his buying or selling price to encourage prosumers and consumers to participate in peer-to-peer energy trading and reduce the load.

Our main objective is to design a flexible and scalable game-theoretic approach considering the real-world scenario. In our proposed approach, the grid's load can be minimized, more prosumers can be encouraged to participate, and the consumer's cost can be minimized.

Table 4.6: consumer's demands and prosumers surplus energy

Bus no.	demand
1	8.195109506
2	66.68447976
3	4.923316825
4	0.658986165
5	2.626520695
6	2.141673925
7	0.980951945
8	0.406213956
9	0.438585186
10	1.444799398
11	1.832604063
Bus no.	Surplus energy
12	39.62499951
13	16.79393834
14	1.456728
15	0
16	0
17	0
18	0
19	0

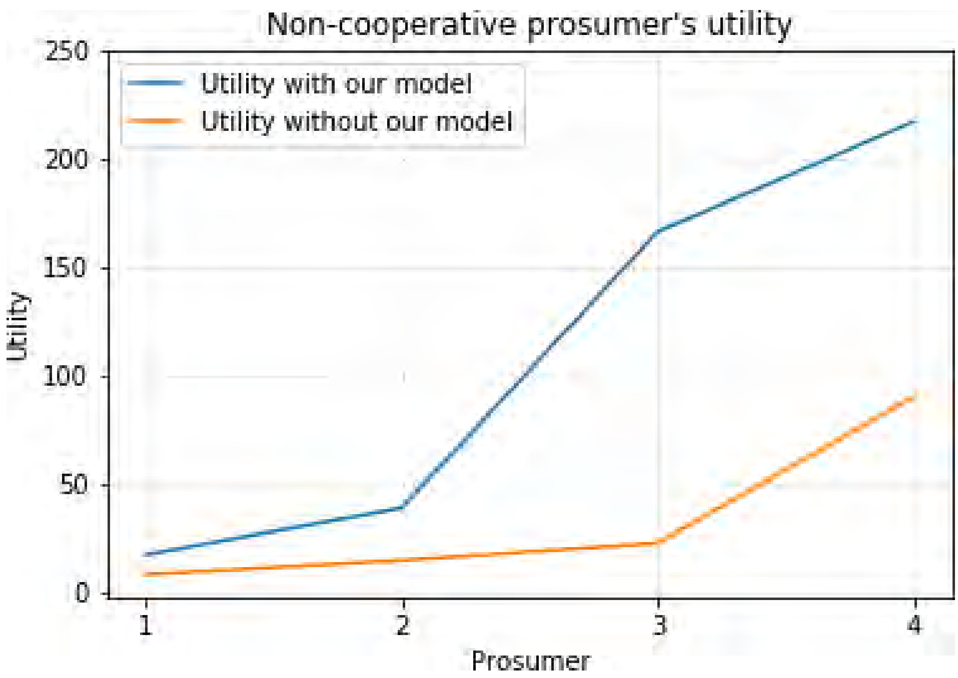

Figure 4.20: Utility of prosumer

Chapter 5

Conclusion

In this last chapter, we conclude our thesis by describing the significant contributions made by the research works associated with the thesis, followed by some directions for future research over the issue.

5.1 Major Contributions

The contributions that have been made in this thesis can be enumerated as follows:

- This thesis addresses the performance barriers affecting the inclusion of several participants.
- Hence, our proposed segmentation method enhances the scalability of these markets. It is vital to notice that for P2P algorithms, the complexity of all agents depends on the number of trading partners. Therefore, the algorithm's complexity can be reduced by limiting the number of trading partners per agent by using our proposed framework.
- Until this thesis, most studies have not simulated P2P energy trading, and very few have simulated with only one seller and multi-buyer.
- Moreover, those studies have some limitations. They have not clarified how to select sellers and buyers among a larger group, how can all the players can be benefited, and most of them consider two players (prosumer and buyer).
- They have not considered the grid's influence and are not applied any constrained. In our proposed framework, the grid has the power to put constraints.
- If any player falls behind the expected price and energy in coalition formation games, they can also be benefitted through our framework.
- This framework ensures benefits for each player.

- Our framework proposed a balanced combination of the cooperative coalition and the non-cooperative Stackelberg game. Our proposed coalition algorithm reduces the complexity of an increasing number of participants, and the Stackelberg game finds the optimal utility and optimal cost.

5.2 Future Directions of Further Research

Some of the future research areas of peer-to-peer energy trading in the smart grid are given below:

- There is a strong need for an energy-trading distribution mechanism in P2P networks that does not pose security and privacy threats to the sellers and EUs, respectively.
- How to integrate blockchain with game theory is a potential future research direction of significant importance.
- However, several factors are not discussed in this work, such as line losses, optimal power flow, the effect of energy storage systems. These factors may have significant effects on P2P energy trading frameworks. In the future, we will consider these factors to increase the effectiveness of the proposed model and make it possible to be used in a real market environment.

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