# FEASIBILITY ANALYSIS OF PEER-TO-PEER(P2P) ENERGY TRADING USING STACKELBERG EQUILIBRIUM

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**ANCY S GEORGE**

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**KOLLAM**

# CERTIFICATE

This is to certify that the Project report entitled **'FEASIBILITY ANALYSIS OF PEER-TO-PEER(P2P) ENERGY TRADING USING STACKELBERG EQUILIBRIUM '** submitted by **Ms. ANCY S GEORGE** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirement for the award of the Masters of Technology in Power Systems, Electrical & Electronics Engineering is a bonafide record of the project work carried out by her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

**Dr.MATHEW P ABRAHAM**
Assistant Professor [Internal Supervisor]
Department of Electrical and Electronics

**EXTERNAL EXAMINER**

**PROF. SHANAVAS T N**
Associate Professor [PG Co-ordinator]
Department of Electrical and Electronics

**Dr. SABEENA BEEVI.K**
Associate Professor[ HOD]
Department of Electrical and Electronics

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# ABSTRACT

The increasing level of Distributed Energy Resources (DER) has widely transformed the production, delivery, and consumption of energy including microgrids. As a result of the increasing levels of DERs, consumers are now becoming prosumers who both produce and consume energy. As renewable energy becomes more prevalent at the residential level, we need to adopt a new market strategy that will help to establish prices, decentralize and make the energy market and the energy infrastructure more flexible. However, integrating renewable energy into today's electricity infrastructure is a difficult task. The new smart grid technology will need to be based on mathematical techniques like game theory. Another difficulty is how the grid decides on a price lower than the P2P price that allows it to sell its energy to prosumers if demand falls below the grid's load requirement. There is a need for local energy markets, to enable the direct selling of renewable energy to consumers and prosumers without intermediaries' involvement. Recent developments have led to peer-to-peer(P2P) trading emerging as a possible mechanism for prosumers to actively participate in the energy market. So, we present a peer-to-peer (P2P) energy-sharing strategy for building prosumers. A Stackelberg game model with building prosumers and system operators as players is included in the proposed scheme. To find Stackelberg equilibrium(SE), an algorithm has been developed for optimizing internal trading prices and consumption while maximizing participants' profits. By analyzing SE, we can come up with a feasible solution in the scenario that peer-to-peer trading becomes profitable for a locality. The proposed system is simulated in MATLAB software and different case studies are furnished to study the benefit of having P2P trading.

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# ABBREVIATIONS

| | |
|---|---|
| DERs | Distributed Energy Resources |
| DG | Distributed Generators |
| DSO | Distribution System Operator |
| ESS | Energy Storage System |
| EU | End Users |
| FiT | Feed-in-Tariff |
| ICT | Information Communication Technologies |
| LEM | Local Energy Market |
| NE | Nash Equilibrium |
| P2P | Peer-To-Peer |
| PCC | Point of Common Coupling |
| PHEV | Plug-in-Hybrid Electric Vehicles |
| PV | PhotoVoltaic |
| SE | Stackelberg Equilibrium |
| SESP | Smart Energy Service Provider |
| SO | System Operator |
| SOC | State of Charge |
| TE | Transactive Energy |
| UG | Utility Grid |

# Chapter 1

# INTRODUCTION

## 1.1 General Background

The increasing level of distributed energy resources (DERs) has fiercely transformed the production, delivery, and consumption of energy including microgrids. As a result of the increasing levels of DERs, consumers are now prosumers who both produce and consume energy. As renewable energy becomes more prevalent at the residential level, we need to adopt a new market strategy that will help to establish prices, decentralize and make the energy market and the energy infrastructure more flexible. There is a need for local energy markets, to enable the direct selling of renewable energy to consumers and prosumers without intermediaries' involvement. Recent developments have led to peer-to-peer(P2P) trading emerging as a possible mechanism for prosumers to actively participate in the energy market. Through P2P, prosumers can exchange surplus energy production with their peers and increase their mutual benefits. Moreover, P2P energy trading offers more flexibility to end users, increasing the availability of clean energy and speeding up the transition to a zero-carbon energy system. Further, the other players in the electricity market can gain benefits including reduced peak demand for electricity, reduction in maintenance and administration costs and improved reliability.P2P energy trading has the potential of bringing together diverse generations (if equipped with DGs) and demand profiles of multiple customers[1].

P2P energy trading offers an option for operators of power systems to manage high DER penetration in the future. The characteristics, features, capacities, locations, and owners of DERs vary widely, and they are found all along the edge of a power grid. By these factors, conventionally centralized DER management is impractical. DERs could by utilizing proper P2P energy trading mechanisms, facilitate inherently a better local power and energy balance on their own. In the upstream power grid, this could relieve pressure and reduce uncertainty. DERs could provide various ancillary services to support the upstream power grid in P2P energy trading markets through specific contract or mechanism design, similar to the function of virtual power plants (VPPs) through what some research has termed federated power plants (FPPs) [2].

## 1.2 Local Energy Trading

Consumers have been inspired to become more active players rather than passive ratepayers as a result of recent improvements in Information and Communication Technologies (ICT) and smart systems. As prosumers, the new active consumers participate in the power generating and consumption process by utilizing local resources, moderating demand, and interacting with other stakeholders. In other words, these new players can use the two-way flow of information and energy to trade both information and energy among themselves and with the grid. These new participants can trade energy locally by selling excess energy to other consumers or prosumers or buying from them when their supply falls short of demand. Transactive energy (TE) as a new notion of an open and flexible market emerges as the number of prosumers in the distribution network grows, attracting great attention to local energy trading.

In a traditional energy grid, generating electricity from generators is transmitted to customers via transmission and distribution networks in a centralized power-producing system. Power is created by a few large-scale generation units and distributed to a variety of home, commercial, and industrial consumers under the centralized generation system. By increasing the level of DER integration on the consumer side, a distributed power generation is forming, in which a large number of small-scale generation units with capacities ranging from a few kilowatts to a few megawatts are connected to the distribution grid, resulting in bidirectional power flows [3]. The growing use of distributed energy resources (DER) has shifted the electrical system from a centralized to a deregulated form. The structure of a centralized and distributed generation system is depicted in Fig. 1.1

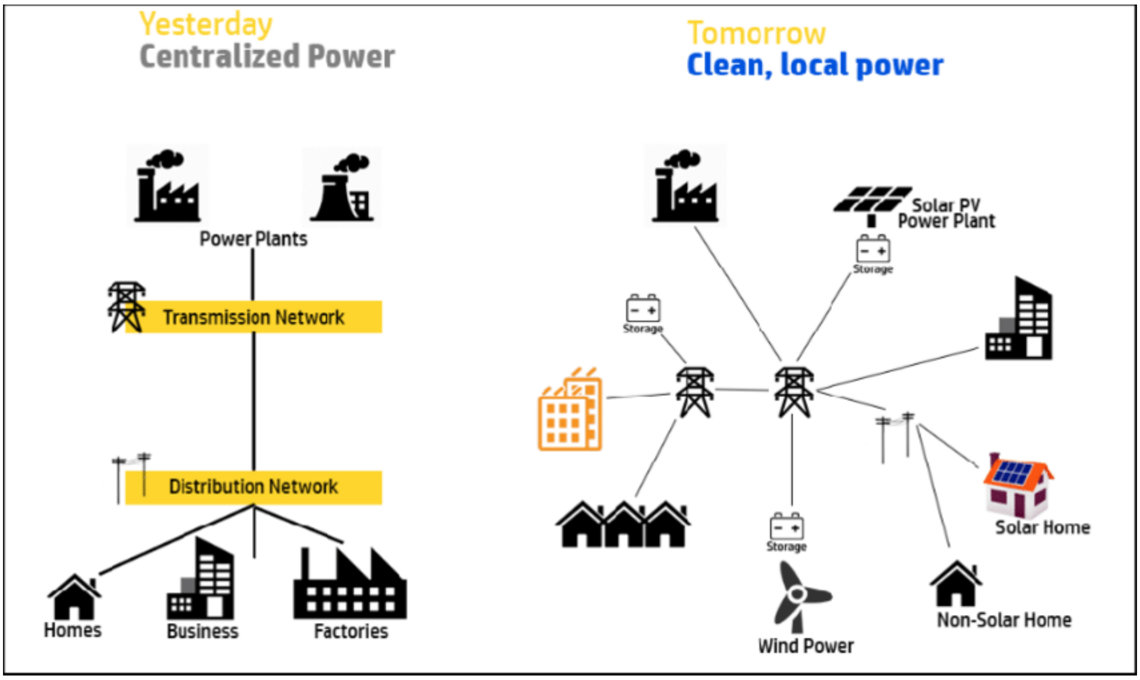

Figure 1.1. Centralised and distributed power generation system[4]

Conventional power systems are designed to provide consumers with vast, centralized production, not millions of customer-generators. Massive deployment of DER generates operational and market challenges, making current incentives and tariffs impossible to maintain. DER transparency issues, congestion, and voltage issues seem to be just a few of the obstacles. Local energy trading allows for control of these new generations by encouraging localized trading at the distribution level. Furthermore, several studies reveal that consumers' willingness to accept local energy resources and share investment for the use of DER has improved in recent years [4]. The Feed-in-Tariff (FiT) scheme encourages DERs to engage in energy trading. Market participants, on the other hand, do not make a significant profit because of the substantial difference between FiT and market pricing, and this strategy does not incentivize them to participate in the market. As a result, it is important to establish a new energy market for local energy trading in distributed generation systems.

## 1.3 Market Structure

Local energy markets can change the structure of the energy system by integrating prosumers with renewable energy resources and consumers into the energy supply system. As illustrated in Fig. 1.2, local energy trade can be classified into three classes depending on market player interaction.

a) Peer-to-peer energy trading: In a fully P2P market, market participants engage directly with one another without the need for intermediaries.

b) Energy trading through a mediator: In this situation, a mediator participates in the market on behalf of sellers and buyers, allocating energy from sellers to buyers, while customers act as price-takers in a passive position.

c) The third scenario is a hybrid of the first two, in which suppliers and purchasers can transfer energy directly or through a middleman. All three market types are represented in the examined papers' market design. Although there have been some recent efforts to build a pure P2P market for local energy trading [5,6], the designed market for local energy trading in the majority of the evaluated studies includes a mediator.

### 1.3.1 Market Players

It is critical to distinguish market players, their responsibilities, and their objectives in any market design. The establishment of local energy trading necessitates the classification of market participants in local energy trading. The following are some of the most important players in the local energy markets:

- Energy suppliers or sellers (Power generators, DERs, and others).
- Energy consumers or buyers (households, factories, and other companies).
- Energy trading companies or intermediaries (power distributors, aggregators, operators, and others).

#### Sellers

Any player with the ability to generate or store energy can participate in the local energy trading market as a seller. DER, such as Distributed Generations (DGs), EESs, Plug-in Hybrid Electric Vehicles (PHEVs), utility companies and generators, or a mix of them as prosumers, energy cells, smart homes, and microgrids, and can all be market producers.

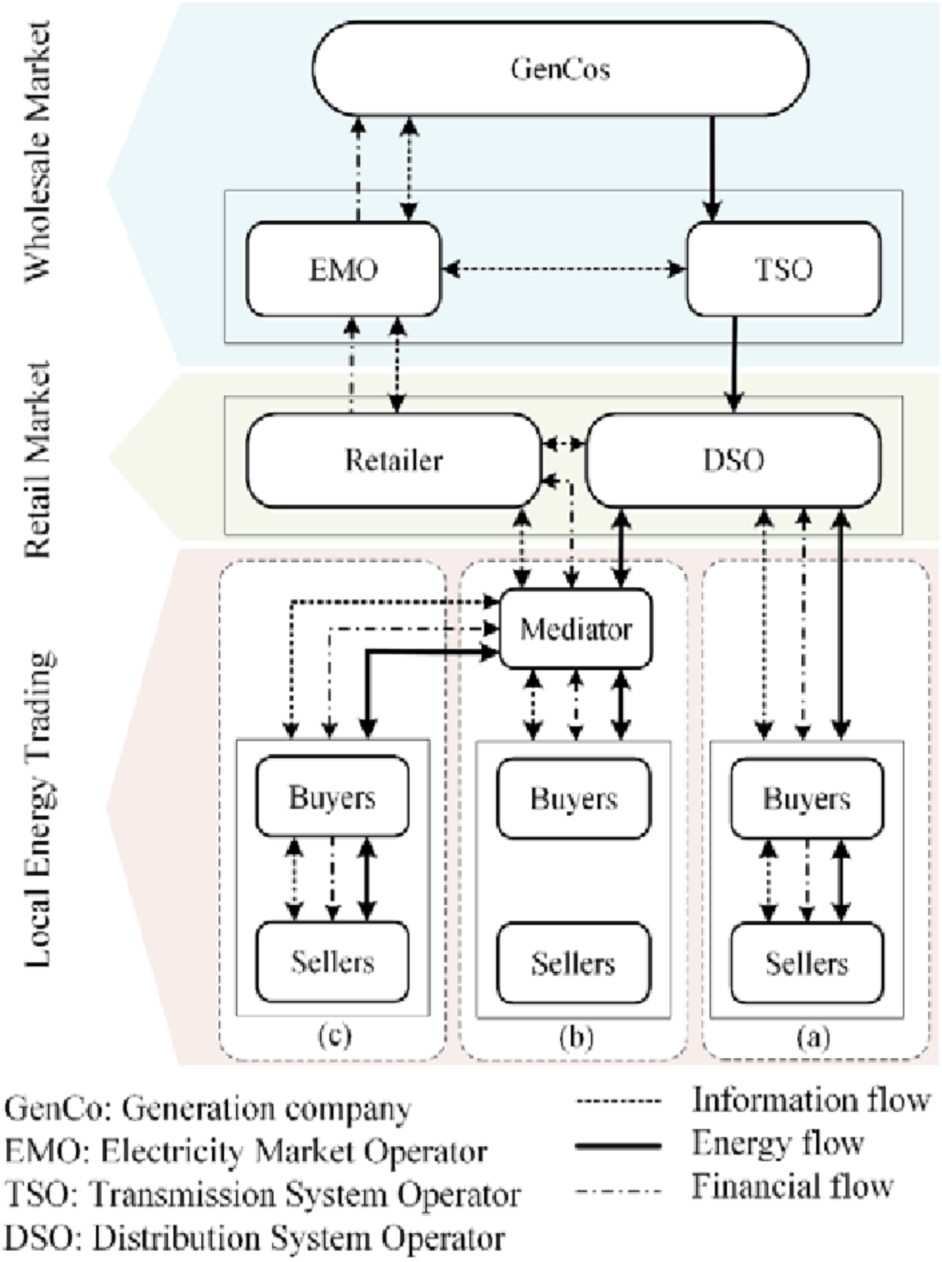

Figure 1.2. Market structure with local energy trading[7]

**Buyers**

In the local energy market, buyers are people who want to buy energy from local generators. Energy can be purchased on the market by both consumers and prosumers. Prosumers with excess energy sell, and if they require more energy, they will enter the market as buyers. Flexible loads with the ability to limit and change their loads might also play a buyer role in the market [7].

**Mediators**

A mediator is somebody in the market who isn't a seller or a buyer. Some players can simultaneously fulfill the roles of mediator and seller/buyer. The mediators were allocated varied roles in the articles that were reviewed. In some cases, they act as a market intermediary. An aggregator is "an independent agent who unites two or more consumers into a single purchasing unit to negotiate the purchase of electricity from retailers" [8], according to a standard definition. In [9], the authors introduce a novel aggregator known as the smart energy service provider (SESP) for scheduling flexible energy resources in local electricity markets with substantial DER penetration. As a mediator, the local energy market (LEM) operator is introduced in [10]. To maximize social surplus, the LEM operator must collect offering/bidding parameters (prices and amounts) from various players.

## 1.4 Peer-to-Peer Energy Trading

The rise of dispersed energy resources has altered energy distribution systems in recent years. Simultaneously, the way energy is generated and consumed is radically changing, and conventional energy users are increasingly becoming prosumers [11]. Prosumer electricity generation is sporadic and difficult to forecast, as it is heavily influenced by the amount of sunlight and temperature (which is always changing). There are various choices available to prosumers that have an excess of electrical energy. The energy can be kept for later use in a storage device, exported to the power grid, or sold to other energy consumers. P2P energy trading refers to direct energy transfer between consumers and prosumers.

The P2P energy trading model is depicted schematically in Fig. 1.3. Consumers, prosumers, electric providers, and the energy sharing coordinator are the four primary participants in the model. Prosumers and consumers are distinguished by the fact that prosumers generate as well as consume power, whilst consumers just consume. The trading arrows and the energy arrows depict the exchange of energy and money between prosumers and consumers. Electricity can be sold by a prosumer to a consumer or another prosumer. The entire negotiation process is carried out on a platform that acts as a coordinator for energy exchanges. Consumers can only receive energy from the energy sharing coordinator, as indicated by the trade arrows pointing in one direction. Prosumers can buy and sell electricity to the energy sharing coordinator using the bidirectional trading arrows [12-14].

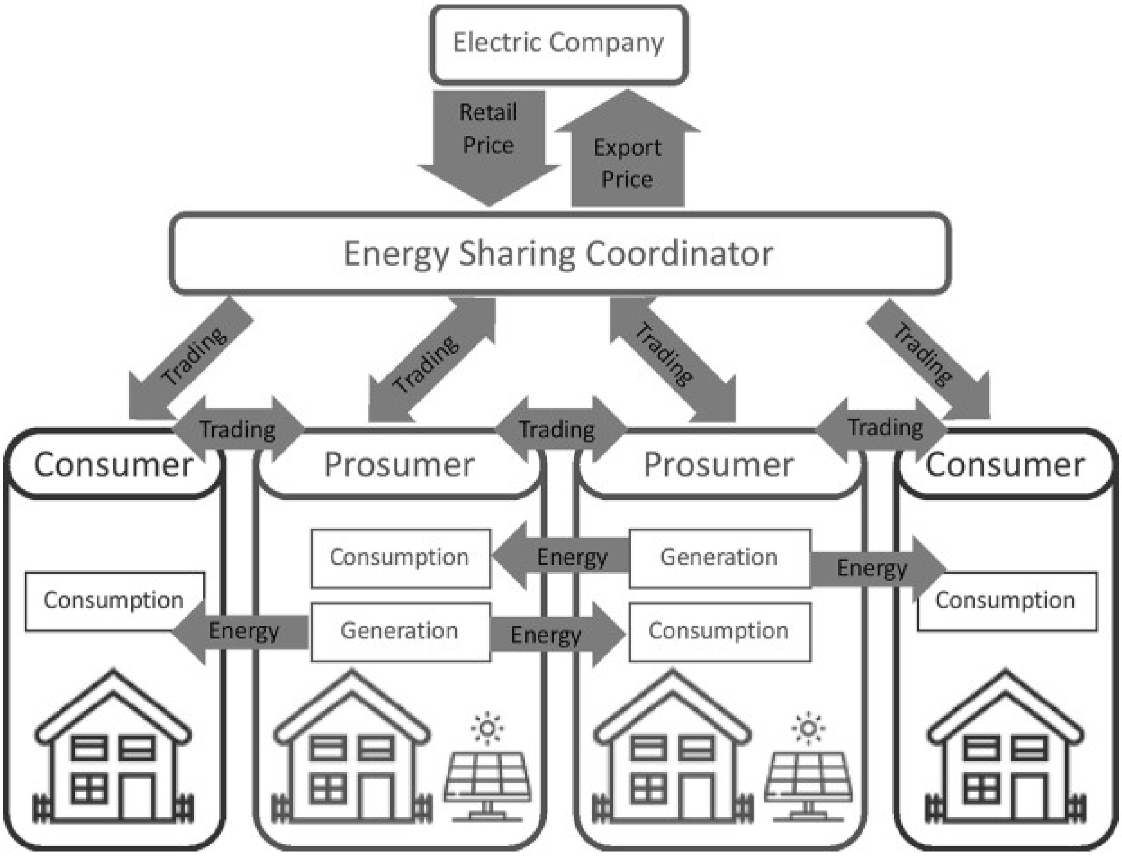

Figure 1.3. P2P energy trading model[12]

## 1.5 Game Theory

At many levels, such as design, control, and execution, several technological obstacles exist when adopting new energy trading schemes. For example, in peer-to-peer (P2P) trading, prosumers are intended to exchange their energy with one another with little (or no) influence from a central controller, making P2P platforms a trustless system. As a result, encouraging prosumers to cooperate in such a distrustful climate is a difficult challenge. Furthermore, modeling the decision-making process for numerous energy trade factors in an energy system with many customers is difficult. Furthermore, because of the difficult technical limits on energy exchange, it differs from any other exchange of goods. It's also a difficult task to figure out how to sell energy in a P2P network without jeopardizing the network's security, as well as how to define different stakeholders' goals. In the design and analysis of energy trading for the smart grid, game theory proves to be a reliable paradigm. A mathematical framework is known as game theory. Auction mechanisms and non-cooperative games are two game-theoretic methodologies commonly employed in energy trading research in the future smart grid.[15,16].

**Non-cooperative Game Theory**

Non-cooperative game theory can be used to study players' strategic decision-making processes when they have partial or competing interests in the outcome of a decision process influenced by their actions. The Stackelberg game [17] is a non-cooperative game that has been widely utilized in the literature to construct P2P commerce. A Stackelberg game is a strategic game in which at least one person is designated as the leader, making the first decision and committing to a strategy before the other players. Other players, on the other hand, serve as game followers, optimizing their plans in reaction to the leader's actions. The Stackelberg equilibrium is the solution concept for a Stackelberg game. In reaction to the Leader's choice, the followers play a non-cooperative Nash game and find a Nash equilibrium. At the Stackelberg equilibrium, neither the leader nor any of the followers have any reason to change their tactics.

**Co-operative Game Theory**

The study of how to incentivize independent decision-makers to act as a single entity in order to advance their position in the game is made possible by cooperative games. The typical form of the coalitional game is the most prevalent type, in which the worth of the coalition is decided by its members independently of the coalition's structure. The most prevalent idea for a solution The characteristic form [18,19], in which the value of the coalition is defined by its members, independent of how the players in the coalition are formed, is the most common form of a coalitional game. A canonical coalitional game, a coalition formation game, or a coalitional graph game are the three forms of coalitional games.In canonical coalition game, no player ever loses when a great alliance of all players is formed in a canonical coalition game. Therefore, the primary goals of such a game are to ascertain whether or not a grand coalition can be established, to ascertain whether the grand coalition is stable, and to develop a fair revenue distribution plan for allocating the coalition's gains among the players. The core is the canonical coalition game solution notion that is most frequently used.

## 1.6 Problem Statement

Smart grids are energy networks comprised of smart nodes that link, control, and interact with one another. Furthermore, their independent interaction efficiently supplies power and electricity to their customers. Peer-to-peer energy trading, on the other hand, is a smart grid's succeeding energy management process that allows customers to independently engage in energy trading with other market participants and the grid. Prosumers are those who generate and consume at the same time when they use renewable energy resources. Consumers will become prosumers as a result of this evolution. A prosumer may have the demand-response capability as both a consumer and a producer. Increasing renewable energy utilization, lowering electricity costs, cutting peak loads, empowering customers, and decreasing network services and investment costs are just a few of the advantages of P2P energy trading. It also provides a solution for customers whose houses were not solar-ready due to backlighting, undersizing, improper orientation, or the need for re-roofing. The main purpose of peer-to-peer sharing is to disrupt the centralized architecture of the electrical grid by enabling direct energy communication and supply between numerous prosumers and DERs (distributed energy resources) inside the energy system. This helps users to buy renewable energy from a peer who has excess renewable energy at a lower rate, reducing their dependency on the grid or a central source.

Instead of relying on the grid, a smart home can generate its energy utilizing solar panels, wind turbines, and other renewable energy sources. This shift to solar energy is being complemented by a rise in the utilization of renewable energy sources. One or more energy storage devices collect low-cost and surplus energy to meet future energy needs, avoiding the need to buy expensive energy from the grid during high-priced periods (for example, peak hours). Solar and photovoltaic (PV) panels will eventually be competitive with natural gas and coal, but this does not rule out the potential of future coal and natural gas producers. Both are distinct since the sun only shines during the day and the wind is most prevalent at night. We will soon be unable to rely completely on renewable energy sources. Furthermore, greater than 20% of solar and wind energy would demand significant investments in transmission lines. Transmission lines are not only expensive but also difficult to obtain because of the NIMBY (not-in-my-back-yard) issue. Transmission lines also take three to four years to build, compared to two years for solar and wind power plants. One option is to incorporate the peer-to-peer energy trading system into the current energy strategy. Integrating renewable energy into today's electricity infrastructure, on the other hand, is a challenging task. Power is traditionally generated centrally and distributed unidirectionally to passive users who pay the utility company a predetermined fee based on contractual agreements. Because energy is used directly after it is generated, balancing supply and demand during peak demand periods is critical to ensure stable operation. Utility companies are occasionally forced to respond with costly high-speed energy production via peak spinning reserves. With a solid knowledge of its behavior and different important design elements, we believe that prosumer-centric and consumer-centric P2P energy trading can drive local energy generation and consumption[20].

## 1.7 Motivation

Game-theoretic approaches are employed to build the P2P trading scheme due to the interactive character of the energy trading process. Game theory is a mathematical tool for analyzing competitive strategies in which the outcome of one player's action is influenced by the actions of others. There are two sorts of game theory: non-cooperative games and cooperative games. A non-cooperative game is a game in which a group of independent players makes strategic decisions with completely or partially conflicting interests in the outcome of a decision that is influenced by their actions. A cooperative game is concerned with how to incentivize individual decision-makers to act as a single entity to increase their position (or utility) in the game. If the only non-cooperative game theory is applied now, the computing complexity of large-scale network trading will increase. Furthermore, real-world scenarios and situations necessitate decision-making, and strategy structures are typically more cluttered, dynamic, and difficult to regulate. Real-life circumstances, gains, and losses, on the other hand, are not usually as clear-cut or easily measured. Furthermore, cooperative game theory struggles to motivate all members of a large organization. In light of the aforementioned challenges, we have proposed a framework that will address all of them[21].

## 1.8 Objectives

The following are the objectives of this thesis:
1. To model the P2P energy trading system as a Stackelberg game(single leader-multi follower).
2. To develop an algorithm to find the Stackelberg Equilibrium(S.E) of the game.
3. To analyze the Stackelberg Equilibrium(SE) and formulate a condition at which peer-to-peer energy trading becomes feasible.
4. To analyze the benefits of having a Peer-to-Peer(P2P) energy trading system among building prosumers during 1 hr time slot in a day-ahead market.

## 1.9 Thesis Outline

The body of this thesis is organized as follows.

In chapter 2, we examine different works of literature and studied different peer-to-peer architectures. Overall review and challenges were discussed. Chapter 3 outlines the system framework and each player's welfare and profit models. Chapter 4 describes the Stackelberg game theory as the system is modeled. As well as the algorithms we developed and tested through different case studies. In Chapter 5, we analyze the feasibility of the system and analyze the feasibility theorem through different case study conditions and Chapter 7 concludes the thesis, by providing a detailed study on the benefits of peer-to-peer energy trading.

## 1.10 Conclusion

This chapter summarises the evolution of peer-to-peer energy trading and the study of game theory. Today's grid is characterized by increasing demand response(DR) programs, distributed energy resources(DER), and other energy-efficient initiatives. With the increasing penetration of DERs, conventional energy consumers become prosumers. When prosumers have a surplus amount of energy, they can send it back to the grid or sell it to end-users, curtail it, or store it with energy storage devices. The trading of energy directly between consumers and prosumers is called Peer-to-Peer (P2P) energy trading.

# Chapter 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter provides a brief review of different peer-to-peer architectures in related works. Section 2.2 outlines the different peer-to-peer architectures in the related literary works. This section focuses on different peer-to-peer architectures in energy trading systems by analyzing various system structures and discussing the bidding and trading strategies in each architecture. Section 2.3 provides detailed background on studies of P2P energy trading in terms of challenges.

## 2.2 Related Works

(1) Haobo Zhang, Hongliang Zhang, Lingyang Song, Yonghui Li, Zhu Han, and H. Vincent Poor, ”Peer-to-Peer Energy Trading in DC Packetized Power Microgrids”, IEEE Journal on Selected Areas in Communications, Vol. 38, no. 1,pp. 17-30,Jan. 2020.

In [22] a DC packetized power microgrid proposed with the help of power router energy is dispatched as power packets. In this trading, the demander submits the bids to compete for power packets the controller decides the scheduling of power packets and allocation of energy. In Fig. 2.1. the DC packetized power microgrid consists of a power packet, power router, utility grid(UG), and energy subscribers(ESs) with their DER batteries. The UG and all the ESs were connected to the power router through communication links and power lines.P2P trading takes place on an auction-based game-theoretic approach where the auctioneer is the centralized controller in the power router and the bidders as demanders. A trading protocol for power packet trading in [21] divides the day's timeline into three steps of trading cycles such as registration, auction, and transmission steps.

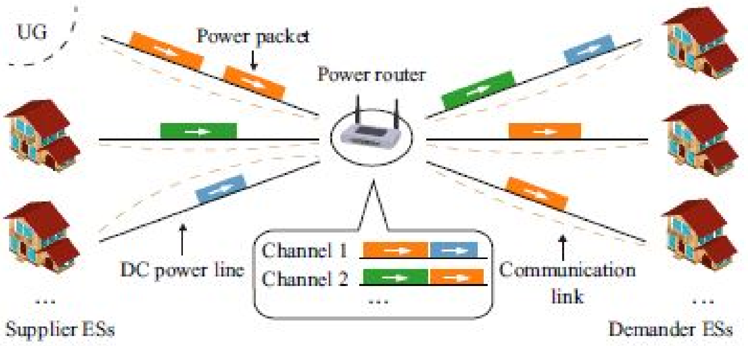

Figure 2.1. Diagram of a DC packetized power microgrid [22].

The first step is the registration step. In this step, each ESs are sorted as demander ESs or supplier ESs.In the next step, from the supplier ESs or UG, the demander ESs will bid for the power packet the auctioneer controls the allocation of energy scheduling of the power packet. In the last step, based on the auction, the traded power packet in the auction step is transmitted using the unique IP address in the transmission step. In [22] suppliers submit their energy of export to the controller and the auctioneer calculates the received energy and informed the demander. Each demander starts bidding and decides whether to participate or not. The controller allocates power packets and the energy is sent to the demander through the power router.

**(2) Luhao Wang; Yumin Zhang; Wen Song; Qiqiang Li, "Stochastic Cooperative Bidding Strategy for Multiple Microgrids With Peer-to-Peer Energy Trading" IEEE Transactions on Industrial Informatics, Vol.18,no.3, pp.1447-57, July .2021.**

In [23] a peer-to-peer energy trading in grid-oriented multiple microgrids(MMGs) using a stochastic cartel game-based strategy is depicted.Fig. 2.2. consists of an MMGs system where neighboring MGs include generators energy storage de- vices(RGUs), renewable generation units, and customers connected through distribution networks. The individual MGs aggregate the energy bids in day-ahead electricity markets and try to dominate prices using a cartel game. The strategic action in the day-ahead markets is how much power is involved in energy production, joint energy bidding, and P2P energy trading.

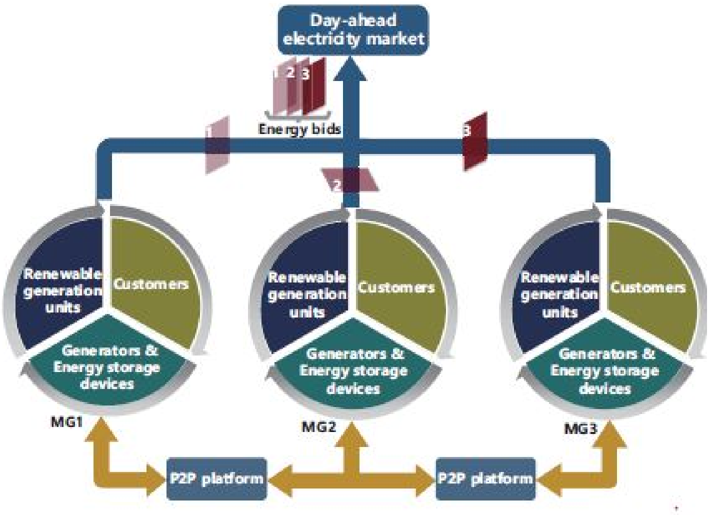

Figure 2.2. Combining the grid-oriented joint bidding from MMGs and P2P energy transactions among MMGs [23].

The bidding model is modeled in the single-sided day-ahead electricity market controlled by utility grid corporations. Individual MGs make energy supply and bidding.MMMGs submit the joint energy profiles by collecting energy bids to maximize benefit.MG sends its expected amount of energy to the utility grid, and all the historical data are transparent to one another during the bidding process. A central market operator in P2P transactions is a distribution system operator who prevents line congestion based on historical data and prior experiences.

**(3) Shichang Cui; Yan-Wu Wang; Nian Liu, "Distributed game-based pricing strategy for energy sharing in microgrid with PV prosumers", IET Renewable Power Generation, Vol.12,no.3, pp.380-8, Feb .2018.**

In Fig. 2.3. the energy sharing framework for PV prosumers in a microgrid is depicted. In this structure, there are two entities, PV prosumers, and MGO.PV prosumers are equipped with PV generators and can act either as buyers or sellers based on their energy consumption levels.MGO is a central market operator who coordinates and manages the energy balance and sharing among the prosumers.

In [24], a Stackelberg game-based energy sharing in a microgrid is presented. In this model, the players such as the microgrid operator(MGO) act as the leader, and PV prosumers act as the followers. The leader decides the internal selling and buying price for energy sharing

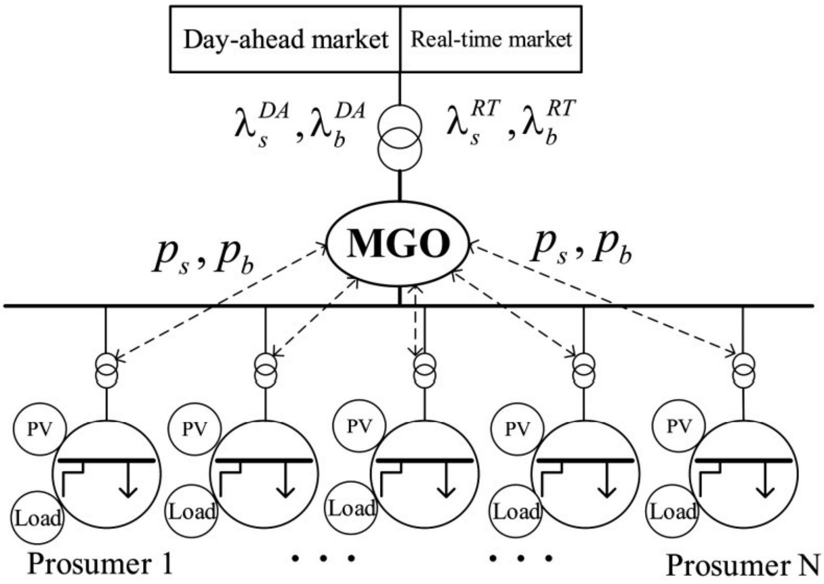

Figure 2.3. Enegy sharing framework of microgrid with PV prosumers[24].

and based on the leader's decision buyers decide the amount of energy. In problem formulation first, formulate the utility function models for the prosumers and profit function for MGO. By this formulation, the followers as prosumers first decide their energy consumption levels and submit their demand to the MGO to maximize their function. Based on the follower's decision price is set by the MGO and sent to the prosumers.Since it is a stackelberg game model there exist a stackelberg equlibrium(SE).By using a heuristic algorithm, Stackelberg equilibrium is found and therefore all the players in SE cannot change their strategies from the optimal points.

**(4) Yunsun Jin; Jeonghoon Choi; Dongjun Won, "Pricing and Operation Strategy for Peer-to-Peer Energy Trading Using Distribution System Usage Charge and Game-Theoretic Model", IEEE Access, Vol. 8, pp.137720-30.July.2020.**

Fig. 2.4.represents a framework of P2P energy trading in a distribution system, which consists of four main components: 1) prosumers; 2) consumers; 3) a marker operator, and 4) a distribution system operator(DSO).

A game-theoretic-based P2P trading strategy is modeled, where the prosumer acts as a leader and determines the trading price and quantity. In contrast, the consumer acts as a follower and responds to the leader's strategy[pricing]. The prosumer has their PV generator and energy storage system, and the consumer is an electricity user without power generation capability. All prosumers and consumers were connected through communication links and power lines. The entire community is connected to the grid through a point of common coupling(PCC).

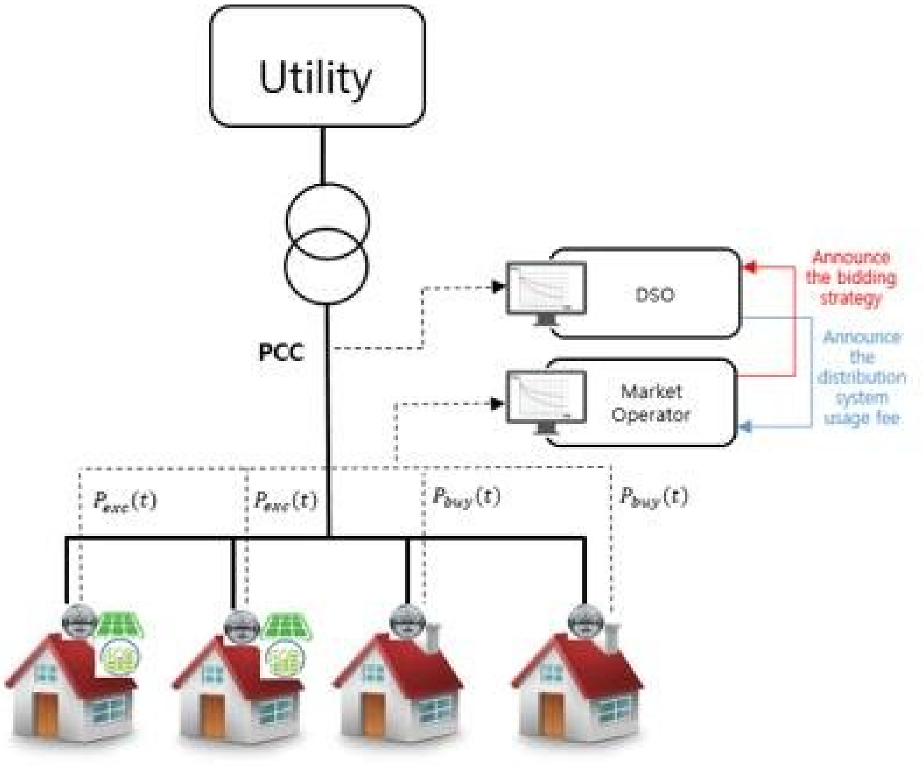

Figure 2.4. A framework of P2P energy trading in a distribution system[25]

First, the prosumer proposes the trading price and the then trading quantity. Based on this, the consumer decides to purchase the quantity of their demand. However, a market operator controls the P2P trading by collecting each player's bidding strategies and exchanging the information with the DSO, who controls and manages the stable operation of the distribution network. Hence, DSO should approve the bidding strategies of each player collected by the P2P market operator. In addition, to reduce the operational burden of the distribution system operator, the distribution system usage charge was calculated[25].

In [25] prosumer first proposes the trading price. Then according to the optimal energy storage scheduling, proposes the trading quantity. The consumer decides to purchase the quantity of energy by adjusting their loads. The process repeats until the market-clearing price is obtained.

**(5) Khorasany M, Mishra Y, Ledwich G., ”A decentralized bilateral energy trading system for peer-to-peer electricity markets”, IEEE Transactions on Industrial Electronics, Vol. 67, no. 6, pp.4646–57, June. 2020.**

A decentralized market with one seller, two buyers, and three lines have presented in Fig. 2.5. Sellers are willing to their surplus energy with buyers having minimum and maximum generation representing $x_1^{min}$ and $x_1^{max}$ respectively.Buyers can demand energy from sellers denoting $y_1^{min}$ and $y_1^{max}$ for buyer 1 minimum, and maximum demanded energy respectively and similarly to buyer 2. The seller will update their price to the buyers. That is, $\lambda_{11}$ represents updated price from seller 1 to buyer 1. Then the buyer updated their energy to the seller. That is,$y_{11}$ is the updated demanded energy from buyer 1 to seller 1. Line flow has calculated by line agents and sends the line flow prices to the corresponding players using particular lines to avoid overflow or congestion in the lines. Due to applying these price signals, players will try to trade energy with nearby players, which reduces power losses[25]. Each market player is a rational decision-maker and tries to maximize their welfare individually to attain social welfare maximization.

In [26], First, the sellers choose the price, and then the selling energy is updated. The seller sent the updated price to the buyers and based on this price buyers updated their energy. In addition to this, line flow prices are calculated.

**(6) Hien Thanh Doan; Jeongho Cho; Daehee Kim, ”Peer-to-Peer Energy Trading in Smart Grid Through Blockchain: A Double Auction-Based Game Theoretic Approach”, IEEE Access, Vol. 9, pp. 49206-18, March.2021.**

The system framework has shown in Fig. 2.6, an energy market consisting of many residential units(RU). Each residential unit can be an individual house with installed renewable sources like PV systems. The whole community consists of three entities:

1. The prosumer acts as a buyer or a seller in P2P electricity trading based on their current energy consumption generation at time slot t.
2. The system operator plays as an auctioneer in the market. The auctioneer’s responsibility is to manage all players and support optimized electricity purchasing and selling. By installing the code from the operator, the prosumer can connect sign up to the energy market network via a browser.
3. A smart controller allows information exchange in the market.

Every prosumer has their smart controllers to exchange information value with others in the P2P trading market. The peer-to-peer trading system using Stackelberg’s non-

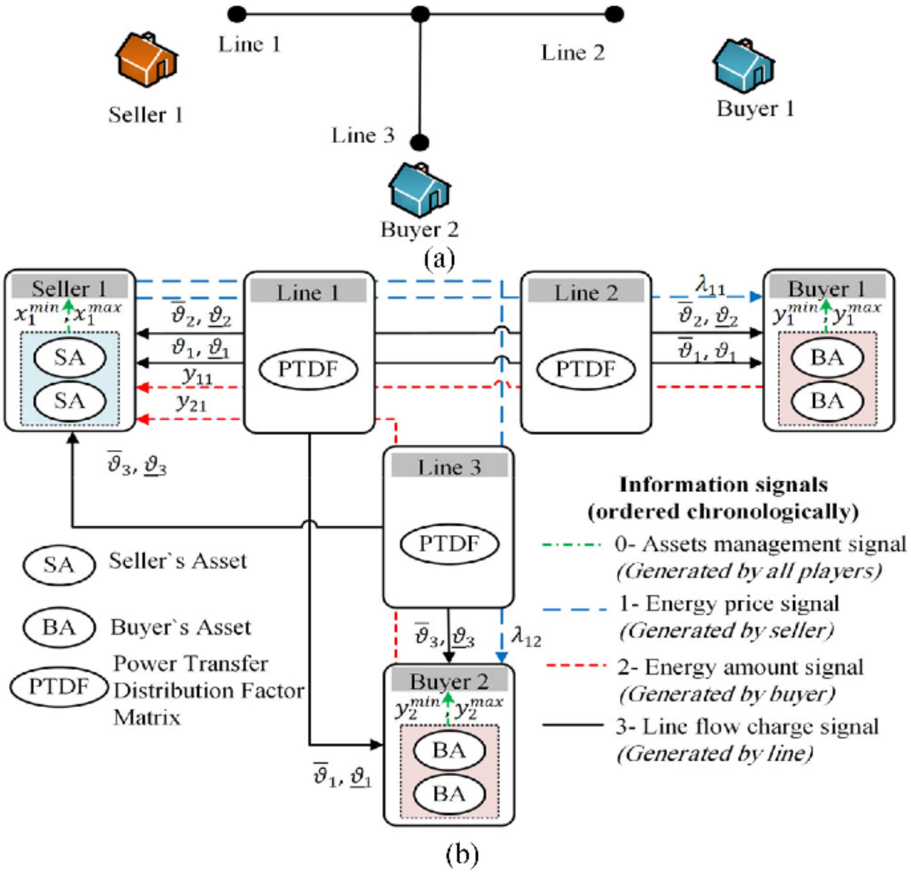

Figure 2.5. A simple network for information flow demonstration; (a) Physical layer (b) Virtual layer[26]

cooperative game theory is modeled. In interactions, the prosumers as buyers meet their demand by buying the required energy from surplus energy. The prosumer submits their bids/asks and energy to the auctioneer by double auction-based game theory. The auctioneer controls the game manages the auction process and determines the winner. Once the auction process is completed, each buyer identifies the auctioneer's price [27]. Buyers try to maximize their benefit by adjusting the quantity of energy to buy according to varying electricity prices. Finally, the auctioneer determines the clearing price and amount of energy for all participants by computing the average social welfare per seller(ASWS).

Bidders submit their reservation price to the auctioneer. The auctioneer determines the numbers of sellers and buyers using a double auction and the winner is determined. The buyers and sellers are sorted in decreasing order and increasing order of their reservation

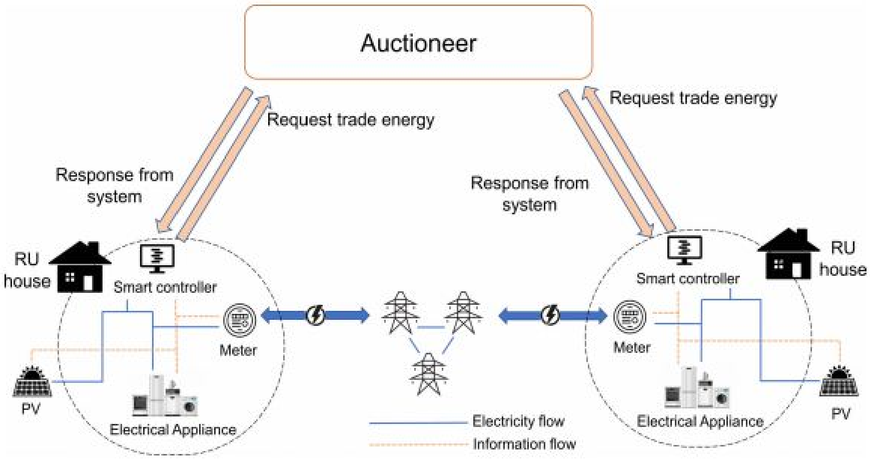

Figure 2.6. Overview of the P2P energy trading system[27]

price respectively. Finally, the clearing price and optimum quantity willing to trade are obtained.

**(7) M. Imran Azim; Wayes Tushar; Tapan Kumar Saha, "Coalition Graph Game-Based P2P Energy Trading With Local Voltage Management", IEEE Transactions on Smart Grid, Vol. 12, no. 5, pp. 4389-402, Sept. 2021.**

A coalition graph game-based P2P energy trading framework has presented in Fig. 2.7.in which prosumers can form the coalition to negotiate and decide the energy sharing parameters such as price and quantity. All prosumers have a smart meter known as a transactive meter (TAM). Compared to a conventional energy meter, TAM is a separate smart meter that can record the solar PV generation data, internal demand,state-of-charge (SoC) of the battery, traded quantity, and price and determine the surplus and deficient energy. A blockchain-based communication platform has been presented, linked with the TAM to receive surplus energy or deficient load signals. The prosumer can start financial deals with other prosumers through the blockchain platform in the virtual layer. The surplus deficient energy and trading quantity pricing data of each prosumer were communicated from its TAM over the protected communication platform. Based on this exchanged information data, selling and buying orders were generated.

A third entity, a P2P market invigilator (PMI), coordinates virtual and physical layer information to the players. Their responsibility is to maintain the network in the physical layer so that each prosumer has to follow the instructions of PMI. They maintain coordi-

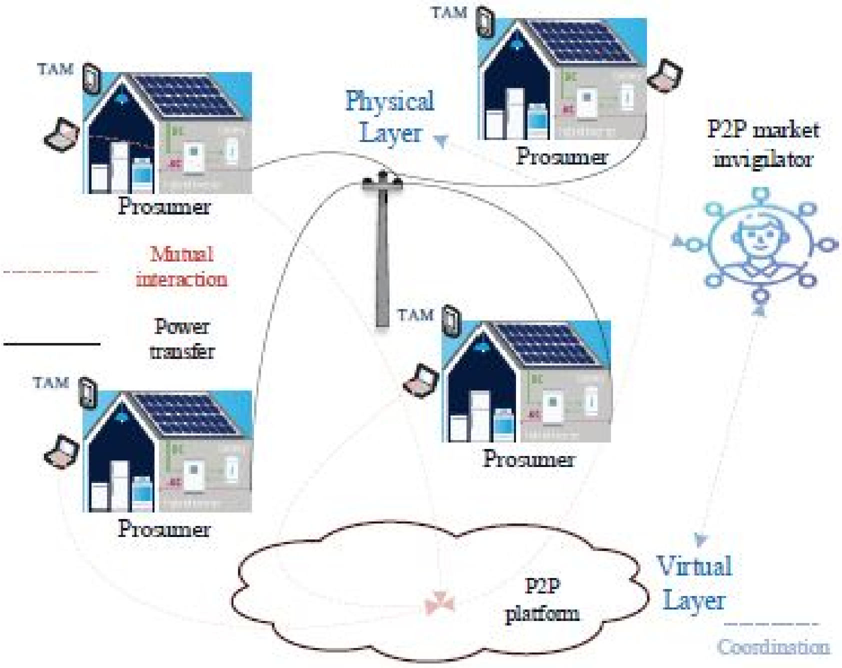

Figure 2.7. A P2P trading framework coordinating virtual and physical layers[28].

nation between physical and virtual layers to develop an attractive P2P trading scheme with prosumers without causing voltage rise issues during P2P penetration[28].

All participants choose their price and quantity of energy as their bids. Then the participants are sorted or tagged as sellers or buyers based on their minimum and maximum declared trading price. In this sellers with the least price get an opportunity to negotiate and selling buying orders are created. Through contracts, financial transactions are created and energy quantities are transferred.

**(8) C Zhang et al., "A Bidding System for Peer-to-Peer energy trading in a Grid-connected Microgrid", Applied Energy, vol. 103, pp. 147-152, Dec. 2016.**

A game theoretic-based peer-to-peer business model using an online platform, Elecbay, is illustrated in [29]. This elecbay(e-Bay) platform allows the players to sign contracts and make payments. Fig. 2.8. represents the operational structure of elecbay. In this model, three entities: buyers, sellers, and suppliers. A central controller, distribution system operators(DSOs), makes the bid acceptance and delivery. Sellers list the items, and consumers browse and order these items by prepayment using the elecbay platform to the DSOs.

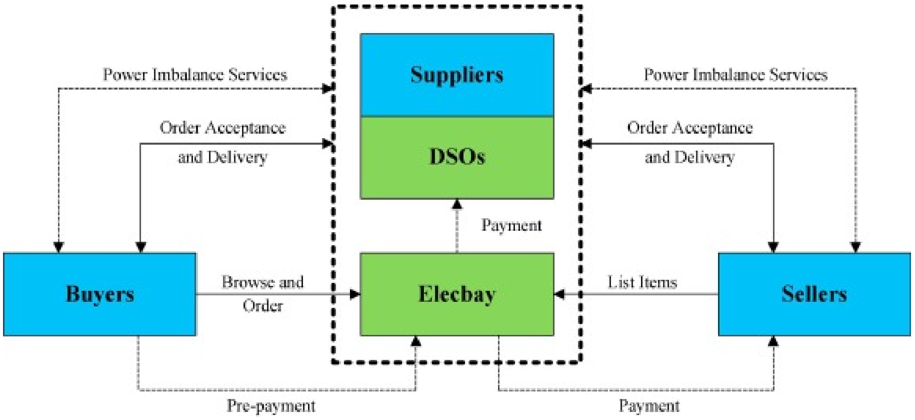

Figure 2.8. Operational structure of Elecbay[29].

**(9) Hanumantha Rao Bokkisam, Shashank Singh, Ritesh Mohan Acharya, and M P Selvan, "Blockchain-based Peer-to-Peer Transactive Energy System for Community Microgrid with Demand Response Management", CSEE Journal of power and energy sytems[early access],2021.**

Fig. 2.9. illustrates a P2P energy trading in the transactive energy market (TEM). In this energy market, there are three agents: participants include both prosumer and consumer, auctioneer or transactive energy market operator (TEMO), and the utility. Each participant has equipped with a smart meter (SM), various household appliances, and a transactive home energy management system (THEMS). Through a communication channel like a blockchain network, the participants were connected to TEMO. By a distribution transformer, the community microgrid is connected to the utility through a smart meter (SM), which measures energy trading with the utility[30]. Using the auction theoretic approach, the auctioneer is a managing and controlling agent who determine the day-ahead internal market-clearing price quantity. Through demand response (DR) management, all the participants try to minimize their electricity bills.

Initially, the smart contract is deployed and the buyer submits its bids and the supplier submits their offers. The smart contract arranges the demand bids and supply bids in descending and ascending order respectively. and calculates the optimal quantity and the clearing price for the market. Winners are determined and allocated this clearing price and quantity. Those who win added their respective clearing quantities to the blockchain ledger and are displayed to the public.

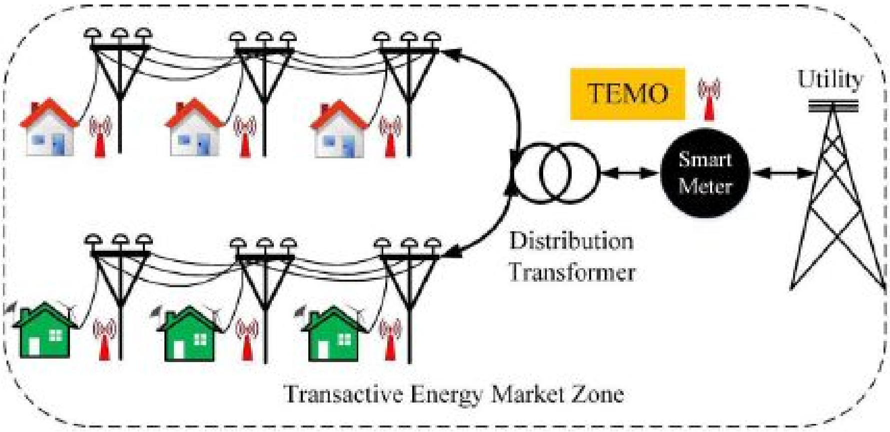

Figure 2.9. Community microgrid with a central market operator[30].

## 2.3 Summary of Related Works

The following are the main issues that related works have faced.

- Primary research on non-cooperative situations has previously been conducted.
- However, there was no clear understanding of the player's domain.
- The players were not subjected to any restrictions.
- Previous works were either consumer- or prosumer-focused.
- Consumers did not embrace some recent energy-trading models and experimental experiments, thus they were dropped. To avoid this, the interests and benefits of the users must be considered.
- The grid's relationship was not taken into account.
- Recently, cooperative game theory has been used in some research.
- There is also no adequate explanation for the area constraint, given the majority of studies are based on energy trading within the same premises.
- Previously proposed games only cater to one consumer, which appears to be impracticable given that P2P allows for several consumers.
- Previous research has only looked at the interactions between prosumers and consumers in cooperative and non-cooperative games.
- In all bidding techniques and pricing mechanisms, there is a high likelihood that any prosumer or consumer may confront an exit situation, either due to a lack of matched entities or because the market does not provide the desired price. This could result in a monopolized market where not all players can trade fairly, resulting in uncertainty and

contract instabilities.

- There is no explanation for the players who will not create a coalition.

We developed a peer-to-peer energy trading framework for building levels, which is a hybrid of cooperative and non-cooperative game theory approaches, to address these shortcomings.

## 2.4 Conclusion

This chapter has presented a framework for peer-to-peer energy trading networks. The "P2P economy" concept served as the foundation for P2P energy trading. It is typically implemented within a local electrical distribution system and is also known as the "sharing economy." P2P energy trading needs a platform to function properly and exchange energy successfully. Elecbay is one such software platform. One day before the day in terms of time blocks, buyers and sellers submit their offers to a market operator. The submission of bids for this day-ahead market auction begins at midnight on one day and ends at midnight on the following day. None of the peers is anticipated to back out of the abovementioned offers after the matching and price allocation. Anyone who disobeys a specific regulation of that community is required to pay a fine. The peer contact is so strong that one peer is dependent on the other since each decision has an impact on the other. It needs a platform for the trading process to exchange energy effectively. Additionally, the platform's various trading regulations have a big impact on the choices that peers make when trading with other peers.

# Chapter 3

# SYSTEM DESCRIPTION

## 3.1 Introduction

This chapter presents our proposed system's architecture, players' strategies, utility function, and profit function of each participant. Section 3.2 outlines the system framework of the peer-to-peer network. In this system model, there are two players, prosumers and system operators. Each participant aims to maximize their benefits and each of the have a welfare function and profit function respectively. Also describes the properties and characteristics of the objective function of each player.

To frame the problem, we propose an energy trading platform with the grid, market operators, and building prosumers, In this framework consumers buys energy from either the prosumer or grid. Prosumers who can generate energy and engage in peer-to-peer trading by selling their surplus energy to other participants or the grid. Grid is the conventional power source of all the building prosumers. Assuming the total demand for the consumers is high during peak hours. To meet this demand grid has to generate more or keep a reserve on standby. Hence grid increases their cost dramatically. Customers can participate in peer-to-peer (P2P) trading, and the grid can also act as a buyer, acquiring energy from prosumers during peak hours if total demand reaches a certain level. Hence encouraging customers to engage in peer-to-peer energy trading by reducing the dependency on the grid, buy lowering the purchasing power during trade, and vice versa. This project's main purpose is to show how peer-to-peer (P2P) trading benefits all parties involved, including the grid, customers, and prosumers. Now, we formulate the system model in the following section.

## 3.2 System Model

Fig. 3.1 shows a representation of the system framework, which depicts three categories of entities: prosumers, SOs, and the grid[21]. Prosumers can flip positions between consumers and producers based on their generational and consumption patterns. The basic role of SO is to facilitate energy trading between peers (buildings) and the grid. Supply and demand are kept in check via trading with the grid. Traditionally, every building has received energy from the grid. The framework and the energy marketplace are explained in the next section.

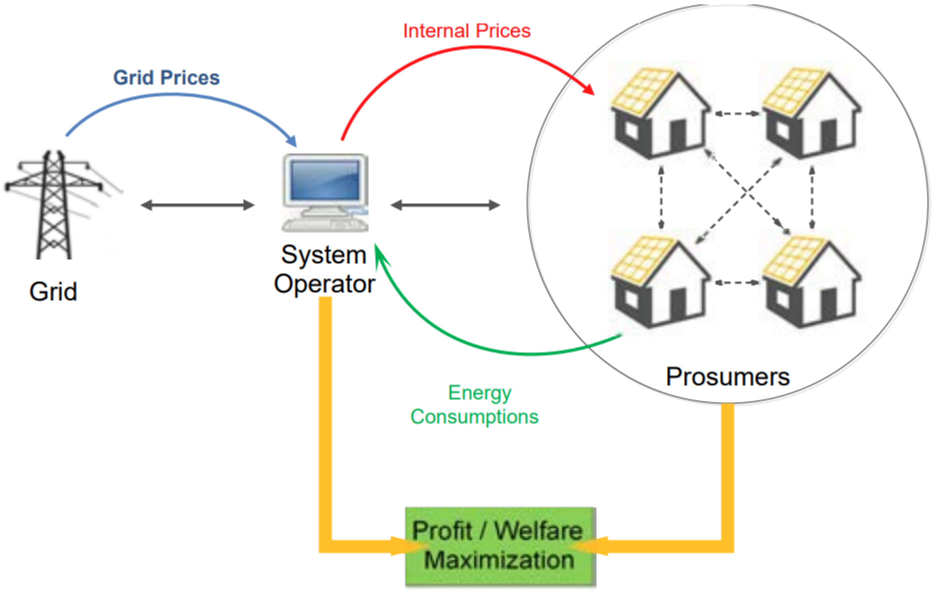

Figure 3.1. Peer-To-Peer Network[21]

### 3.2.1 Prosumers:

PV prosumers are end-users who have PV systems installed on their dwellings and play energy-consuming and energy-supplying roles in building levels depending on their power consumption as well as their solar power production. When energy generation exceeds energy consumption, prosumers act as sellers by selling surplus energy. Alternatively, the prosumers act as buyers, they are the ones who purchase the additional energy for their energy demands. Another type of prosumer is when energy production and energy consumption are equal, then they act as self-sufficient prosumers.

### 3.2.2 Welfare Model of Prosumers

Prosumers can anticipate energy usage and generation one day ahead of time. The prosumer welfare function includes the revenue/bill earned from selling/buying energy, as well as the utility function. The utility function reflects the level of happiness or enjoyment that a customer feels after consuming a certain amount of energy [25]. Two types of utility functions are often used to model energy consumers: Utility functions can be divided into two categories: There are two types utility functions: 1) quadratic utility function and 2) logarithmic utility function. The logarithmic utility function $\psi_n \ln(1+\zeta_n)$ is utilised here. The purpose of the prosumers is to maximize the welfare function, taking into account that they can act as both sellers and buyers at any same time.

$$\max_{\zeta_n} \sum F_{1,n}, \tag{3.2.1}$$

$$\text{subject to, } \zeta_{n,\min} \leq \zeta_n \leq \zeta_{n,\max}. \tag{3.2.2}$$

$$F_{1,n}(\zeta_n) = \psi_n \ln(1+\zeta_n) + P_s\left(E_g^n - \zeta_n\right); E_g^n \geq \zeta_n, \tag{3.2.3}$$

$$F_{1,n}(\zeta_n) = \psi_n \ln(1+\zeta_n) + P_b\left(E_g^n - \zeta_n\right); E_g^n < \zeta_n. \tag{3.2.4}$$

Where, $\psi_n(\geq 0)$ is the priority parameter of prosumer $n$, this parameter changes according to the behavioural characteristics of the prosumer at different times.$E_{\mathrm{g}}^n$ is the energy produced by $n^{th}$ prosumer. The first and second derivatives of (3.2.3) - (3.2.4) can be obtained as follows.

$$\begin{aligned} \frac{\partial F_{1,n}(\zeta_n)}{\partial \zeta_n} &= \begin{cases} \frac{\psi_n}{1+\zeta_n} - P_s & E_g^n \geq \zeta_n, \\ \frac{\psi_n}{1+\zeta_n} - P_b & E_g^n < \zeta_n, \end{cases} \\ \text{and } \frac{\partial^2 F_{1,n}(\zeta_n)}{\partial^2 \zeta_n} &= -\frac{\psi_n}{(1+\zeta_n)^2}. \end{aligned} \tag{3.2.5}$$

The welfare function is concave in each case, as shown by the negative second-order derivative (3.2.5). As a result, there is an optimal solution for maximizing prosumer welfare.

The optimum outcome is written as follows.

$$\text{For Sellers,} \quad \zeta_n = \frac{\psi_n}{P_s} - 1; \quad \zeta_{n,\,\min} \leq \zeta_n \leq E_{\mathrm{g}}^n, \tag{3.2.6}$$

$$\text{For Buyers,} \quad \zeta_n = \frac{\psi_n}{P_b} - 1; \quad E_g^n \leq \zeta_n \leq \zeta_{n,\max}, \tag{3.2.7}$$

$$\text{For Self Sustained Prosumers,} \quad \zeta_n = E_g^n. \tag{3.2.8}$$

Prosumers must choose a role (Buyer or Seller) at the start of each time slot and stick to it throughout.

We can demonstrate the optimal solution for prosumers by plotting the optimized value of the objective function using the Matlab platform. The characteristic of this welfare function is an example of linear programming problems. In this problem, we can find out the optimal value of the linear function. This optimal value may be either a minimum point or a maximum point. Here the players try to maximize their objective function (3.2.1). The players can either take their role as seller or buyer and their welfare function is given by (3.2.3) and (3.2.4) respectively. This objective function consists of several variables and has to maximize consumption subjected to the constraints of minimum consumption to maximum consumption. By using the Matlab tool. the function is optimized and a feasible solution is plotted.

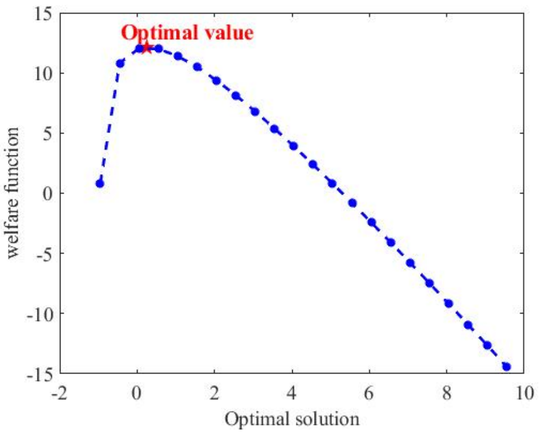

Figure 3.2. Objective function of seller

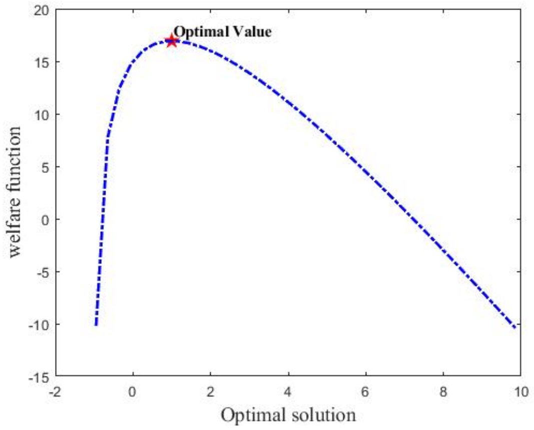

Figure 3.3. Objective function of Buyer

Fig. 3.2 and Fig. 3.3 shows the optimal solution for the welfare function of seller and buyer, which is given by (3.3.6) and (3.3.7) respectively. From this graph, it is clear that there exists a unique solution for this objective function.

### 3.2.3 System Operator:

The System Operator (SO) is responsible for coordinating the energy sharing between consumers and maintaining the supply and demand balance of the grid. The System Operator (SO) organizes energy sharing and maintains the supply and demand balance in the microgrids. The SO is the central market operator and the person who decides prices internally within the energy-sharing framework. Further, the price difference could compensate for the operation costs and bring profits to SO, which motivates SO to fulfill its duty. Nevertheless, ensuring smooth system operation is the primary objective of the central entity, rather than earning profits, for maximizing social welfare.

### 3.2.4 Profit Model Of System Operator

To maintain the balance between energy supply and demand, the system operator will trade with the grid at the prices $P_{gb}$ and $P_{gs}$. The internal prices $P_b$ and $P_s$ for energy exchange within the cluster will be determined by the operator. Profit $(F2)$ maximization is the optimization model for SO, and it is as follows.

$$\begin{gathered}\max \sum_{P_s,P_b} F_2, \\ \text{subject to } P_{gb} \leq P_s, P_b \leq P_{gs}. \\ F_2 = P_b E_{buy} - P_s E_{sell} + P_{gb} \Delta E_i; E_{sell} \geq E_{buy},\end{gathered} \tag{3.2.9}$$

$$F_2 = P_b E_{buy} - \phi_s E_{sell} + P_{gs} \Delta E_{\mathrm{sell}} < E_{buy}, \tag{3.2.10}$$

$$\Delta E = \left(E_{sell} - E_{buy}\right). \tag{3.2.11}$$

The SO will buy $E_{\mathrm{sell}}$ energy from all sellers $\left(E_{\mathrm{g}}^{n} \geq \zeta_n\right)$ and sell $E_{buy}$ to all buyers $\left(E_{\mathrm{g}}^{n} < \zeta_n\right)$

$$E_{sell} = \sum_{n \in N_s} \left(E_g^n - \zeta_n\right); \quad E_g^n \geq \zeta_n \tag{3.2.12}$$

$$E_{buy} = \sum_{n \in N_b} \left(\zeta_n - E_g^n\right); \quad E_g^n < \zeta_n \tag{3.2.13}$$

The number of sellers and buyers is represented by $N_s$ and $N_b$, respectively. In addition, the SO will set internal pricing $P_{gb} < P_s < P_b < P_{gs}$, so that local production and consumption.

Each prosumer to optimize its $\zeta_n$ in response to the prices sent by the SO. Sequentially, the updated $\zeta_n$ is sent to the SO, which then updates the $P_b$ and $P_s$, as follows.
Case 1: $E_{\text{sell}} > E_{buy}$

$$\begin{aligned} &\frac{\partial F_2}{\partial P_s} = 0 \\ &\quad - \sum_{n \in N_s} E_g^n - N_s + P_{gb} \sum_{n \in N_s} \frac{\psi_n}{P_s^2} = 0. \end{aligned} \tag{3.2.14}$$

$$P_{1s}^* = \begin{cases} \sqrt{\frac{P_{gb} \sum_{n \in N_s} \psi_n}{p_1}} & P_{gb} \le P_{1s}^* \le P_{gs} \\ P_{gb} + \frac{E_{sell}}{\beta_1} & \text{Otherwise} \end{cases} \tag{3.2.15}$$

$$P_{1b}^* = \begin{cases} \sqrt{\frac{P_{gb} \sum_{n \in N_b} \psi_n}{p_2}} & P_{gb} \le P_{1b}^* \le P_{gs} \\ P_{gs} - \frac{E_{sell}}{\beta_2} & \text{Otherwise} \end{cases} \tag{3.2.16}$$

$$p_1 = \sum_{n \in N_s} E_{\text{g}}^n + N_s \text{ and } p_2 = \sum_{n \in N_b} E_g^n + N_b. \tag{3.2.17}$$

Case 2: $E_{\text{sell}} < E_{buy}$

$$P_{2s}^* = \begin{cases} \sqrt{\frac{P_{gs} \sum_{n \in N_s} \psi_n}{p_1}} & P_{gb} \le \phi_{2s}^* \le P_{gs} \\ P_{gb} + \frac{E_{buy}}{\beta_1} & \text{Otherwise} \end{cases} \tag{3.2.18}$$

$$P_{2b}^* = \begin{cases} \sqrt{\frac{P_{gs} \sum_{n \in N_b} \psi_n}{p_2}} & P_{gb} \le P_{2b}^* \le P_{gs} \\ P_{gs} - \frac{E_{buy}}{\beta_2} & \text{Otherwise .} \end{cases} \tag{3.2.19}$$

Here, $\beta_1$ and $\beta_2$ are speed adjustment parameters.
Case 3: $E_{\text{sell}} = E_{buy}$

$$\text{From (18) and (19), } P_s = \frac{P_b \sum_{n \in N_s} \psi_n}{p_1 + p_2 - \sum_{n \in N_b} \psi_n}, \tag{3.2.20}$$

Substituting this in the profit function of SO:

$$F_2 = \sum_{n \in N_b U N_s} \psi_n - P_b p_2 - \frac{P_b \sum_{n \in N_s} \psi_n}{p_1 + p_2 - \sum_{n \in N_b} \psi_n} p_1, \tag{3.2.21}$$

Taking the first derivative of (3.2.21) concerning $P_b$ and equating it to zero. The optimal values are.

$$P_{3b}^{*} = \begin{cases} \frac{1}{p_1+p_2}\left(\sum_{n\in N_b}\psi_n + r_1\right) & P_{gb} \leq P_{3b}^{*} \leq P_{gs} \\ P_{gs} - \frac{E_{sell}}{\beta_2} & \text{Otherwise} \end{cases} \tag{3.2.22}$$

$$P_{3s}^{*} = \begin{cases} \frac{1}{p_1+p_2}\left(\sum_{n\in N_s}\psi_n + r_2\right) & P_{gb} \leq P_{3b}^{*} \leq P_{gs} \\ P_{gb} + \frac{E_{buy}}{\beta_1} & \text{Otherwise .} \end{cases} \tag{3.2.23}$$

Where,

$$r_1 = \sqrt{\frac{p_1 \sum_{n\in N_b}\psi_n \sum_{n\in N_s}\psi_n}{p_2}} \tag{3.2.24}$$

$$r_2 = \sqrt{\frac{p_2 \sum_{n\in N_b}\psi_n \sum_{n\in N_s}\psi_n}{p_2}}. \tag{3.2.25}$$

We can demonstrate the objective function of the system operator, using the Matlab platform. The system operator profit function is a nonlinear equation with a multi-variable. The objective function(3.2.9) has to maximize two variables, that is internal selling price and buying price respectively. The solution of this objective function gives two optimized values. This function is subjected to constrained given by Eqn(3.2.9).the system operator profit function can be either of the equations in (3.2.10) based on the condition of energy buy from all sellers and sell to all the buyers.

Figure 3.4. Objective function of system operator

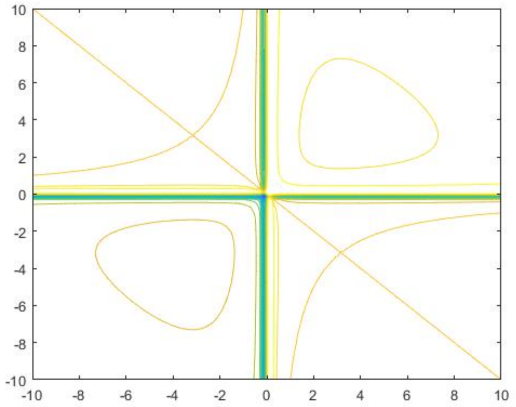

Figure 3.5. Contour lines

Fig. 3.4 is the three-dimensional view of the profit function of the system operator and Fig. 3.5 is their contour lines representation. However, at times analyzing a three-dimensional image might be cumbersome or challenging. Contour maps give the means to express the function while merely drawing on the two-dimensional input space. The contour lines, clearly show there exist unique solutions.

## 3.3 Conclusion

This chapter summarizes the framework of the proposed model. In this system model, there are three entities, that is the grid, system operator, and building prosumers. The main two players are prosumers and system operators. The prosumers can either act in the seller or buyer role. The system operator is the market operator, who coordinated and controls the trading system. In this trading platform SO plays first and starts bids as selling price and buying price to prosumers updated from the grid price and sent to the prosumers. Prosumers set their consumption value and sent it to SO. Based on this value SO adjust the internal price and sent it again to prosumers. This process continues until optimal values are obtained. Each participant aims to maximize their welfare function. The objective function properties are identified and plotted. It identifies that there exists a unique solution for each function.

# Chapter 4

# STACKELBERG GAME ANALYSIS

## 4.1 Introduction

This chapter provides a brief introduction to Stackelberg's game theory. Section 4.2 outlines how the system is modeled using the Stackelberg game and describes the strategic form of the game. In the Stackelberg game, there is a leader and follower, either single or multiplayer. In this model, we consider the single leader-multi-follower methods. Here leader first takes the decision and followers follow the leader's decision and take the strategies. The solution to the Stackelberg game is the Stackelberg equilibrium. Section 4.3 outlines the Stackelberg equilibrium and proves the existence and uniqueness of SE. Section 4.4 outlines the optimization process involved in this study and discusses the optimization tool used for the process. Section 4.5 outlines the algorithm used to find the SE. Section 4.6 deals with the various case studies conducted to study the algorithm and obtain the Stackelberg equilibrium(SE).

## 4.2 Stackelberg Game

There are two players in a standard Stackelberg game: a leader and a follower. The leader is also referred to as a defender, while the follower is referred to as an attacker. Before the adversary best reacts to the leader's mixed strategy, the leader commits to a mixed strategy that may be viewed by the other agent (the follower or adversary). To arrive at the randomized schedule, the individual strategies of the optimal mixed approach are assigned appropriate weights. Because the attacker can undertake surveillance and attack any deterministic approach, the defender randomizes the schedules. The Stackelberg game is a non-cooperative game in which the goal is to discover the best potential solution for both prosumers and the SO's objective functions.

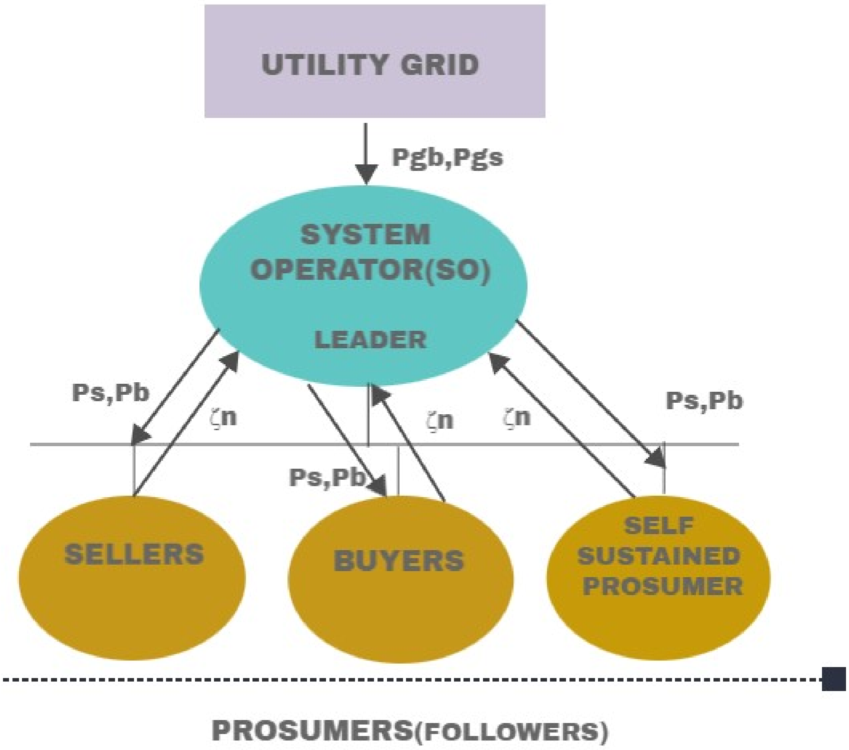

Figure 4.1. Stackelberg Game Model

As illustrated in the Fig. 4.1, the system framework is modeled using the Stackelberg game. SO is the leader, and the prosumers are the followers in this scenario. According to the Stackelberg game, the SO offers first and provides internal purchasing and selling prices to the prosumers. The prosumers follow the leader's decision and optimize their consumption based on internal prices and communicate it to the leader. The leader will once again change the prices and re-send them to the prosumers. This is an iterative process that is repeated until the optimum internal prices and consumption levels are found. For non-cooperative players, we design the Stackelberg game.
The strategic form of the game (G) is presented as follows,

$$G = \left\{ N \cup \{SO\}, \{\zeta_n\}_{n\in N}, \phi_b, \phi_s, F_{1,n}, F_2 \right\}. \tag{4.2.1}$$

which contains the following components:
(i) PV prosumers in set $N$ are followers deciding their energy consumption strategies according to internal prices determined by SO, who is the leader of the game.
(ii) $N$ is the set of strategies of each PV prosumer n $\in N$.
(iii) $F_{1,n}$ is the welfare function of prosumer $n$, who decides energy consumption level to maximize welfare.
(iv) $P_b$ and $P_s$ are the internal buying price and selling price, set by SO,
(v) $F_2$ is the profit function of SO, and it gains the total profit SO obtained from managing energy sharing and trading with the day-ahead market.
SO and PV prosumers devise strategies to maximize their welfare or profit. One possible solution for the proposed game is the SE, in which the leader determines its optimal internal prices based on the best actions of the followers.

## 4.3 Stackelberg Equilibrium

**Definition 4.3.1.** Consider the Stackelberg game(G) defined in (4.2.1), a set of strategies ($\zeta_n^*$, $P_s^*$, $P_b^*$) constitutes an SE of this game,if and only if satisfies the following set of inequalities.

$$Prosumer, \quad F_{1,n}(\zeta_n^*, P_s^*, P_b^*) \geq F_{1,n}(\zeta_n, P_s^*, P_b^*); \quad \forall n \in N, \tag{4.3.1}$$

$$\text{SO}, \ \ F_2(\zeta_n^*, P_s^*, P_b^*) \geq F_2(\zeta_n^*, P_s, P_b); \quad \forall P_b \in P_b; \forall P_s \in P_s. \tag{4.3.2}$$

When all the players in ($N \cup$ SO) achieve the SE, the SO cannot increase its profit by adjusting internal prices from the SE prices $P_s^*$ and $P_b^*$.Similarly, no prosumer can improve their welfare by choosing other strategies different from $\zeta_n^*$.

### 4.3.1 Existence and uniqueness of SE

An equilibrium in pure strategies is not always guaranteed in the Stackelberg game. As a result, we must examine if a SE exists in the proposed Stackelberg game.

**The existence of SE:**

Theorem: In the proposed Stackelberg game G between SO and PV prosumers in the set $N$, there is always a unique SE.

*Proof.* : With respect to $\zeta_n$, $\forall n \in N$,and hence for any pair of internal prices $P_b$ , $P_s$, the welfare function (3.3.3) with negative second-order derivative (3.3.5) is strictly concave. To maximize its utility, each PV prosumer n will have a unique $\zeta_n$ according to (3.3.6-8). When all players in the energy-sharing game G, including each prosumer and SO, achieve their optimal solutions based on all players' strategies, the game reaches SE. As a result, it is clear that the suggested game G has reached a SE after the SO has found an optimal pair of internal pricing $P_b^*$, $P_s^*$ while prosumers select their unique energy consumption $\zeta_n^*$. □

**The uniqueness of SE:**

To verify the uniqueness of SE, we must first prove the uniqueness of optimal prices $P_b$, $P_s$, PV prosumers have their own unique energy usage when SO sets internal prices as $P_b$, $P_s$.

*Proof.* : Substituting (3.3.12) and (3.3.13) into (3.3.10),

$$E_{\text{sell}} = \sum_{n \in N_s} \left( E_g^n - \frac{\psi_n}{P_s} \right) + N_s, \tag{4.3.3}$$

$$E_{buy} = \sum_{n \in N_b} \left( \frac{\psi_n}{P_b} - E_g^n \right) - N_b. \tag{4.3.4}$$

Substituting (4.3.3) and (4.3.4) into (3.3.10), and differentiating twice with respect to $P_s$ and $P_b$,

$$\begin{aligned} H_1 &= \begin{bmatrix} -\frac{2P_{gb}\left(\sum_{n \in N_s} \psi_n\right)}{P_s^3} & 0 \\ 0 & -\frac{2P_{gb}\left(\sum_{n \in N_b} \psi_n\right)}{\phi_b^3} \end{bmatrix}, \\ H_2 &= \begin{bmatrix} -\frac{2P_{gs}\left(\sum_{n \in N_s} \psi_n\right)}{P_s^3} & 0 \\ 0 & -\frac{2P_{gs}\left(\sum_{n \in N_b} \psi_n\right)}{P_b^3} \end{bmatrix}. \end{aligned} \tag{4.3.5}$$

Hessian matrices with regard to $P_s$ and $P_b$ are both negative in this situation. As a result, there are unique $P_s$ and $P_b$ values, resulting in a unique Stackelberg Equilibrium for the game. □

## 4.4 Optimization

To optimize the constrained objective function, Matlab provides an inbuilt tool called fmincon. Fmincon is a Nonlinear Programming solver provided in MATLAB's Optimization Toolbox. By using Matlab fmincon, find the minimum of the constrained objective function to a single variable or multi-variable. An objective function is subjected to a set of constraints and some boundary values. The output is the optimized value, $X_{opt}$. The optimization flow diagram is depicted in Fig. 4.2.

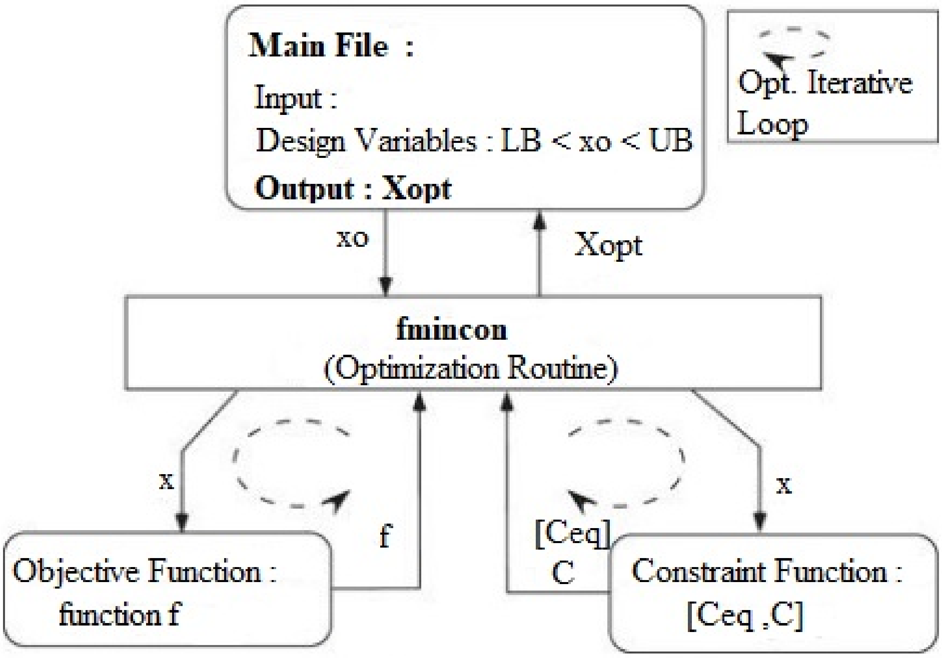

Figure 4.2. Optimization Flow Diagram

## 4.5 Algorithm

Algorithm 1 summarizes P2P energy trading using the Stackelberg game and finds the Stackelberg equilibrium(SE). There are two players in this game, system operator and prosumers. Each player aims to maximize their benefit and find the optimum points. Each player's objective function is minimized by using Matlab inbuilt tool called Fmincon. Once obtained values are converges nearly to zero, SE is obtained, otherwise process repeats

Algorithm 1.Algorithm to find Stackelberg Equilibrium

```
1: Initialise variables
Initialize internal buying and selling prices equal to the grid prices
2: Prosumers have to decide their roles(Buyer or Seller) at the beginning of every time slot.
3: While condition true do
4: Find optimum consumption $\zeta_n^*$ by minimizing welfare function of prosumer using fmincon tool
5: Transmit $\zeta_n^*$ to the SO
6: The SO will now update the prices as $P_s$ and $P_b$ by minimizing the profit function of system operator using fmincon tool.
7: If Convergence criteria ($\left|P_{s,i+1}^* - P_{s,i}^*\right| \leq \epsilon, \left|P_{b,i+1}^* - P_{b,i}^*\right| \leq \epsilon$ and $\left|\zeta_{n,i+1}^* - \zeta_{n,i}^*\right| \leq \epsilon$)satisfied, SE is obtained and terminate;
8: else, Send the updated new prices to all prosumers and go to step 3.
```

## 4.6 CASE STUDY-1

**Basic Data**: For numerical tests, we conduct a test case study by considering seven PV prosumers among the residential levels. Their energy generation and energy consumption details are given in table 4.1. According to Indian energy exchange(IEX) limited rate policy,we set the grid buying price($P_{gs}$) and grid selling price($P_{gs}$) as 3 Rs/kWh and 8 Rs/kWh respectively.

We consider the test cases for a one-hour time slot of the day-ahead market. At the beginning of the time slot, prosumers have to choose their role as sellers or buyers. As shown in Table 4.1, the first three prosumers act as buyers because their generation is less compared to consumption. And the last three prosumers act as the sellers since their generation is much better than their demand. Prosumer-4 is the self-sufficient prosumer, where generation and consumption are the same.

Table 4.1. Energy Details of each prosumers

| Prosumers | Energy Generation for all the prosumers($E_{gen}$) for 1 hr(kWh) | Energy consumption for all the prosumers for 1 hr(kWh) |
|---|---|---|
| 1 | 0 | 3.0 |
| 2 | 1.5 | 2.5 |
| 3 | 2 | 3.5 |
| 4 | 3.5 | 3.5 |
| 5 | 4 | 3.2 |
| 6 | 4.5 | 4.2 |
| 7 | 4.5 | 4.0 |

### 4.6.1 Result Analysis

Based on the data and proposed algorithm, the SE of the game is obtained for a 1 hr time slot. Initially, we consider the internal prices equivalent to grid prices. Here is an important parameter, prosumer preference factor $\psi_n$ which depicts the behavior of each prosumer. This parameter has great significance in P2P trading. We randomly choose the parameter values by trial and error for each prosumer as shown in Table 4.2. The P2P trading is done and the algorithm computes the optimum consumption of each prosumer as shown in Table 4.2.

Table 4.2. Optimum Consumption after P2P trading(SE)

| Prosumer preference parameter($\psi_n$) | Optimal solution,$\zeta_n^*$ (In P2P) |
|---|---|
| 100(buyer) | 11.50 |
| 100(buyer) | 11.50 |
| 100(buyer) | 11.50 |
| 10(seller) | 2.333 |
| 10(seller) | 2.333 |
| 10(seller) | 2.333 |

The obtained optimum energy consumption of each prosumer, the SE points are plotted as shown in Fig. 4.3

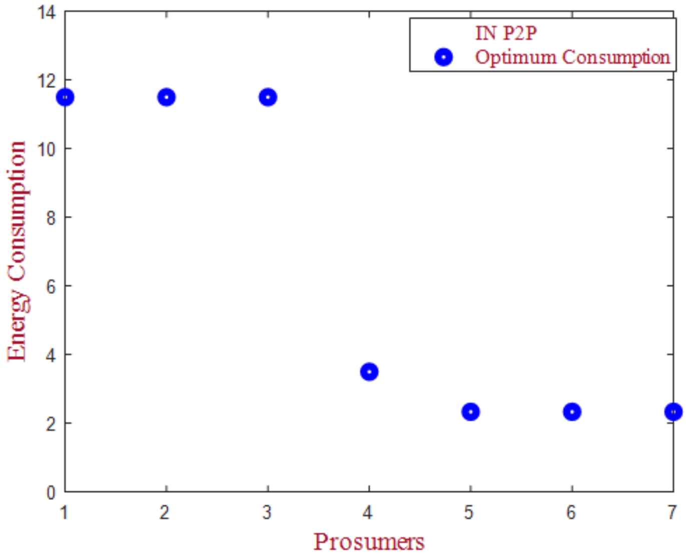

Figure 4.3. Optimum Consumption of each prosumer

The internal prices after the P2P trading are obtained as shown in figures. 4.4 and 4.5, respectively.

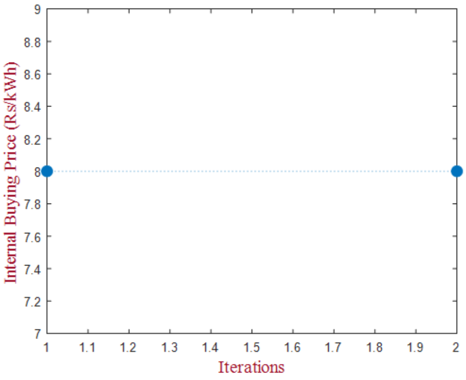

Figure 4.4. Iterative variation of buying price

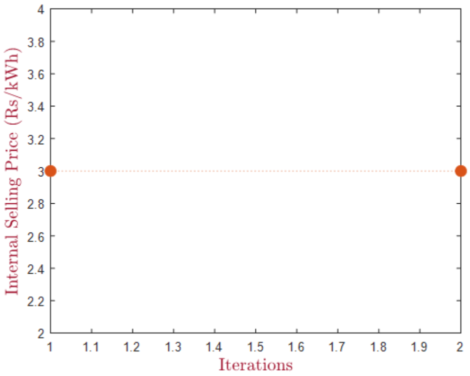

Figure 4.5. Iterative variation of selling price

The internal selling price converges to 3 Rs/kWh and the buying price converges to 8 Rs/kWh. As we can see, the internal trading prices are the same as the grid prices. So after P2P trading, consumers don't get a benefit from this trading. because they have to pay the same prices in P2P trading. There is not much difference between grid trading and P2P trading. The internal buying price and selling price at SE are 8 Rs/kWh and 3 Rs/kWh respectively.Hence the SE is obtained as ($\zeta_n^*$,$P_b^*$.$P_s^*$).

## 4.7 CASE STUDY-2

Basic Data: Similarly, we take a set of another test case study by considering seven PV prosumers among the residential levels. Their energy generation and energy consumption details are given in Table 4.3. According to Indian energy exchange(IEX) limited rate policy,we set the grid buying price($P_{gs}$) and grid selling price($P_{gs}$) as 3 Rs/kWh and 8 Rs/kWh respectively.

We consider the test cases for a one-hour time slot of the day-ahead market. At the beginning of the time slot, prosumers have to choose their role as sellers or buyers. As shown in Table 4.3, the first three prosumers act as buyers because their generation is less compared to consumption. And the last three prosumers act as the sellers since their generation is much better than their demand. Prosumer-4 is the self-sufficient prosumer, where generation and consumption are the same.

Table 4.3. Energy Details of each prosumers

| Prosumers | Energy Generation for all the prosumers($E_g$) for 1 hr(kWh) | Energy consumption for all the prosumers for 1 hr(kWh) |
|---|---|---|
| 1 | 0.497 | 0.509 |
| 2 | 0.341 | 0.550 |
| 3 | 0.312 | 0.489 |
| 4 | 0.312 | 0.312 |
| 5 | 0.532 | 0.324 |
| 6 | 0.524 | 0.324 |
| 7 | 0.519 | 0.347 |

### 4.7.1 Result Analysis

From the proposed algorithm, the SE of the game is obtained for a 1 hr time slot. Here also Initially we consider the internal prices equivalent to grid prices. We randomly choose the prosumer preference parameter values by trial and error and the optimum consumption of each prosumer after P2P trading as shown in Table 4.4. respectively.

Table 4.4. CASE 2: Optimum Consumption after P2P trading

| Prosumer preference parameter($\psi_n$) | Optimal solution,$\zeta_n^*$ (In P2P) |
|---|---|
| 25(buyer) | 2.2516 |
| 25(buyer) | 2.2516 |
| 25(buyer) | 2.2516 |
| 5(seller) | 0.4843 |
| 5(seller) | 0.4843 |
| 5(seller) | 0.4843 |

The optimum consumption of each prosumers are plotted as shown in Fig. 4.6.

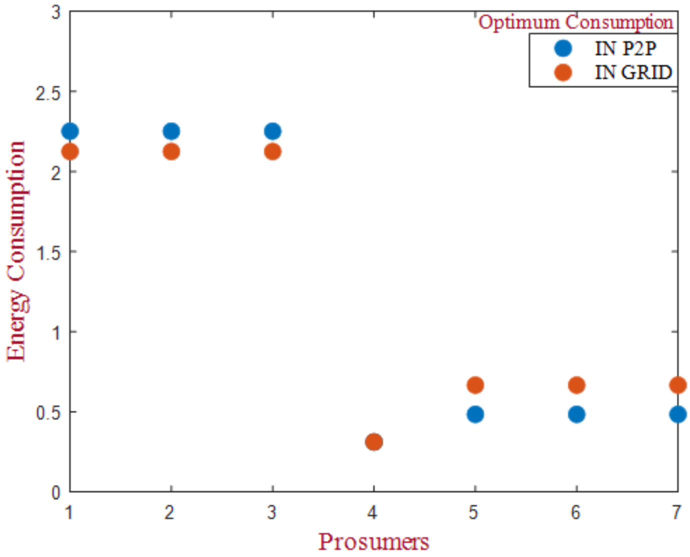

Figure 4.6. Optimum Consumption of each prosumer

The internal buying and selling prices after P2P trading are plotted as shown in figures. 4.7

and Fig. 4.8respectively.

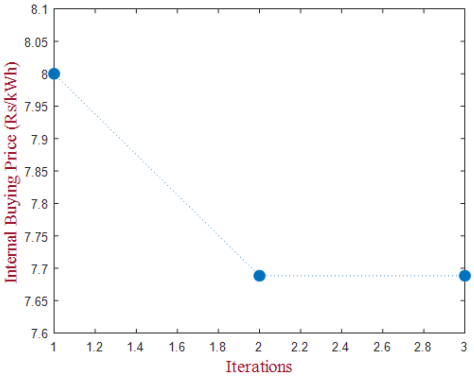

Figure 4.7. Iterative variation of buying price

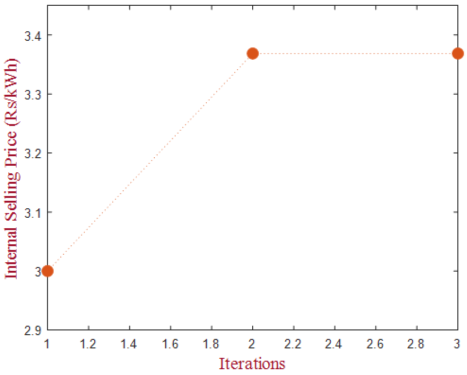

Figure 4.8. Iterative variation of selling price

The internal selling price converges to 3.3686 Rs/kWh and the buying price converges to 7.6885 Rs/kWh after the third iteration. As we can see, the internal trading prices are between the grid prices. Prosumers will undoubtedly benefit greatly from P2P trading in comparison to grid trading following this P2P trading. As a result, this benefits by promoting local production and consumption. The internal buying price and selling price at SE are 7.6885 Rs/kWh and 3.3686 Rs/kWh, respectively. The SE is thus calculated as $(\zeta_n^*, P_b^*.P_s^*)$.

## 4.8 Conclusion

This chapter summarises the Stackelberg game and Stackelberg equilibrium (SE). Also, the existence and uniqueness of SE are proved. An algorithm has been developed to find the SE. To obtain the SE, we conducted two case studies. In the first case study, after P2P trading, consumers don't get much benefit. because the internal prices and grid prices are similar after trading. The second case study, while analyzing the SE points, clearly shows that P2P trading promotes the local generation and local consumption. The obtained internal trading prices are between the grid prices as mentioned in the constraints of the system operator. So from obtained SE points, it identifies that under some scenarios P2P trading is feasible and it has some relation to the significance of the prosumer preference parameter.

# Chapter 5

# FEASIBILITY STUDY USING STACKELBERG GAME

## 5.1 Introduction

This chapter provides the feasibility condition under the scenario that peer-to-peer energy trading is beneficial. After analyzing Stackelberg Equilibrium(SE), it identifies that there is an important parameter, the prosumer preference parameter much more significant in energy trading. Section 5.2 outlines the definition of feasibility and formulates a theorem and describes the proof of feasibility solution. Section 5.2. Section 5.3 carries out a study while taking various circumstances and case studies into account. Peer-to-peer energy trading is advantageous in some circumstances but impractical in others. To explore the advantages of prosumers having P2P trading, several conditions are chosen based on the prosumer preference parameter, are analyzed, and findings are provided.

## 5.2 Feasibility of P2P Trading

Peer-to-Peer energy trading is an emerging platform that empowers consumers to become prosumers leading to the deployment of renewable energy resources and reducing grid dependency and increasing the flexibility of the grid.

Consider the Stackelberg game(G) defined as follows,

$$G = \left\{ N \cup \{\mathrm{SO}\}, \{\zeta_n\}_{n\in N}, P_b, P_s, F_{1,n}, F_2 \right\}, \tag{5.2.1}$$

Here:

$N$ = Set of PV prosumers consist of sellers($N_s$) and buyers($N_b$).

SO = System Operator of the Game.

$\zeta_n$ = Energy consumption of each prosumer.

$P_s$ = Internal selling price set by the SO.

$P_b$ = Internal buying price set by the SO.

$F_{1,n}$ = Welfare function of each prosumer.

$F_2$ = Profit function of SO.

### 5.2.1 Definition: Feasibility of P2P trading

Definition: Consider a market structure with an $N$ set of prosumers who have energy generation $E_g^n$ and preference parameter $(\psi_n)$ parameters.P2P trading is possible for a given set of $(\psi_n)$ and $E_g^n$ if any one prosumer's welfare function from P2P trading($F_{1,n}$) is greater than the welfare function from trading with the grid $(\bar{F}_{1,n})$ for the same set of parameters.

$$\text{That is, For any } n \in N, \qquad F_{1,n} > \bar{F}_{1,n}. \tag{5.2.2}$$

### 5.2.2 Theorem

Theorem: Consider the Stackelberg game defined as, $G = \big\{N \cup \{\mathrm{SO}\}, \{\zeta_n\}_{n\in N}, P_b, P_s, F_{1,n}, F_2\big\}$. Let each prosumer's energy generation and preference parameters be $E_g^n$ and $\psi_n$, respectively. P2P trading is feasible if the following conditions are satisfied.

$$\frac{(\sum_{n\in N_s} E_g + N_s)P_{gb}^2}{P_{gb}} < \sum_{n\in N_s} \psi_n < \frac{(\sum_{n\in N_s} E_g + N_s)P_{gs}^2}{P_{gb}}, \tag{5.2.3}$$

$$\frac{(\sum_{n\in N_b} E_g + N_b)P_{gb}^2}{P_{gb}} < \sum_{n\in N_b} \psi_n < \frac{(\sum_{n\in N_b} E_g + N_b)P_{gs}^2}{P_{gb}}. \tag{5.2.4}$$

*Proof.* : Let us consider an energy market with two participants: prosumers and system operators. PV prosumers are followers who can act as both sellers and purchasers (expressed by $N_s$ and $N_b$). $E_g$ and $\zeta_n$ reflect the energy generation and consumption of prosumers, respectively. $\psi_n$ is the prosumer n preference parameter, which represents each prosumer's characteristics as a seller and buyer. The system operator,SO, is the market operator who coordinates energy sharing among prosumers. The SO will buy $E_{sell}$ energy from all sellers and sell $E_{sell}$y to all buyers. To maintain the balance between energy supply and demand, the system operator will trade with the grid at the prices $P_{gb}$ and $P_{gs}$. The internal prices $P_b$ and $P_s$ for energy exchange within the cluster will be determined by the operator. Consider the profit function ($F2$) of system operator,

$$F_2 = P_b E_{buy} - P_s E_{sell} + P_{gb} \Delta E; E_{sell} \geq E_{buy}, \tag{5.2.5}$$

$$\text{subject to } P_{gb} \leq P_s, P_b \leq P_{gs}. \tag{5.2.6}$$

Then substituting $E_{sell}$ in (4.3.3) and $E_{buy}$ in (4.3.4) to (5.2.3),profit function ($F2$) can be obtained as follows:

$$\begin{aligned} F_2 = P_s(\sum_{n \in N_s} E_g + N_s) + p_{gb} \sum_{n \in N_s} \psi_n + P_b(\sum_{n \in N_b} E_g + N_b) \\ + p_{gb} \sum_{n \in N_b} \psi_n + \text{ a constant term.} \end{aligned} \tag{5.2.7}$$

Then, by differentiating with respect to the internal selling price and the internal buying price as follows, we arrive at the solution of equation (5.2.7):

$$P_s = \sqrt{\frac{P_{gb} \sum_{n \in N_s} \psi_n}{(\sum_{n \in N_s} E_g + N_s)}}, \tag{5.2.8}$$

$$P_b = \sqrt{\frac{P_{gb} \sum_{n \in N_b} \psi_n}{(\sum_{n \in N_b} E_g + N_b)}}. \tag{5.2.9}$$

Obviously, we have the constraints, $P_{gb} < P_s < P_{gs}$ and $P_{gb} < P_b < P_{gs}$.

Therefore, we add constraints for (5.2.8) and (5.2.9), and the necessary condition is thus achieved as follows:

$$P_{gb} < \sqrt{\frac{P_{gb} \sum_{n \in N_s} \psi_n}{(\sum_{n \in N_s} E_g + N_s)}} < P_{gs}, \tag{5.2.10}$$

$$P_{gb} < \sqrt{\frac{P_{gb} \sum_{n \in N_b} \psi_n}{(\sum_{n \in N_b} E_g + N_b)}} < P_{gs}. \tag{5.2.11}$$

Considering this $\psi_n$ and $E_g^n$, leads the optimum internal trading prices at SE be $P_{gb} < P_s^* < P_b^* < P_{gs}$. Therefore, prosumers' welfare function ($F_{1,n}$) presented at (5.2.12) and (5.2.13) is better to welfare function at grid trading($\bar{F}_{1,n}$).That is, $F_{1,n} > \bar{F}_{1,n}$

$$\text{Sellers, } F_{1,n}(\zeta_n) = \psi_n \ln(1+\zeta_n) + P_s\left(E_g^n - \zeta_n\right); E_g^n \geq \zeta_n, \tag{5.2.12}$$

$$\text{Buyers, } F_{1,n}(\zeta_n) = \psi_n \ln(1+\zeta_n) + P_b\left(E_g^n - \zeta_n\right); E_g^n < \zeta_n. \tag{5.2.13}$$

A utility function term and a cost function term make up this welfare function. We can prove that at these SE prices, the welfare function is improved compared to trading at grid prices and P2P trading is feasible. The utility function is the level of happiness or satisfaction experienced by prosumers after consuming energy, and the cost function is the revenue or bill generated by consuming or selling energy. □

## 5.3 CASE STUDY

In this section, we analyze the proposed method and verify the feasibility condition to evaluate the performance and benefits of having peer-to-peer energy trading. Firstly we define all the parameters. To analyze we consider a case study and its different conditions. Then the basic result of the simulation process is described. And then the results are evaluated and analyzed.

To evaluate the feasibility condition, we consider a set of data consisting of energy generation and consumption details respectively. From the feasibility theorem, there is a relationship between energy generation and the preference parameter of prosumers. We consider different preference parameters for the study.

### Basic Data

We consider a residential building with 7 PV prosumers, for numerical case studies. We have collected their power consumption data for a particular hour from Southern California Edison (SCE) Company[25]. Tables 5.1 indicate the hourly generation and load profiles of each prosumer at one hour time slot.We consider the grid price as $P_{gb} = 3$ Rs/kW h and $P_g s = 8$ Rs/kW h respectively.

There are seven prosumers, prosumers can act as sellers, buyers, or self-sufficient prosumers, They have to fix their role at the beginning of the time slot. Here the first three prosumers act as the buyer since they have less energy generation. The last three prosumers are sellers because they have more generations compared to their demand. The fourth prosumer is self-sufficient because their generation and demand are equal.

Table 5.1. Energy Details of each prosumers

| Prosumers | Energy Generation for all the prosumers($E_{gen}$) for 1 hr(kWh) | Energy consumption for all the prosumers for 1 hr(kWh) |
|---|---|---|
| 1 | 13.0630 | 17.1913 |
| 2 | 27.2727 | 30.4667 |
| 3 | 12.6881 | 17.9401 |
| 4 | 39.2083 | 39.2083 |
| 5 | 15.9523 | 14.6073 |
| 6 | 32.6736 | 26.4312 |
| 7 | 20.4551 | 14.6073 |

**Basic results of the simulation**

Based on the data and the proposed algorithm, the SE of energy sharing can be achieved at one hour of the day-ahead market. The feasibility can be verified by considering different prosumer preference parameters. One test case with its different conditions can be focused on to analyze this.

### 5.3.1 Condition 1: Considering Prosumer Preference Parameter follows the feasibility theorem

Table 5.2. shows the optimum consumption and welfare function of prosumers during P2P trading and trading with the grid by providing a particular prosumer preference parameter. The first three prosumers act as the buyers and a particular preference parameter is selected that satisfies the feasibility condition. Similarly, the last three prosumers are sellers and their preference parameters are given in table 5.2.

Table 5.2. Optimum Consumption and Welfare function of prosumers during P2P trading and trading with grid

| Prosumer preference parameter($\psi_n$) | Optimal solution,$\zeta_n^*$(In P2P) | Optimal solution,$\zeta_n^*$ (With Grid) | Welfare function(In P2P) *10e3 | Welfare Function (With Grid) *10e3 |
|---|---|---|---|---|
| 290(buyer) | 37.3862 | 35.25 | 0.8741 | 0.2921 |
| 600(buyer) | 78.4198 | 74.00 | 2.2384 | 0.6144 |
| 290(buyer) | 37.3862 | 35.25 | 0.8712 | 0.2893 |
| 100(seller) | 26.4545 | 32.333 | 0.2958 | 0.1200 |
| 100(seller) | 28.4545 | 32.333 | 0.3526 | 0.1768 |
| 100(seller) | 28.4545 | 32.333 | 0.3111 | 0.1353 |

Fig. 5.1 is the optimum consumption of each prosumer during P2P trading and grid trading.

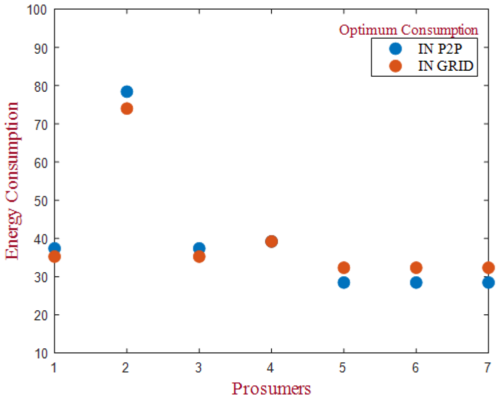

Figure 5.1. Optimum Consumption in trading with both P2P and Grid

Fig. 5.1, clearly show the consumption of buyers is more in P2P trading than in grid trading. Also, sellers engage more to sell than consuming since their consumption is less in P2P trading compared to the grid.

Figures. 5.2 and 5.3 are the welfare function of sellers and buyers during P2P trading and grid trading respectively.

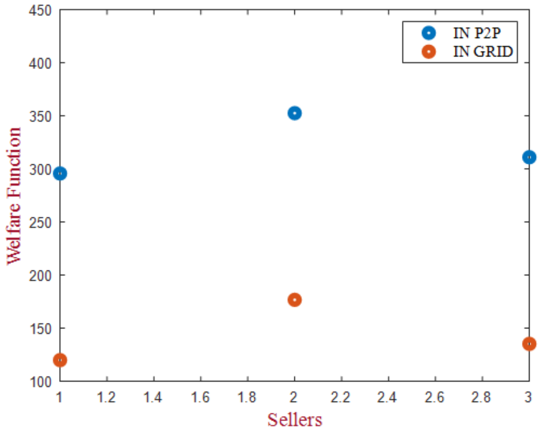

Figure 5.2. Seller Welfare Function

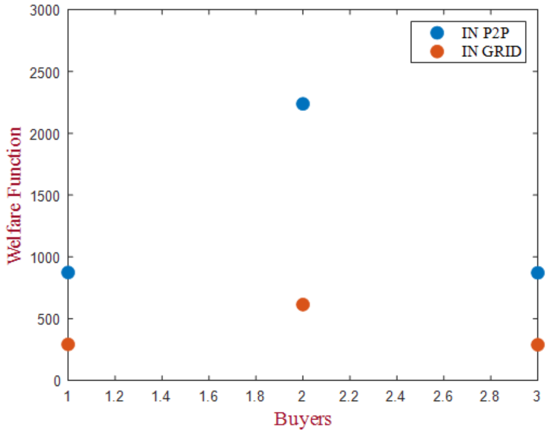

Figure 5.3. Buyer Welfare Function

From the figures, the welfare functions of sellers and buyers are better in P2P trading compared to grid trading.

Figs. 5.4 and 5.5 shows the internal selling and buying day-ahead prices at 1 hr time slot respectively.

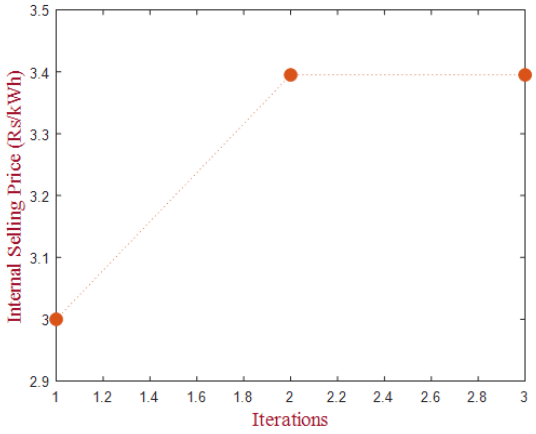

Figure 5.4. Internal Selling Price

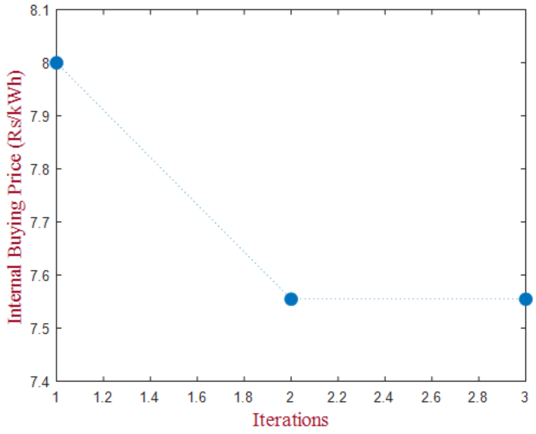

Figure 5.5. Internal Buying Price

After P2P trading, the internal selling price and buying price converge to 3.3951 Rs/kWh and 7.5548 Rs/kWh after the third iteration respectively.

### 5.3.2 Condition 2: Considering Prosumer Preference Parameter follows the feasibility theorem

Table 5.3 shows the Optimum Consumption and Welfare function of prosumers during P2P trading and trading with the grid by providing a particular prosumer preference parameter that is better than the previous case.

Table 5.3. Optimum Consumption and Welfare function of prosumers during P2P trading and trading with grid

| Prosumer preference parameter($\psi_n$) | Optimal solution,$\zeta_n^*$ (In P2P) | Optimal solution,$\zeta_n^*$ (With Grid) | Welfare function(In P2P) *10e3 | Welfare Function (With Grid) *10e3 |
|---|---|---|---|---|
| 200(buyer) | 31.1517 | 24.00 | 0.5816 | 0.2137 |
| 500(buyer) | 79.3792 | 61.50 | 1.8692 | 0.5100 |
| 100(buyer) | 15.0758 | 11.50 | 0.2629 | 0.1420 |
| 100(seller) | 26.2696 | 32.33 | 0.2927 | 0.1241 |
| 150(seller) | 39.9043 | 49.00 | 0.5302 | 0.2201 |
| 100(seller) | 26.2696 | 32.33 | 0.3093 | 0.1406 |

Fig. 5.6 is the optimum consumption of each prosumer during P2P trading and grid trading.Fig. 5.6, clearly show the consumption of buyers is more in P2P trading than in grid trading. Also, sellers engage more to sell than consuming since their consumption is less in P2P trading compared to the grid. Compared to the previous condition, consumption is changed dramatically for this particular set of prosumer preference parameters.

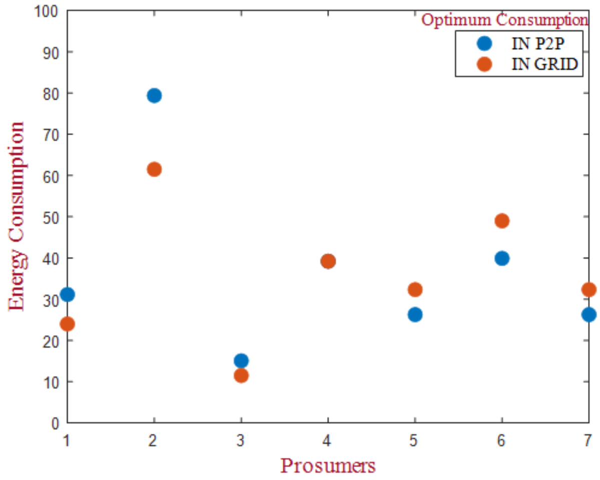

Figure 5.6. Optimum Consumption in trading with both P2P and Grid

Figs. 5.7 and 5.8 are the welfare function of sellers and buyers during P2P trading and grid trading respectively.

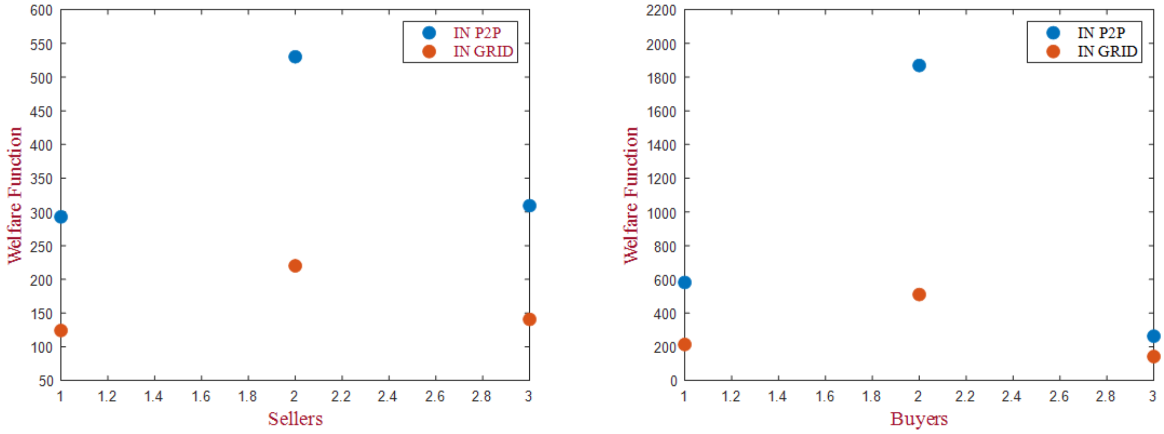

Figure 5.7. Seller Welfare Function

Figure 5.8. Buyer Welfare Function

From the figures, the welfare functions of sellers and buyers are better in P2P trading compared to grid trading.

Figs. 5.9 and 5.10 shows the internal selling and buying day-ahead prices at 1 hr time slot respectively.

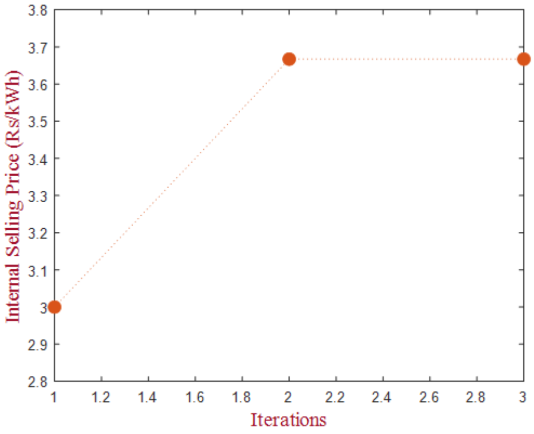

Figure 5.9. Internal Selling Price

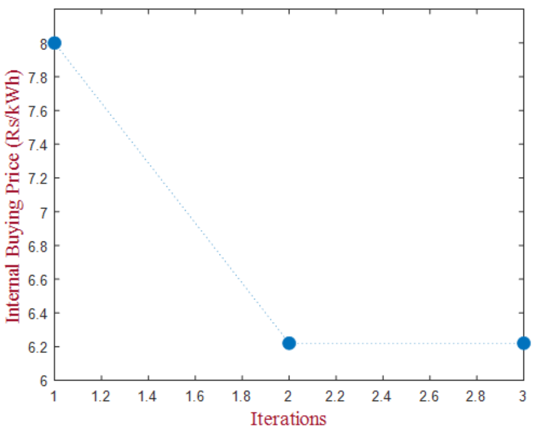

Figure 5.10. Internal Buying Price

After P2P trading, the internal selling price and buying price converge to 3.6671 Rs/kWh and 6.2205 Rs/kWh after the third iteration respectively. Compared to the previous condition, under this prosumer preference parameter, internal trading prices are much better for prosumers, Hence it leads the welfare function to more benefit in P2P trading than grid trading.

### 5.3.3 Condition 3: Considering Prosumer Preference Parameter violates the feasibility theorem

Table 5.4 shows the Optimum Consumption and Welfare function of prosumers during P2P trading and trading with the grid by providing a particular prosumer preference parameter. In this case, we select the prosumer preference parameter that violates the feasibility. Under this condition, peer-to-peer energy trading is not feasible.

Table 5.4. Optimum Consumption and Welfare function of prosumers during P2P trading and trading with grid

| Prosumer preference parameter($\psi_n$) | Optimal solution,$\zeta_n^*$ (In P2P) | Optimal solution,$\zeta_n^*$ (With Grid) | Welfare function(In P2P) *10e3 | Welfare Function (With Grid) *10e3 |
|---|---|---|---|---|
| 400(buyer) | 49.00 | 49.00 | 1.2773 | 1.2773 |
| 700(buyer) | 86.50 | 86.50 | 2.6563 | 2.6563 |
| 300(buyer) | 36.5 | 36.5 | 0.8968 | 0.8968 |
| 40(seller) | 12.33 | 12.33 | 0.1145 | 0.1145 |
| 50(seller) | 15.667 | 15.667 | 0.1917 | 0.1917 |
| 30(seller) | 9.00 | 9.00 | 0.1034 | 0.1034 |

Fig. 5.11 is the optimum consumption of each prosumer during P2P trading and grid trading.

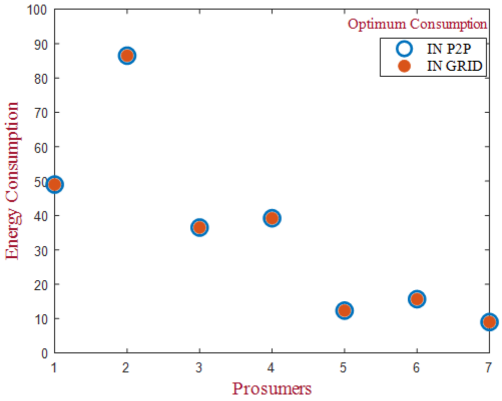

Figure 5.11. Optimum Consumption in trading with both P2P and Grid

Fig. 5.11, clearly show the consumption of buyers is same in P2P trading and in grid trading.

Figs. 5.12 and 5.13 are the welfare function of sellers and buyers during P2P trading and grid trading respectively.

From the figures, the welfare functions of sellers and buyers are also the same in P2P

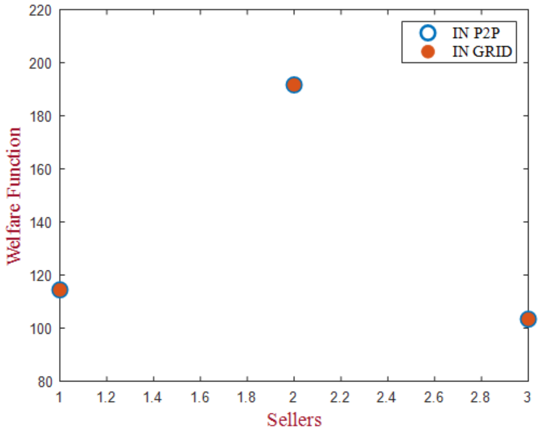

Figure 5.12. Seller Welfare Function

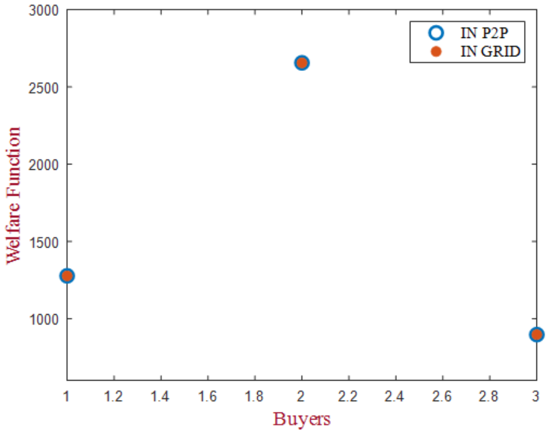

Figure 5.13. Buyer Welfare Function

trading and grid trading. Hence prosumers don't get benefits from P2P trading compared to the grid.

Fig. 5.14 and 5.15show the internal selling and buying day-ahead prices at 1 hr time slot respectively.

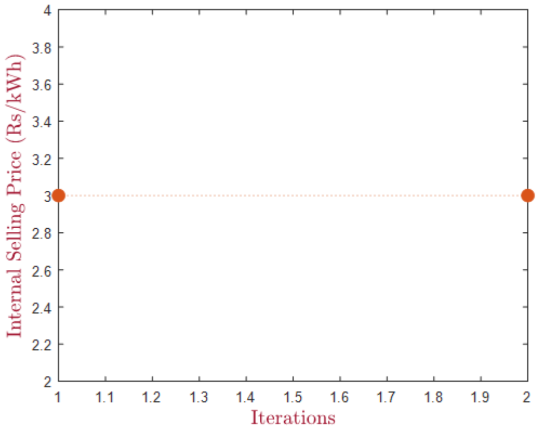

Figure 5.14. Internal Selling Price

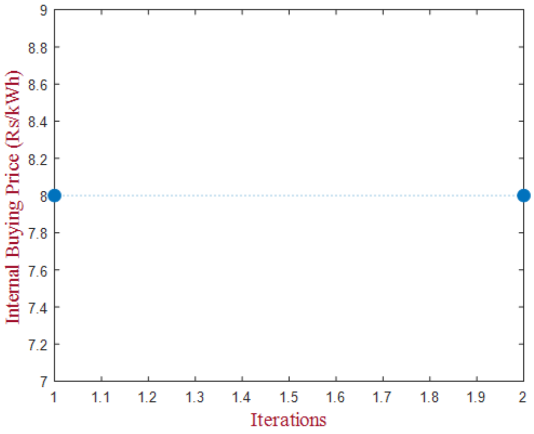

Figure 5.15. Internal Buying Price

After P2P trading, the internal selling price and buying price converge to 3 Rs/kWh and 8 Rs/kWh after the third iteration respectively. The prices are the same as the grid prices as depicted in the figures.

## 5.4 Result Analysis

The proposed SO algorithm can enable energy-sharing SE in a microgrid.SO does not require prosumers to provide any personal information, such as their $\psi_n$ or $E_g$, and prosumers just need to get internal price information and submit their energy sharing profiles, such as energy demand or surplus energy. Precision tuning of $\psi_n$ is critical because it determines optimal prosumer consumption and community internal prices. As a result, $\psi_n$ has been set to take into account the roles of prosumers, such as buyer, seller, or self-sufficient, as well as their goals to optimize welfare. Because prosumer welfare is multi-objective and consists of two variables, utility, and profit, careful tuning of $\psi_n$ is required to observe the dominance of each term as prosumer roles are switched. As a result, $\psi_n$ is assigned a low value for sellers to reflect profit dominance, a higher value for buyers to reflect utility term dominance and a medium value for self-sufficient prosumers.
Variations of $P_s$, $P_b$, and $\zeta_n$ with each iteration at one hour have been depicted to evaluate the performance of the Stackelberg equilibrium algorithm. Internal prices are initialized at grid prices, improve dramatically in the first iterations, and converge within 3 iterations, as seen in the figures. Furthermore, the behavior of prosumer 3 (seller) and prosumer 3 (buyer) shows that the buyer consumes less at grid pricing and consumes more at P2P trading. Similarly, at grid prices, the seller is shown to consume more, but at P2P trading, he consumes less and tries to engage more to sell. Furthermore, $\psi_n$ has been calibrated to maximize welfare, which means that sellers will optimize profit by selling more, while buyers would maximize utility by consuming more.

## 5.5 Conclusion

This chapter summarises the feasibility analysis using the Stackelberg game. A study on the feasibility of peer-to-peer energy trading is conducted and the theorem is proved by considering various case studies. It is clear that under some scenarios P2P trading is feasible, by considering the welfare function of prosumers.

# Chapter 6

# CONCLUSION

The increasing levels of distributed energy resources over the recent decades, make the energy distribution system more advanced. However, this leads to great change in the way the energy is generated and utilized. This has been a boom in the increase of customers into prosumers who play a vital role in energy generation, which leads to a more decentralized and open grid. A few studies have focused on fastening the evolution of peer to peer market by involving prosumers in the energy market system. For an extremely low-carbon transition, peer-to-peer energy trading is a captious approach for improving the flexibility of the energy system. At household levels, P2P trading allows the extensive usage of renewable sources.

The overall contribution of this study was to present a holistic perspective of the benefits of using the P2P paradigm. This thesis first introduces a Stackelberg game-based framework to support the P2P energy trading market. In this game, the leader is SO, who sets the internal selling and buying prices, while the followers are PV prosumers, who determine their energy consumption in response to internal prices. We have proposed an algorithm for finding SE, and we have strictly demonstrated the existence and uniqueness of SE in the game by demonstrating that the $SO'$s profit function is concave and strictly unimodal. SO does not demand any personal privacy information from prosumers, who only need to communicate with SO for a fixed time. We developed a feasible solution based on SE under the assumption that peer-to-peer energy trade is profitable. The proposed strategy has been proved to be efficient and practical for real microgrids by simulations done on the MATLAB platform.

# Chapter 7

## PUBLICATIONS

1) Ancy S George, Mathew P Abraham and Arya M.G, “An Oligopoly Model Based Peer-to-Peer Energy Trading Architectures - A Review”, *Second International Conference on Power, Energy, Control, Signals and Systems(IPECS)*, June, 2022

2) Ancy S George, Mathew P Abraham and Arya M.G, “Feasibility Analysis Of Peer-To-Peer(P2P) Energy Trading Using Stackelberg Equilibrium”, *IET Generation, Transmission and Distribution.*, 2022
(To be Submitted)

# REFERENCES

[1] **Li Z, Bahramirad S, Paaso A, Yan M, Shahidehpour M.** "Blockchain for decentralized transactive energy management system in networked microgrids",*Electr Journal* Vol.32,pp.32: 58–72,2019

[2] **Morstyn T, Farrell N, Darby SJ, McCulloch MD**. ,"Using peer-to-peer energytrading platforms to incentivize prosumers to form federated power plants". *Nat Energy*,Vol.3,no.2,pp.94–101.,2018

[3] **Mengelkamp E, Notheisen B, Beer C, Dauer D, Weinhardt C.**,"A blockchain-based smart grid: towards sustainable local energy markets".,*Comput Sci-Res Dev*,Vol.33, pp.207–14,2018

[4] **Arpita De**. "Optimal sizing and positioning of grid integrated distributed generator: a review". *International Journal of Engineering Technology*,Vol.9.,no.,2pp.299-313,2020

[5] **Zhou Y, Wu J, Long C**,. "Evaluation of peer-to-peer energy sharing mechanisms based on a multiagent simulation framework". *Appl Energy*,vol. 222,pp.993–1022.,2018

[6] **Papadaskalopoulos D, Strbac G.**, "Decentralized participation of flexible demand in electricity markets–part I: market mechanism"., *IEEE Trans Power Syst.*Vol.28,no.4, pp.3658–66.,2013

[7] **Mohsen Khorasany, Yateendra Mishra*, Gerard Ledwich**. ,"Market Framework for Local Energy Trading: A Review of Potential Designs and Market Clearing Approaches". *n IET Generation, Transmission and Distribution*,Vol.12,no.22,pp.5899 – 5908.,2018

[8] **A. Ehsan and Q. Yang**, "Optimal integration and planning of renewable distributed generation in the power distribution networks: A review of analytical techniques," *Applied Energy*, vol. 210, pp. 44-59,2018.

[9] **S. Abapour, K. Zare, and B. Mohammadi-Ivatloo**, "Dynamic planning of distributed generation units in active distribution network," *IET Generation, Transmission*

*Distribution*, vol. 9, no. 12, pp. 1455-1463, 2015.

[10] **T. van der Schoor and B. Scholtens**, "Power to the people: Local community initiatives and the transition to sustainable energy," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 666-675, 2015/03/01/ 2015.

[11] **W. Tushar, C. Yuen, H. Mohsenian-Rad, T. Saha, H. V. Poor, and K. L. Wood**, "Transforming Energy Networks via Peer-to-Peer Energy Trading: The Potential of Game-Theoretic Approaches," *IEEE Signal Processing Magazine*, vol. 35, no. 4, pp. 90-111, 2018.

[12] **Esteban A. Soto, Lisa B. Bosman, Ebisa Wollega, Walter D. Leon-Salas**,"Peer-to-peer energy trading: A review of the literature",*Applied Energy*,Volume 283,2021.

[13] **M. Pilz and L. Al-Fagih**, "Recent Advances in Local Energy Trading in the Smart Grid Based on Game–Theoretic Approaches," *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1-1, 2017.

[14] **X. Yan, J. Lin, Z. Hu, and Y. Song**, "P2P trading strategies in an industrial park distribution network market under regulated electricity tariff," in 2*017 IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 26-28 Nov. 2017.

[15] **T. Morstyn, A. Teytelboym, and M. D. McCulloch**, "Bilateral Contract Networks for Peer-to-Peer Energy Trading," *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1-1, 2018.

[16] **C. Park and T. Yong**, "Comparative review and discussion on P2P electricity trading," *Energy Procedia*, vol. 128, pp. 3-9, 2017.

[17] **C. Zhang, J. Wu, M. Cheng, Y. Zhou, and C. Long**, "A Bidding System for Peer-to-Peer Energy Trading in a Grid-connected Microgrid," *Energy Procedia*, vol. 103, pp. 147-152, 2016.

[18] **C. Long, J. Wu, C. Zhang, L. Thomas, M. Cheng, and N. Jenkins**, "Peer-topeer energy trading in a community microgrid," in *2017 IEEE Power Energy Society General Meeting*, 16-20 July 2017.

[19] **Luo Y, Itaya S, Nakamura S, Davis P**., "Autonomous cooperative energy trading between prosumers for microgrid systems. In: in *39th annual IEEE conference on local computer networks workshops*; 2014.

[20] **Zhou Y, Wu J, Long C**. "Evaluation of peer-to-peer energy sharing mechanisms based on a multiagent simulation framework. *Appl Energy* ;222:993–1022.,2018

[21] **Kirtan Patel, Sumedha Sharma and Ashu Verma**, "Distributed Framework for

P2P Energy Sharing among Building Prosumers using Stackelberg Game", *IEEE Power Energy Society General meeting* ,May. 2020.

**[22] Haobo Zhang,Hongliang Zhang, Lingyang Song,Yonghui Li, Zhu Han, and H. Vincent Poor**,"Peer-to-Peer Energy Trading in DC Packetized Power Microgrids",*IEEE Journal on Selected Areas in Communications*,Vol. 38,no. 1,pp. 17-30,Jan. 2020.

**[23] Luhao Wang;Yumin Zhang;Wen Song;Qiqiang Li**,"Stochastic Cooperative Bidding Strategy for Multiple Microgrids With Peer-to-Peer Energy Trading" *IEEE Transactions on Industrial Informatics*,Vol.18,no.3,pp.1447-57,July .2021.

**[24] Kirtan Patel;Sumedha Sharma;Ashu Verma**,"Distributed Framework for P2P Energy Sharing among Building Prosumers using Stackelberg Game",*IEEE Power Energy Society General Meeting (PESGM)*,pp.2-6, Aug. 2020.

**[25] Shichang Cui ; Yan-Wu Wang ; Nian Liu** ,"Distributed game-based pricing strategy for energy sharing in microgrid with PV prosumers", *IET Renewable Power Generation*,Vol.12,no.3,pp.380-8,Feb .2018.

**[26] Yunsun Jin;Jeonghoon Choi;Dongjun Won**,"Pricing and Operation Strategy for Peer-to-Peer Energy Trading Using Distribution System Usage Charge and Game Theoretic Model",*IEEE Access*,Vol. 8,pp.137720-30.July.2020.

**[27] Khorasany M, Mishra Y, Ledwich G.**, "A decentralized bilateral energy trading system for peer-to-peer electricity markets", *IEEE Transactions on Industrial Electronics*,Vol. 67,no. 6,pp.4646–57,June. 2020.

**[28] Hien Thanh Doan;Jeongho Cho;Daehee Kim**,"Peer-to-Peer Energy Trading in Smart Grid Through Blockchain: A Double Auction-Based Game Theoretic Approach",*IEEE Access*, Vol. 9,pp. 49206-18,March.2021.

**[29] M. Imran Azim;Wayes Tushar;Tapan Kumar Saha**,"Coalition Graph Game-Based P2P Energy Trading With Local Voltage Management",*IEEE Transactions on Smart Grid*, Vol. 12,no. 5,pp. 4389-402, Sept. 2021.

**[30] Rao Bokkisam, Shashank Singh, Ritesh Mohan Acharya, and M P Selvan**,

"Blockchain-based Peer-to-Peer Transactive Energy System for Community Microgrid with Demand Response Management", *CSEE journal of power and energy sytems*[early access],2021.