AMERICAN UNIVERSITY OF BEIRUT

A MODEL FOR P2P ENERGY TRADING IN A MICROGRID UNDER SCHEDULED BLACKOUTS

by
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A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Electrical and Computer Engineering
of the Maroun Semaan Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
April 2022

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to whom supported me during the period of my Master's. My foremost gratitude goes toward my principal supervisor, Prof. Riad Chedid for the continuous support of my master’s study and research, for his patience, motivation enthusiasm, and immense knowledge. His admirable supervision, encouragement, and guidance helped me all the time in my research. I also wish to extend my sincere appreciation to the committee members, Prof. Sami Karaki, Prof. Dany Abou Jaoude, and Prof. Martin Kaltschmitt for their invaluable support and great advice.

I gratefully acknowledge the American University of Beirut, not only for providing the funding for my master's, which allowed me to undertake this research but also for allowing me to develop my teaching and learning skills.

Special thanks to my lovely family, for their constant encouragement and support in my whole life. Words cannot express how grateful I am to my mother, and father for all the sacrifices that they have made on my behalf. Their prayer for me was what sustained me thus far.

ABSTRACT
OF THE THESIS OF

Mira Ismail Daher for Master of Engineering
Major: Electrical and Computer Engineering

Title: A Model for P2P Energy Trading in a Microgrid under Scheduled Blackouts

Peer-to-peer (P2P) energy trading has emerged as a next-generation energy management mechanism for the smart grid, allowing each network prosumer to trade energy with one another and with the grid. This poses a significant challenge in terms of modeling the decision-making process of each participant with conflicting interests and motivating prosumers to participate in energy trading to achieve different energy management goals. In this thesis, we propose a novel game-theoretic model for peer-to-peer (P2P) energy trading among prosumers in a residential microgrid. During the trading process, there are two separate competitions. The first one is between the registered sellers to offer their energy prices and is modeled as a non-cooperative game. The second game is between the registered buyers for the process of selecting the appropriate seller and it is modeled as an evolutionary game. To model the interaction between both the sellers and the buyers, an M-leader N-follower game is used. Iterative algorithms are proposed for the game modeling to find the equilibrium state which corresponds to their convergence. The proposed trading method is applied to a residential microgrid characterized by a heavy reliance on the intermittent grid and diesel generation units. Results demonstrate the applicability of the proposed P2P trading method among prosumers making sure that it provides significant financial and technical benefits for the whole system.

TABLE OF CONTENTS

ILLUSTRATIONS

Figure

TABLES

Table

ABBREVIATIONS

Abbreviation	Explanation
DG	Diesel Generators
PV	Photovoltaic
DER	Distributed Energy Resources
ESS	Energy Storage systems
P2P	Peer-to-Peer
FIT	Feed-in tariff
BS	Bill Sharing
MMR	Mid-Market Rate
DSO	Distribution System Operators
BESS	Battery Energy Storage Systems
GDR	Generation to Demand Ratio
ESS	Evolutionary Stable Strategy
SDR	Supply to Demand Ratio
NE	Nash Equilibrium

CHAPTER I

INTRODUCTION

The integration of distributed generators (DGs) into electrical power systems is widely promoted by countries around the world with the goal of reducing carbon emissions and improving energy security and affordability. These renewable energy based DGs have been exploited to solve the foreseeable fossil fuel shortage problem. Nowadays the global capacity of solar photovoltaics (PV) is continuing to grow exponentially, and PV is very likely to become one of the prime sources of electricity supply worldwide [1].

A. Renewables and Microgrids

Although renewable energy is sustainable, it brings significant challenges to the stability and the operational safety of a large power network due to its intermittent and location-variant nature. As a result, microgrids have been proposed to address these challenges by coordinating the control of distributed energy resources (DER), local active loads, and energy storage systems (ESSs) within certain regions [3,5,7,8,11,26,27]. Within a microgrid, the distributed renewable energy sources, such as wind power and solar energy, can switch traditional energy consumers to prosumers [17]. Multiple microgrids located in a large area can be networked to improve the efficiency and the reliability of the distribution network further. However, since the installed DERs in microgrids belong to different owners, it is not realistic to directly control or operate them by a central authority. Recently, peer-to-peer (P2P) energy trading has emerged as a novel paradigm for decentralized energy market designs. P2P energy trading allows the end-users to join the trading without a central authority unit while contributing to the effective management of energy supply and demand by facilitating a direct exchange of energy in defined local or virtual communities [21].

B. Research Studies

Over the last few years, there has been a significant increase in the number of research and demonstration projects on peer-to-peer energy sharing around the world. A comparative review and discussion on P2P electricity trading were conducted in [6]. The study compared the most popular peer-to-peer electricity trading cases in Germany, the United States, the Netherlands, and the United Kingdom. Some of these projects were focusing on the market design and business models for P2P markets while others were implementing local control and ICT platforms for prosumers and microgrids. At the load control and ICT level, EMPOWER11 developed a real-time platform based on cloud technology to execute the metering and trading within a local community. In terms of the market design proposals, the Enerchain [24] intends to develop a P2P trading platform to replace, the wholesale electricity market. Sonnen Community [2] is using batteries, unlike the previous operators. Sonnen batteries, a business entity, allow the installers of renewable energy facilities to store the electricity from the renewables in their batteries and vend the electricity. Some projects, such as Peer Energy Cloud and Smart Watts in Germany, focused on information and communication technologies, and support energy sharing. Similarly in the US, projects such as Transactive Grid developed decentralized energy sharing platforms based on blockchain technology.

C. Defining P2P Energy Trading

The core of energy sharing projects are energy sharing models, which define how prosumers exchange and trade energy with one another.

In this field, numerous studies have been conducted, and they will be divided into three categories:

1) One centralized authority is responsible for energy sharing.
2) Energy sharing is achieved by the interaction between an operator (price maker) and a group of prosumers (price takers).
3) Energy sharing is accomplished through the interaction of a group of prosumers, also known as peer-to-peer (P2P) energy sharing.

In the field of computer science, a peer-to-peer (P2P) network is a commonly used model for resource sharing in which resources are located in and provided by computers (i.e. peers) at the network's edge. A community microgrid can be modeled as a P2P network because it is made up of many prosumers in close proximity to their generation and demand. In the prosumer-based group microgrid, a P2P energy sharing model tends to be sufficient for energy trading, where excess energy from various small-scale DERs is traded locally.

The remainder of the thesis is structured as follows: chapter 2 reviews related literature and positions in recent research regarding market designs and business models. Chapter 3 provides problem definition with its system formulations using the evolutionary and the non-cooperative games among the buyers and the sellers, respectively. Chapters 4 and 5 models the system theoretically and mathematically respectively. Chapters 6 and 7 describe the formulation of the games with their algorithms. Chapter 8 shows study results and provide, concluding remarks, and further research directions.

CHAPTER II

LITERATURE REVIEW

P2P energy trading enables community members with PV and/or energy storage systems to buy from and sell their self-generated energy to other members of the community without the need for an intermediary. This type of trading is based on dynamic prices that reflect electricity demand and supply at a given time point in the predefined market. Dynamic electricity prices are likely to exceed predetermined feed-in tariff (FIT) remunerations in times of high demand, which are steadily decreasing in many countries around the world.

A. Literature on P2P Energy Trading Projects

Peer-to-Peer (P2P) energy trading among the smart homes in a microgrid is a recently adopted trend [8,14,23], where the global smart home market size is expected to reach $53.45 billion by 2022 and the number of households that adopt smart home systems is forecasted to grow at a compound annual growth rate of 14.5% between 2017 and 2022 [22]. The work in [8] evaluates the impact of Peer-to-Peer (P2P) energy trading among the smart homes in a microgrid by addressing the energy cost optimization problem in the smart homes which are connected for energy sharing. Results show that, for real datasets, 99% of the solutions generated by the algorithm are optimal solutions. P2P energy networks' dynamic market mechanisms are expected to boost the supply of intermittent renewable energy on demand while also shifting consumption to periods of renewable electricity surplus and/or low electricity prices [2,4,5,10, 12,14,19,20].

To provide a comprehensive understanding of the relevant consumer-centric electricity markets, the work in [4] looks at P2P markets from a wider perspective that includes all involved agents in the power system. Analysis of the different P2P market structures, the full P2P, the community-based market, and the hybrid P2P market designs were investigated including a description of the suitable optimization techniques for negotiation and market clearing. To demonstrate the effectiveness of each proposed design, a benchmark test case illustrating the application of P2P markets in the three proposed designs was simulated over one year with a 30 minute time-step using available Australian data. Research [2] examined the role of battery flexibility by proposing two market designs centered on the role of electricity storage in the peer-to-peer electricity trading paradigm. It focused on the value of prosumer batteries in the P2P trade. This battery flexibility optimization model was implemented to represent the peer-to-peer interactions in the presence of storage for a small community in London, The United Kingdom, investigating the contribution of batteries located at the customer level versus a central battery shared by the community and showing that the combined features of trade and flexibility from the storage produce savings of up to 31% for the end-users using these local electricity market designs. Another market design in [5] focused on a two-stage matching method which includes bilateral and pool-based ones to match the generation and demand in the hierarchical P2P markets, proving that the design has the potential to bring greater social welfare as compared to the conventional market paradigm. Another market design implemented in [20] focused on a new business model comprising multiple stakeholders. The model developed a framework for the future flexible retail energy market, in community microgrids, for minimizing daily operational costs.

B. Literature Related to Game-Theoretic P2P Energy Trading Projects

The formal study of the mathematical model of several decision-making players with possible cooperation and conflicting objectives is known as game theory. A cooperative game is a competition between groups of players with cooperative behavior, whereas a non-cooperative game is one in which players make decisions independently. Game theory has been used in power systems to understand participants' behavior in deregulated environments and to allocate costs among market players as depicted in [7]. Some P2P energy trading models have been proposed to solve the renewable energy dilemma using game-theoretic approaches [3, 7, 11, 18, 25]. In [3,11] using game theory and Nash equilibrium, a trading platform in a microgrid was presented by building a four-layer system architecture for the P2P trading to discuss the business model and its possible implementations. In addition to this study, two iterative algorithms were proposed for the implementation of the games in [18] by proposing a novel game-theoretic model for peer-to-peer (P2P) energy trading among the prosumers in a community where such an equilibrium state exists in each of the games. The research in [7] has also introduced different P2P market paradigms using bill sharing (BS), mid-market rate (MMR), and auction-based pricing strategies. A Stackelberg game model with multi-leader and multi-follower is proposed in [29] for energy trading in integrated energy systems. The Stackelberg game is a non-cooperative game-theoretic approach that differentiates all the participants into leaders and followers according to the sequence of their actions [30]. In [31] a Stackelberg game with one leader and multi followers is presented for energy sharing among storages. A three-stage Stackelberg game is offered in [32] for energy management, where the backward induction method is applied to solve the game problem. Game-theoretic approach studies showed that P2P energy trading can improve the local balance of energy generation and consumption and that P2P trading has the potential to enable a large penetration of RESs in the power grid by also providing significant financial and technical benefits to the whole community.

1. Designs for P2P Markets

Following [36,37] and the relevant literature, this section lists and discusses the P2P structures that have been proposed so far for P2P markets:

(i) Full P2P market.
(ii) Community-based market
(iii) Hybrid peer-to-peer (P2P) market. What distinguishes them from one another is the degree of decentralization and topology, which can range from full P2P to hierarchical P2P structures.

Peers directly negotiate with each other to sell and buy electric energy in a full P2P market. As a result, two peers can agree on a transaction for a specific amount of energy and price without the need for centralized supervision. Sorin et al. [39] proposed a fully P2P market design between producers and consumers that is based on multi-bilateral economic dispatch.

Product differentiation in the P2P structure allows consumers to express their preferences, such as local or green energy. Mostyn et al. [38] developed a P2P energy trading system for prosumer real-time and forward markets. The proposed framework incorporates each agent's preferences for upstream-downstream energy balance and forward market uncertainty.

A microgrid energy market is developed and published in [40] linked with the iconic Brooklyn experiment. This framework enables small agents to trade energy locally in a local microgrid market without the need for a central entity. P2P energy trading between electric vehicles was implemented by Alvaro-Hermana et al. [41].

The proposed approach aims to increase bilateral trade between residential prosumers rather than them purchasing from the pool market. According to recent research, this market design is gaining traction in the industrial and academic fields. Moreover, to design an appropriate market for local energy trading, the first step is to distinguish market players and their objectives clearly. The corresponding objective function of market participants should then be extracted. Different methods for market clearing can be used with an objective function.. Figure 1 illustrates the overall procedure of market design for local energy trading systems. The objectives illustrated in the above literature and details are provided in the following chapters.

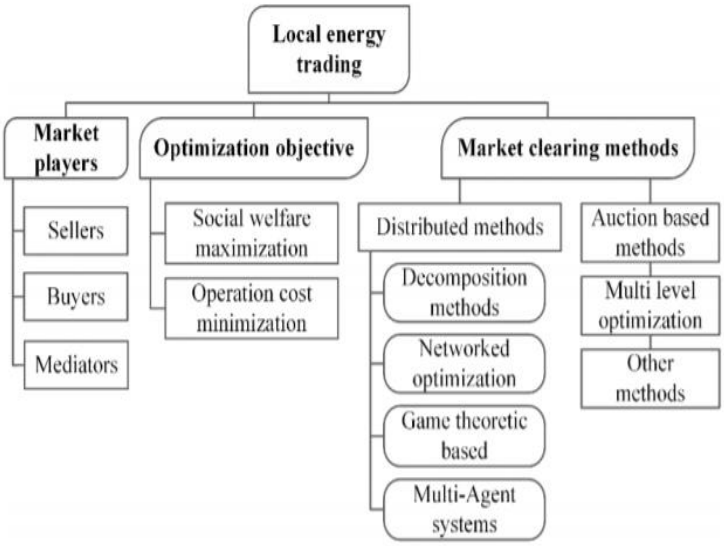


Figure 1: Overall procedure of market design for local energy trading [42]

The market settlement, supply and demand balancing can be done in three ways in the electricity market: centralized, distributed, and decentralized. In the centralized method, a central operator collects information and data from all market participants in order to settle the market. Because of the nature of the centralized approach, each agent requires a two-way communication channel for transferring data to the system's control center.

As a result of the numerous communication links that become necessary as the number of agents grows, the system will face a barrier. The central operator makes decisions for all players and sends the control signals to manage their market actions. As a result, prosumers and consumers are unable to participate actively in the market. This method is simple to implement and does not necessitate the installation of new infrastructure on the premises of market participants. Centralized methods, on the other hand, can jeopardize players' privacy because they must reveal personal information to the central operator. Furthermore, in a market with many players, the scalability of this approach would be difficult.

To address these issues, distributed and decentralized methods have been proposed. Each subscriber has his/her controller in these methods, and they try to get more profit or stability from the market. These methods can be used to create an iterative price negotiation system [42]. When all players agree on the value of the shared information in distributed approaches, they reach an agreement. Voltage, power mismatches, and market price are examples of quantities and control signals that can be used as shared information among market participants. Computation and control can be distributed across the grid using the distributed method. Decentralized methods do not need a coordinator and can be implemented completely independently.

Protecting market players' privacy and reducing the number of communication links are two of the most valuable benefits of a decentralized and distributed market clearing. A decentralized system is more stable than a centralized system with identically connected leaders; for example, if some leaders lose contact with agents, the centralized system might stop functioning while the decentralized system can remain functioning independently.

Each player uses local information provided by its neighbors and locally measured parameters such as voltage and frequency in the distributed consensus-based control approach. Different participants in the electrical market, such as consumers and prosumers, have their own private cost or welfare function that influences their market behavior. It is widely assumed that if they want to get more satisfaction and benefits in the electrical competition market, they must consider privacy principles. Because sensitive private data will not be released and shared globally, the distributed algorithm can protect the agents' privacy to a large extent.

CHAPTER III

PROBLEM DEFINITION

As observed from the provided literature, most of the studies concentrated on proposing a P2P energy trading model and deducing the benefits under a reliable grid operation or in islanded operation. However, the literature studies lacked a market model suitable for developing countries where the grid is unreliable, and the DERs might not be able to cover the entire network's demand as is the case of Lebanon.

Since P2P energy trading in a microgrid is also a new concept, a proper modeling framework is required to define the business model, to determine energy prices. The business model and energy pricing play a vital role because they determine the suitability of P2P trading in a microgrid in terms of the financial benefits.

Different market structures can be implemented for P2P energy trading as shown in Figure 2(a) and a distributed bilateral trading market as shown in Figure 2(b). In this thesis, a bilateral trading market is proposed where there is no coordinator, and all players can negotiate directly to reach an agreement on the price and amount of the traded energy. Therefore, for proper implementation of P2P markets, an appropriate model of negotiation mechanism and market clearing should be designed. As the number of players in the consumer-centric markets increases, the communication and computation overheads would be the main barriers to the real-world implementation of P2P markets.

Thus, this study aims to design a system architecture for the P2P energy trading model and proposes an associated market model for P2P trading using a game-theoretic approach among prosumers in a grid-connected microgrid characterized by an unreliable grid supply. A residential microgrid is taken to be the platform for such implementation, where it is made up of several residential prosumers. All the households are assumed to have installed PV panels so that they can self-generate their energy. Initially, the distribution network is assumed to be supplied by an unreliable grid and a private diesel generator (DG) plant with a limited capacity.

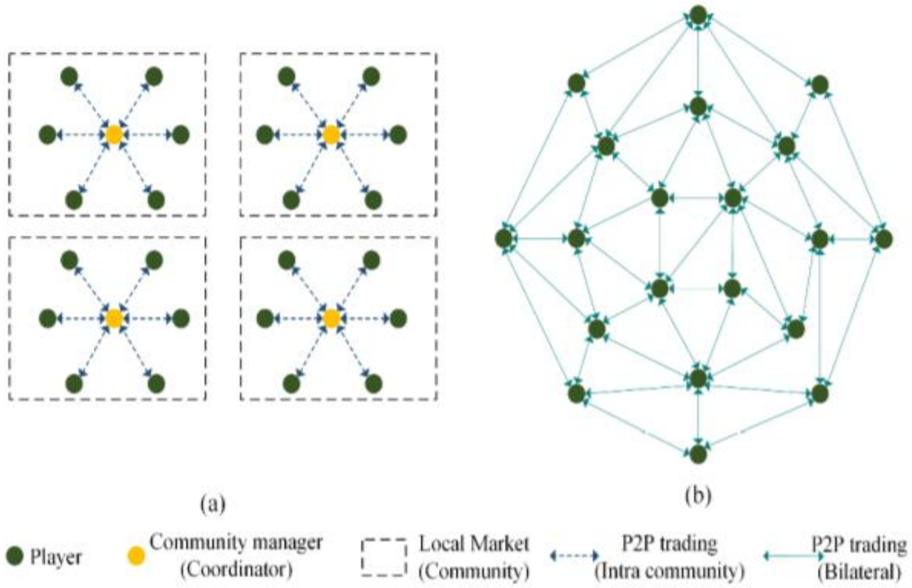


Figure 2: Comparison between the community-based and the distributed bilateral trading markets [42]

CHAPTER IV

SYSTEM MODELLING

Figure 3 depicts a four-layer system architecture for P2P energy trading that identifies and categorizes the key elements and technologies involved in P2P energy trading according to their functions. The system architecture three dimensional as illustrated below.

The key functions involved in P2P energy trading are divided into four interoperable layers in the first dimension. Each layer is introduced as follows. The power grid layer includes all physical components of the power system, such as feeders, transformers, smart meters, loads, and distributed energy resources (DERs). These components form the physical electricity distribution network where P2P energy trading is implemented. The information and communication technology layer, which includes communication devices, protocols, and information flow, is the second layer. The control layer is the third layer which mainly describes the strategies for preserving high-quality and reliable power supply while adjusting the actual energy exports to match the scheduled ones, and such a layer contains load control, frequency control, voltage control, etc. The fourth and final layer is the business layer. This layer defines the energy market participants and illustrates the trading strategy process among them and determines how electricity is traded among peers as well as the third parties. It mainly involves peers, suppliers, distribution system operators (DSOs), and energy market regulators. This layer can be used to develop a variety of business models for implementing various forms of peer-to-peer energy trading.

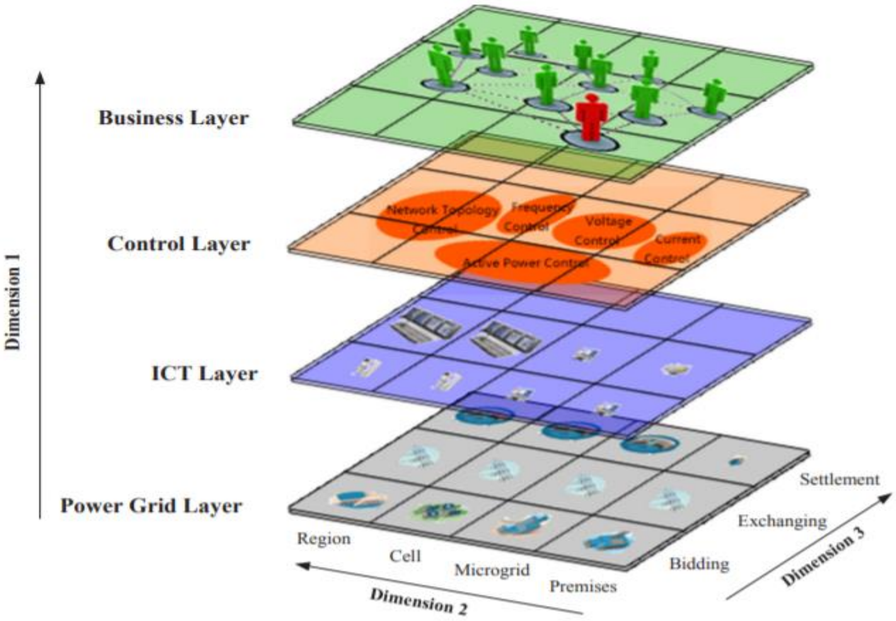


Figure 3: Four-layer system architecture

The second dimension, in the proposed system’s architecture, categorizes loads and distributed energy resources in the distribution network based on their size. While the third dimension organizes the time sequence of the proposed energy trading market model. This dimension organizes the bidding process, energy trading agreements, energy exchange, and settlement processes. A thorough description of the three dimensions is provided in the upcoming sections.

A. The First Dimension

1. *Physical Components Layer*

a. Grid Modelling

The distribution network is assumed to operate under an unreliable grid characterized by scheduled daily blackouts as in the case of many developing countries like Lebanon. The grid’s assigned energy outage is set to 8 hours a day.

Daily scheduled outage occurs at certain periods as shown in table 1. Figure 4 shows the grid scheduled blackouts for 24 hours.

Blackout Timing #1	6:00 am to 9:00 am
Blackout Timing #2	14:00 am to 17:00 pm

Table 1: Scheduled Daily Grid's Outage

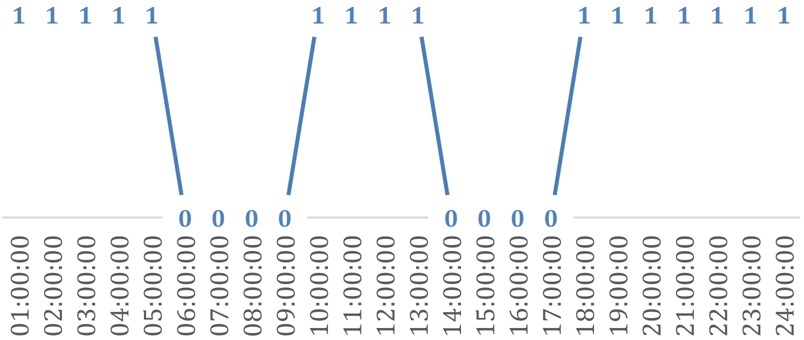


Figure 4: Grid State

According to the Lebanese scenario, the tariff on energy consumption is around 9.6 cents/kWh. However, the true production cost of energy is around 15cents/kWh though not implemented for political reasons.

To model grid blackouts, a binary operator (Φ) will be assigned to the power supplied by the grid, such that when Φ is high (1), the grid is ON and when Φ is low (0), the grid is OFF. Therefore, the grid output power will be represented using the following equation (1):

$$\mathrm{P}_{\mathrm{Grid,t}} = \Phi(\mathrm{t}) * \mathrm{P}_{\mathrm{G,t}} = \begin{cases} \text{P\_\{G, t\}} & \text{for } \Phi = 1 \\ 0 & \text{for } \Phi = 0 \end{cases} \tag{1}$$

b. Diesel Modelling

The presence of a reliable and dispatchable electric power source, in the absence of a reliable grid, is essential in any hybrid power system. Since the grid understudy, is characterized by scheduled blackouts, diesel engine generators are available to enhance the network's ability to compensate for energy outages.

The diesel generator in this study is a central unit that serves the system subscribers when grid electricity is not available.

The cost of energy generated by a diesel generator is calculated following the diesel oil consumption per day in addition to the system maintenance and operation cost.

Based on the real-world situation in Lebanon, the energy generated by diesel generators is sold to the public at a price of around 36 cents per kWh, which varies depending on the price of diesel oil.

c. Photovoltaic Modelling

PV output can be modelled using the following equations (2 to 14) [45] [46] [47][48]:

$$P_{PV,AC}(t) = PVout(t) \times \eta_{inv} \tag{2}$$

$$PVout(t) = FF(t) \times Isc(t) \times Voc(t) \tag{3}$$

$$Isc(t) = \frac{S}{S_{STC}}\left[I_{SC,STC} + K_i(Tc(t) - 25)\right] \tag{4}$$

$$Voc(t) = V_{OC,STC} - K_v \times (Tc(t) - 25) \tag{5}$$

$$FF(t) = FF_0(t) \times [1 - r_s(t)] \tag{6}$$

$$FF_0(t) = \frac{V_{OC,0}(t) - lnln\left[V_{oc,0}(t) + 0.72\right]}{V_{oc,0}(t) + 1} \tag{7}$$

$$V_{oc,0}(t) = Voc(t) \times \frac{q}{nk[Tc(t)+273.15]} \tag{8}$$

$$r_s(t) = R_s \frac{Isc(t)}{Voc(t)} \tag{9}$$

$$Tc(t) = Ta(t) + s\frac{NOCT-20}{0.8} \tag{10}$$

$$R_s \ = \ R_{s,STC} = r_{s,STC} \frac{V_{OC,STC}}{I_{SC,STC}} \tag{11}$$

$$r_{s,STC} = 1 - \frac{FF_{STC}}{FF_{0,STC}} \tag{12}$$

$$FF_{STC} = \frac{V_{mppt,STC} \times I_{mppt,STC}}{V_{OC,STC} \times I_{SC,STC}} \tag{13}$$

$$FF_{0,STC} = \frac{V_{OC,0,STC} - lnln\left[V_{OC,0,STC} + 0.72\right]}{V_{OC,0,STC} + 1} \tag{14}$$

Where, $P_{PV,AC}$ is the AC output power (in kW), $PV_{out}(t)$ is the maximum output power (in kW) at any time t, η_{inv} is inverter efficiency, Isc(t) and $V_{oc}(t)$ are the short circuit current (in Amps) and open circuit voltage (in Volts) under operating conditions, s is the solar irradiance (kW/m^2) at any time t, FF and FF_0 are the actual and ideal fill factor of the module, $V_{oc,0}(t)$ is the normalized open circuit voltage at any time t, q is the charge of an electron, n is the ideality factor assumed equal to 1, k is Boltzmann’s constant, $T_c(t)$ is the module’s temperature at any time t (in ˚C), R_s is the module series resistance, $r_s(t)$ is the normalized module series resistance at any time t, $T_a(t)$ is the module ambient temperature (in ˚C) and NOCT is the nominal operating cell temperature (in ˚C) provided by the manufacturer. “r_s, STC” is the normalized series resistance under standard test conditions (STC), FF_{STC} and $FF_{0, STC}$ are the actual and ideal fill factor under STC respectively and $V_{oc,0, STC}$ is the normalized open circuit voltage under STC.

Hourly measurements of solar irradiance and ambient temperature are required to calculate the PV system's hourly output. Figures 5 and 6 illustrate the annual temperature and irradiance profiles respectively (assumed to be the same for the coastal zone of Lebanon). Using the PV module characteristics, provided in table 2, and the set of equations (2)-(14), the output power of the PV module selected can be derived as shown in figure 7.

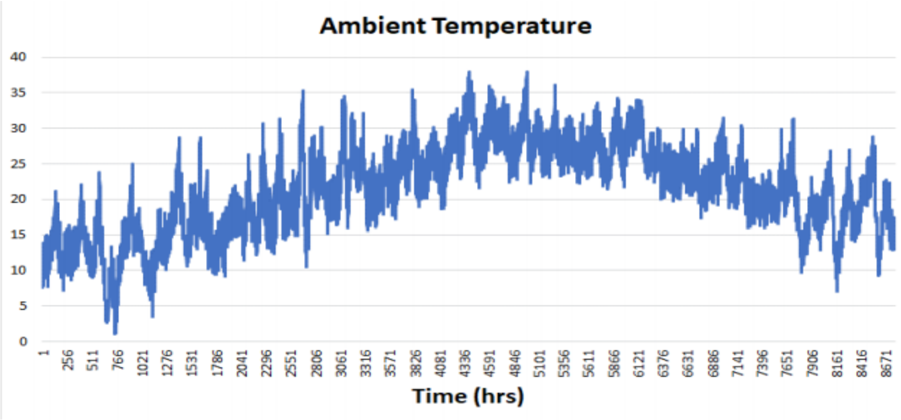


Figure 5: Ambient temperature annual profile

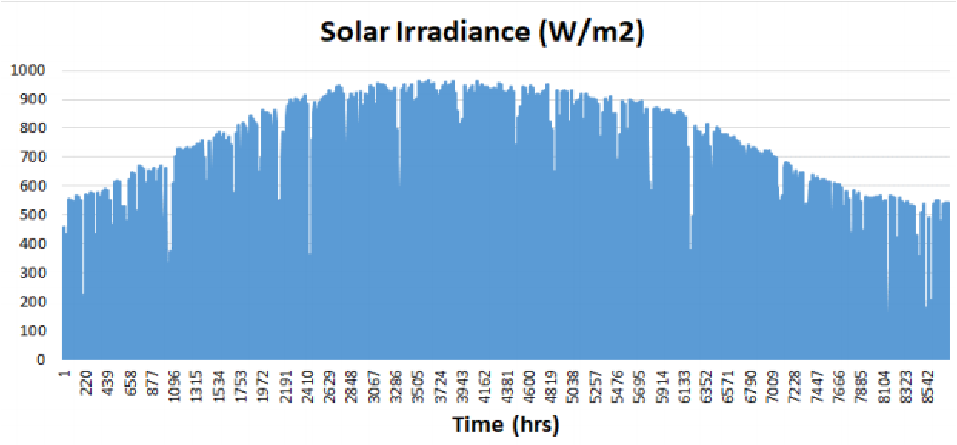
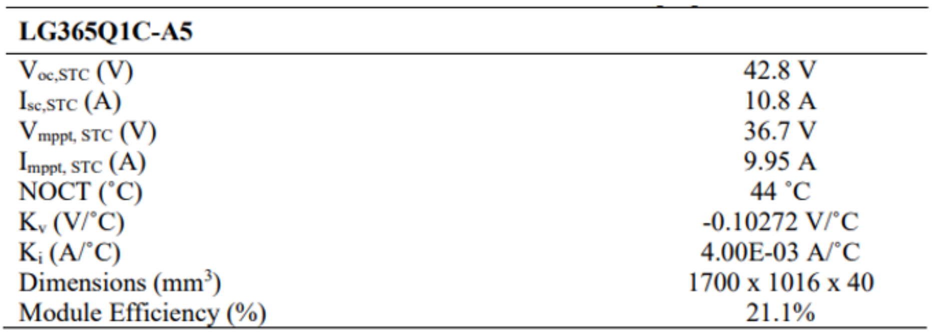


Figure 6: Solar irradiance annual profile



LG365Q1C-A5	
$V_{oc,STC}$ (V)	42.8 V
$I_{sc,STC}$ (A)	10.8 A
$V_{mppt,\ STC}$ (V)	36.7 V
$I_{mppt,\ STC}$ (A)	9.95 A
NOCT (˚C)	44 ˚C
K_v (V/˚C)	-0.10272 V/˚C
K_i (A/˚C)	4.00E-03 A/˚C
Dimensions (mm^3)	1700 x 1016 x 40
Module Efficiency (%)	21.1%

Table 2: PV Module Electrical Parameters

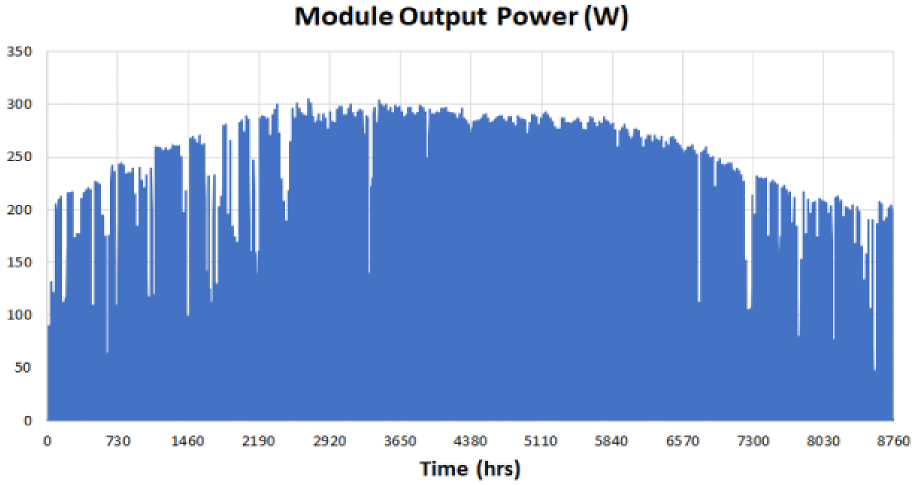


Figure 7: PV module annual output power profile

PV's financial modelling is illustrated in the following two equations:

$$AP^{PV} = CC^{PV} * CRF(i, N) + OM^{PV} \tag{15}$$

$$COE = \frac{AP^{PV}}{\sum_{t=t1}^{T} P^{PV}(t)} \tag{16}$$

Where, CC^{PV}, OM^{PV}, AP^{PV}, and COE^{PV} are the capital cost (in \$), operation and maintenance cost (in \$), annual loan payment (in \$), and cost of energy (in \$/kWh) respectively.

The PV system capital cost connected to each prosumer premise is taken as a bank loan with specified information as given below in table 3.

PV Module of Prosumer X	
INPUT	
Power (kW)	X
Cost ($/kW)	874.285
O&M ($/kW/year)	Y
Loan period (years)	Z
Interest Rate (%)	M
Loan Percentage	100%

Table 3: Bank Loan Specified Information

The annual loan payment is calculated according to equation (15) with its energy cost as in equation (16).

2. *Information and Communication Layer*

The ICT layer consists of communication devices, protocols, applications, and information flow. Communication devices refer to sensors, wired/wireless communication connections, routers, switches, servers, and various types of computers.

3. *Control Layer*

The control layer primarily consists of the electricity distribution system's control functions. Different control strategies are defined in this layer for preserving the quality and reliability of the power supply and controlling the power flow.

4. *Business Layer*

The business layer controls how electricity is exchanged between peers and with third parties. Peers, suppliers, distribution system operators (DSOs), and energy market regulators are the main participants. Various kinds of business models could be developed in this layer to implement different forms of P2P energy trading. This layer could be used to develop a variety of business models for implementing various forms of peer-to-peer energy trading.

B. Second Dimension

The size of the peers participating in P2P energy trading, i.e. premises, microgrids, cells, and regions consisting of multi-cells, is the second dimension of the system architecture. In our case, we are considering premises in a microgrid for the P2P simulation.

C. Third Dimension

The time sequence of the P2P energy trading process is depicted in the third dimension. Bidding is the first process of P2P energy trading when prosumers reach trading agreements with each other before the energy exchange. Energy customers interact with one another during the bidding process to agree on the price and amount of energy to be traded. The second process is energy exchanging, which involves the generation, transmission, and consumption of energy. Bills and transactions are finally settled through settlement arrangements and payment during the settlement process.

As prosumers, the new active consumers participate in the power generation and consumption process by utilizing local resources, managing demand, and interacting with other interested parties. In other words, these new players can use the two-way flow to exchange both information and energy among themselves and with the grid. These new players can trade energy locally by selling excess energy to other consumers or prosumers or buying energy when their supply cannot meet their demand.

With the existing infrastructures explained, the main aim of this study is to develop an algorithm for P2P energy trading. The detailed working processes of the control layer, communication systems, and physical infrastructures in the community microgrid are beyond the scope of this study.

D. Proposed Model

Figure 8 shows a detailed explanation of the proposed residential microgrid system comprising several prosumers. Detailed assumptions considered in this community are given below:

- The proposed P2P energy trading approach will be tested on a residential microgrid system characterized by scheduled and repetitive grid blackouts and heavy reliance on diesel generators.
- This entity is conventionally connected to the utility grid that is characterized by an intermittent power supply, in addition to the diesel generation entity of limited capacity.
- The diesel generator is taken as a central unit for all the community in common and not a unit at each prosumer premise and it is available when needed by anyone.
- The Lebanese scenario is taken into consideration in this study to shed light on the importance of P2P energy trading, especially since grid power is not always available.

- All prosumers in the microgrid comprise photo-voltaic (PV) systems installed in their premises with a capacity based on their demand profiles.
- Subscribers do not have battery energy storage systems (BESS) since deploying energy storage systems in the residential sector is still costly.

Figure 8 depicts the operation of a residential microgrid made up of prosumers who buy and sell energy from and to one another using the proposed games described in the following chapters.

Furthermore, if there is an energy surplus between prosumers in the microgrid, they will sell it to the utility company, if the grid on. If there is a deficit and one of the alternative sources (grid or diesel) is available, in the absence of sufficient solar energy, the deficit is satisfied from one of these two sources.

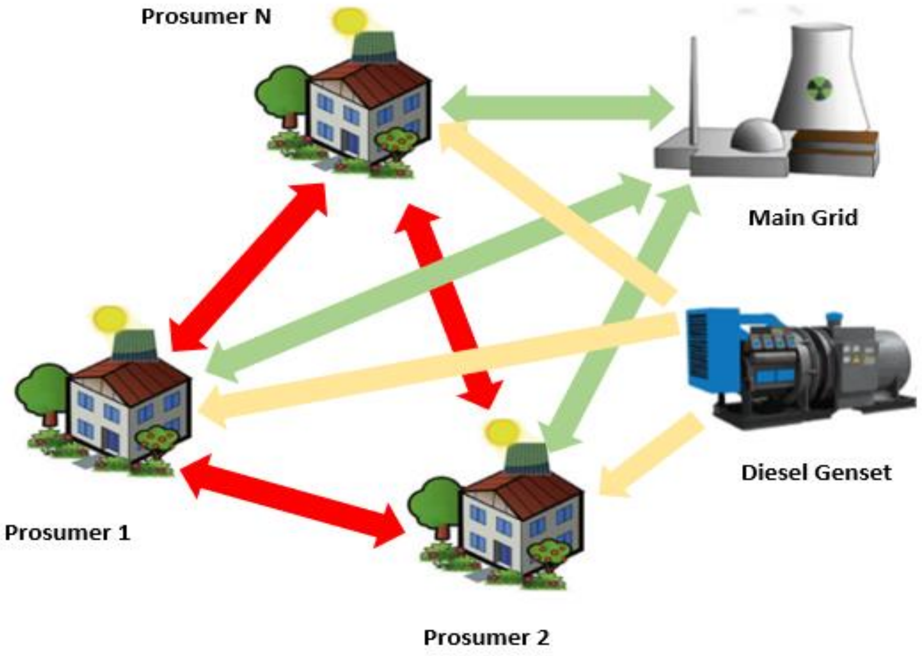


Figure 8: Illustration of the System Model

CHAPTER V

MATHEMATICAL MODELLING

- **Let Ň denote the set that contains the total number of prosumers in the microgrid with n ∈ Ň:**

  Ň = {1, 2, 3, …N}, where N denotes the total number of prosumers in the community and n denotes each prosumer.

- **Let Ť denote the set that contains all the operation time slots in the microgrid:**

  Ť = {1, 2, 3, … T}, where T denotes the total number of operation time slots. We assume that the total operation time is divided into different slots of equal intervals (Δt = 1 hour for the simulation of 24 hours on a selected day).

- **The PV generation profile of prosumer n during a day can be defined as follows:**

  $G_{pv}^{n} = \{G_{pv,n}^{1}, G_{pv,n}^{2}, G_{pv,n}^{3}, \ldots, G_{pv,n}^{T}\}$, where n Є N & t Є Ť (17)

- **The nominal demand profile of prosumer n during period t Є Ť can be defined as follows:**

  $D_n = \{D_n^1, D_n^2, D_n^3, \ldots, D_n^T\}$, where n Є N & t Є Ť (18)

- **Prosumers in the considered community are classified according to their generation to demand ratio (GDR) as sellers or buyers at a given time t Є T as given below:**

  $$GDR_n^t = \frac{G_{pv,n}^t}{D_n^t} \quad (19)$$

- **Let Š denote the set of prosumers selected as sellers indexed by k Є Š at time slot t such that its GDR is greater than 1 defined as follows:**

Š = {n Є N | $GDR_n^t > 1$} (20)

- **The amount of power that prosumer k Є Š can sell is a function of the GDR and the demand of that seller k at time t:**

$$P_{sell,k}^t = (GDR_k^t - 1)*D_k^t \quad (21)$$

In other words, $P_{sell,k}^t$ can be written as the demand subtracted from the generation.

- **Let ß denote the set of prosumers selected as buyers indexed by z Є ß at time slot t such that its GDR is less than 1 defined as follows:**

ß = {n Є N | $GDR_n^t < 1$} (22)

- **The amount of maximum power the prosumer z Є ß can import is a function of the GDR and the demand of that buyer z at time t:**

$$P_{buy,z}^t = (1 - GDR_z^t)* D_z^t \quad (23)$$

In other words, $P_{buy,z}^t$ can be written as the generation subtracted from the demand.

- **Proposed Utility Function**

The utility function is a tool to measure the feeling of comfort or satisfaction the prosumer gets when a certain amount of power is purchased. The utility of prosumer n can be interpreted as follows at a time t:

$$U_n^t (x_n^t) = \emptyset_n^t * x_n^t - \frac{\propto_n}{2} * (x_n^t)^2 , \; x_{n,min}^t \leq x_n^t \leq x_{n,max}^t \quad (24)$$

where $\emptyset_n^t > 0$ is a prosumer preference time-varying parameter characterizing the prosumers' behaviors, which vary from prosumer to prosumer and may also vary along the time. Different values of $\emptyset_n^t$ at different time slots of this utility function can capture the dynamics of user demand.

$\propto_n > 0$ is a predetermined constant. The terms x_n^t, $x_{n,min}^t$, $x_{n,max}^t$ are the actual power consumption, its lower limit, an upper limit for prosumer n at time t, respectively.

Values of $\emptyset_n^t$ and $\propto_n$ are declared in the results section based on simulations.

- **Proposed welfare functions of the Buyers and the Sellers**

The main reason for P2P trading is the participation of the sellers and the buyers in a way that maximizes their welfare function which is defined below. A prosumer that consumes x kW electricity during a designated number of hours at a rate of φ dollars per kWh is charged φ*x dollars per hour. Hence, the welfare of each user can simply be represented below. If a buyer **z Є ß** chooses a seller **k Є Š,** the welfare function is defined as follows:

$$W_z^t = U_z^t\,(x_z^t) - \varphi_k^t * x_{k,z}^t \tag{25}$$

- **Constraints for buyer's Welfare Function:**

$$x_{z,min}^t \le x_z^t \le x_{z,max}^t \tag{26}$$

$$x_z^t = x_{k,z}^t + G_z^t \tag{27}$$

$$x_{k,z,min}^t = x_{z,min}^t - G_z^t \tag{28}$$

$$x_{k,z,max}^t = x_{z,max}^t - G_z^t \tag{29}$$

$$x_{k,z,min}^t \le x_{k,z}^t \le x_{k,z,max}^t \tag{30}$$

where φ_k^t, $x_{k,z}^t$, $x_{k,z,min}^t$, $x_{k,z,max}^t$ are the price decided by seller k, the actual power the buyer z buys from seller k, and its lower and upper power limits buyer z can buy from the seller k at time t, respectively.

- **The Welfare Function can be written as follows when substituting equation (27) in equation (25) for any buyer z Є ß:**

$$W_z^t(x_{k,z}^t) = U_z^t(x_{k,z}^t + G_z^t) - \varphi_k^t * x_{k,z}^t \tag{31}$$

In the case of sellers, because they get a profit when they sell energy to needy buyers, their welfare function is an addition, and it is represented as the utility gained by the seller as a result of the seller-buyer interaction added to the price of energy sold multiplied by the amount of energy sold. There are two types of energy that a seller can sell:

1) The seller may sell all his generated energy denoted as $P_{sell,k}^{t}$
2) The seller may sell all the demanded energy denoted as S_k^t

- **The Welfare Function can be written as follows for any seller k Є Š:**

$$W_k^t = U_k^t(x_k^t) + \varphi_k^t * min(P_{sell,k}^t, S_k^t) \tag{32}$$

$P_{sell,k}^{t}$ is the total demand for electricity coming to seller k at time t and is defined in the following section.

- **Cost Function of the Utility Company**

We consider a cost function $C_u(y)$ indicating the cost of providing y units of energy offered by the energy provider in each time slot t ∈ T

$$C_u(y) = Rate_{EDL} * Energy\ Consumed \tag{33}$$

- **Cost Function of the Diesel Generation Unit**

We consider a cost function $C_d(d)$ indicating the cost of providing d units of energy offered by the diesel energy provider in each time slot t ∈ T

$$C_d(d) = Rate_D * Energy\ Consumed \tag{34}$$

CHAPTER VI

FORMULATION OF GAMES

A. Evolutionary Game among Buyers

The competition among multiple buyers to select the sellers to buy energy provided by them is modeled as an evolutionary game. All the buyers are arranged into a single group in this study, and there is only one population. The evolutionary game in the community for P2P energy trading can be described precisely as follows:

The players of the game are the set of buyers indexed as z and their strategy is to pick a seller among the sellers indexed as k. When receiving the prices announced by the sellers, each buyer selects a seller for buying power. Each purchaser then changes its selection strategy progressively and participates in the selection process independently. The outcome of the evolutionary game called the Evolutionary Stable Strategy (ESS) or probability vector for seller selection, gives the probabilities for each buyer choosing a certain seller at time t.

The optimal value of power buyer z obtained from seller k can be achieved by maximizing the welfare target equation when buyer z selects seller k, given before by (18) subject to (21-23). It can be written as follows:

$$x_{k,z}^{t\,*} = arg_{x_{k,z}^{t}} \max W_z^t \tag{35}$$

If the probability of buyer z Є ß choosing a seller k Є Š is given by ρ_k^t at time t, where ρ_k^t is $0 \leq \rho_k^t \leq 1$, and since it is a probability distribution then $\sum_{z=1}^{\text{ß}} \rho_k^t = 1$. Buyers in the population have identical strategies. The population state that contains the probabilities of buyers choosing sellers at time t is as follows:

$$\rho^t = \{\rho_1^t, \rho_2^t, \rho_3^t, \ldots, \rho_S^t\}$$

The total demand of electricity comes to the seller k at time t is given by the following equation:

$$S_k^t = \rho_k^t \sum_{z=1}^{ß} x_{k,z}^{t\,*} \tag{36}$$

To know the actual amount of power that buyer z buys from seller k at time t we have to define the supply to demand ratio for each seller and it's given below:

$$SDR_k^t = \frac{P_{sell,k}^t}{S_k^t} = \frac{P_{sell,k}^t}{\rho_k^t \sum_{z=1}^{ß} x_{k,z}^{t\,\circ}} \tag{37}$$

The actual amount of power that buyer z buys from seller k at time t is given below as follows:

If $SDR_k^t \geq 1$ then $x_{k,z,ac}^t = \rho_k^t * x_{k,z}^{t\,\circ}$ (38)

If $SDR_k^t < 1$ then $x_{k,z,ac}^t = \rho_k^t * x_{k,z}^{t\,\circ} * SDR_k^t$ (39)

Equations (38) and (39) resulted from equation (37) where the supply to demand ratio (SDR) has two options to depict the actual amount of energy that was sold by seller k at time t.

If we assume that the net utility of a certain seller k can be defined as the accumulated welfare of all the buyers obtaining power from seller’s k. In other words, the net utility computes the sum of the welfare of a selected seller coming from all the buyers who bought energy from that seller at the time t. It can be written as follows with two options as depicted in equations (40) and (41).

Two possibilities are related to $P_{sell,k}^t$ and S_k^t

If $P_{sell,k}^t \geq S_k^t$, then the net utility is formed as follows:

$$\sigma_k^t = \frac{1}{2} \sum_{z=1}^{ß} \propto_z (x_{k,z}^{t\,\circ})^2 + C \tag{40}$$

If $P_{sell,k}^t < S_k^t$

$$\sigma_k^t = [SDR_k^t - \frac{(SDR_k^t)^2}{s}] \sum_{z=1}^{ß} \propto_z (x_{k,z}^{t\,\circ})^2 + C \tag{41}$$

1. Replicator Dynamics Equation

The replicator dynamics are designed to depict the following buyer selection dynamics:

$$\dot{\rho}_k^t \;=\; \rho_k^t \,(\,\sigma_k^t \;-\; \varphi^t) \tag{42}$$

Where φ^t denotes the average utility. This average utility is essential in the game to depict that all sellers are treated the same and no prosumer is getting higher satisfaction in the game. The average utility can be calculated as follows:

$$\varphi^t \;=\; \sum_{k=1}^{\check{\mathrm{S}}} \quad \rho_k^t \,*\, \sigma_k^t \tag{43}$$

An Evolutionarily Stable Strategy (ESS) is a strategy that, if adopted by a population in each environment it cannot be invaded by any alternative strategy that is initially rare.

The condition for stable state in evolutionary game can also be written as follows:

$$\dot{\rho}_k^t \;=\; 0 \tag{44}$$

In other words:

$$\sigma_1^t \;=\; \sigma_2^t = \sigma_S^t = \;\varphi^t \tag{45}$$

Then the equilibrium in the evolutionary game is the ESS and denoted by:

$$\rho^{t^\circ} \;=\; \{\rho_1^{t^\circ}, \rho_2^{t^\circ}\,, \rho_3^{t^\circ}, \ldots, \rho_S^{t^\circ}\}$$

The discrete replicator for approximation of replicator dynamics is defined as follows:

$$\rho_k^t\,(s+1) \;=\; \rho_k^t\,(s) \;+\; \tau_1\, \rho_k^t\,(s)\,(\,\sigma_k^t\,(s) \;-\; \varphi^t(s)) \tag{46}$$

For the game to terminate the condition below should be satisfied:

$$|\sigma_k^t\,(s) \;-\; \varphi^t(s))\;\;| < \in \tag{47}$$

Where s is the iteration number, τ_1 is the adjustment parameter, and $\in$ is a small positive constant.

B. Non-Cooperative Game among Sellers

Auctions and strategic voting are examples of non-cooperative games in which players make decisions independently. A Nash equilibrium is the result of a non-cooperative game involving two or more players, in which each player is assumed to be knowledgeable of the other players' equilibrium strategies, and no player has anything to gain by changing only their strategy.

Each seller aims to maximize its welfare in our P2P trading platform by selling the power to buyers in need. They are noncooperative and behave rationally. This non-cooperative game can be designed between the participating sellers k Є Š as the players in the game. Their primary task is to adopt a strategy that offers the price of energy and the amount of energy available for sale. In addition to their utility that shows their level of comfort, and it is the player's welfare in our case.

The welfare function of the seller is mentioned before in equation (18), and it can be written equivalently as according to the value of SDR for each seller at time t:

$$W_k^t = U_k^t(x_k^t) + \pi_k^t * S_k^t \qquad \text{If and only if } P_{sell,k}^t > S_k^t \tag{48}$$

$$W_k^t = U_k^t(x_k^t) + \pi_k^t * P_{sell,k}^t \qquad \text{If and only if } S_k^t > P_{sell,k}^t \tag{49}$$

This non-cooperative game starts by announcing the prices of energy by the sellers k Є Š at time t. There are limits on the prices φ_k^t such that $\pi_k^t \in [\pi_{k,min}^t, \pi_{k,max}^t]$. In this study, we choose the minimum cost of a seller generating his electricity as the lower limit and an upper limit equal to the diesel gensets price which is the highest energy price in the community. The solution of the game is called Nash equilibrium (NE), which includes the energy price announced by the sellers and the amount of the energy to be sold at each time instant t.

C. Stackelberg Game

To model the interaction between the sellers and the buyers, which is the main purpose of the P2P trading, we considered the Stackelberg game which is an M-leader, N-follower game.

In our case, the sellers are the multiple leaders, and the buyers are the multiple followers. Stackelberg's game establishes a relationship between the evolutionary game and the noncooperative game. The output of the non-cooperative game, which is the price vector announced by the sellers in our case, is used as an input to the evolutionary game to update the seller selection strategy.

To update the price vector, the output of the evolutionary game, which is the ESS or seller selection probability, is used as an input to the non-cooperative game. So, the three games are all related to one another. All buyers receive from the sellers the announced price vector and engage in the evolutionary game. Once the ESS is obtained in the evolutionary game, sellers update their price to obtain the Nash equilibrium which is the price vector and indeed the amount of energy to be sold. In the Stackelberg game between sellers and buyers, an iterative distributed algorithm is designed to obtain the NE among the sellers so that the Stackelberg equilibrium (SE) is reached.

To meet the above requirements, an iterative distributed algorithm is used. The price updating strategy of the seller k is designed as follows:

$$\pi_k^t(i+1) = \pi_k^t(i) + \tau_2(S_k^t(i) - P_{sell,k}^t) \quad (50)$$

For the game to terminate the condition below should be satisfied:

$$|\pi_k^t(i+1) - \pi_k^t(i)| < \in \quad (51)$$

In other words when this condition is satisfied:

$$\left|S_k^t(i) - P_{sell,k}^t\right| < \in \quad (52)$$

Where i is the iteration counter, τ_2 is the speed adjustment parameter and $\in$ is a small positive number.

CHAPTER VII

ALGORITHMS

A. Evolutionary Game Algorithm

To achieve the evolutionary equilibrium, we present an evolutionary algorithm for the population of buyers. Each buyer participates in an evolutionary game to determine the probability of purchasing power from a specific seller, which is an ESS, in this algorithm. This game is embedded inside the Stackelberg game or in other words the bigger game. The game starts when the sellers input their prices to be seen by the registered buyers in the game. After that, the game assigns random initial population states for the buyers. For this game to reach its evolutionary stable strategy the average net utility of the sellers assigned by the buyers must be to a large intent equal to the individual utility of the seller. The flowchart of the algorithm shown in figure 9 depicts the flow of the game to reach an evolutionary stable strategy.

The game starts with the price vector imported from the biggest Stackelberg game, since as shown before the evolutionary game is considered as a sub of the M-leader N-follower Stackelberg game. The game continues by computing the optimal amount of power traded between seller k and buyer z which is computed by maximizing the quadratic welfare function as stated in equation (35). After ending the optimization problem, the algorithm computes the supply to demand ratio and then the average and net utilities. These utilities are the core of this evolutionary game since they depict, at the end of this game and convergence, the net utility is equal to the average utility and states that every seller that participates in the game is equally satisfied, and no seller has more incentive than the other sellers. The difference between the net and the average utilities keeps updating until the game reaches its stable state.

B. Stackelberg Game Algorithm

When there are multiple sellers in a certain P2P energy trading platform, they may compete in terms of price to sell energy to the group of buyers. We consider the case in which the seller has an amount of energy that he has to sell at each time instant for the game to converge.

We modeled this competitive scheme as a non-cooperative game in which the Nash equilibrium is considered as the solution. Therefore, the payoff of each seller is maximized on an individual basis, and all of them are satisfied with the solution.

As for the game to converge the sellers must sell all the energy they offer to the buyers in need. In addition, to achieve the Nash equilibrium in a Stackelberg game, an iterative algorithm is presented in which a seller gradually adjusts the strategy based on the evolution of the buyers. The game begins with the initialization of the prices set by the game's sellers. After that and to reach the Nash equilibrium, the power demand is calculated and compared with the power exported by the seller. Figure 11 depicts the game flow where it randomly starts initializing the price vector by the sellers and then executing algorithm 1. After the execution of algorithm 1, the power demand is then calculated for all the sellers receiving the requested amount of power from the buyers as depicted in equation (36). After computing this total demand, the value is then compared with the amount of power that the seller was able to export as shown in equation (21). This value keeps iterating until this condition is satisfied. In other words, the game converges when the needed energy from the sellers is completely satisfied.

C. Complete system Algorithm

P2P trading aims to maximize the welfare of both buyers and sellers and reduce the dependence on the upstream grid and diesel generation units. In P2P energy trading, if any prosumer (seller) has excess PV energy, the prosumer's priority is to supply to the neighbors who have unmet consumption (buyers) in the community and if there is any remaining power, it is sent back to the grid if the grid is available at that time. However, if the grid is not available it will be dumped.

As shown in figure 9, the algorithm starts by inputting the total generations and the demands of all the users in the community for each time instant of the day. After that, and for each time instant of the day the generation to demand ratio is calculated to know which prosumer is a seller and which one is a buyer. The algorithm then flows in a way when the demand is higher than the PV generation, the prosumer (buyer) with the deficit electricity satisfies its demand by buying PV power from the neighbors who have an excess of electricity through the P2P market at first, and then the remaining, if there is any, is met by buying energy from the upstream grid if available. If the grid is not available at that time, the prosumer must buy energy from the diesel generator unit available in the microgrid.

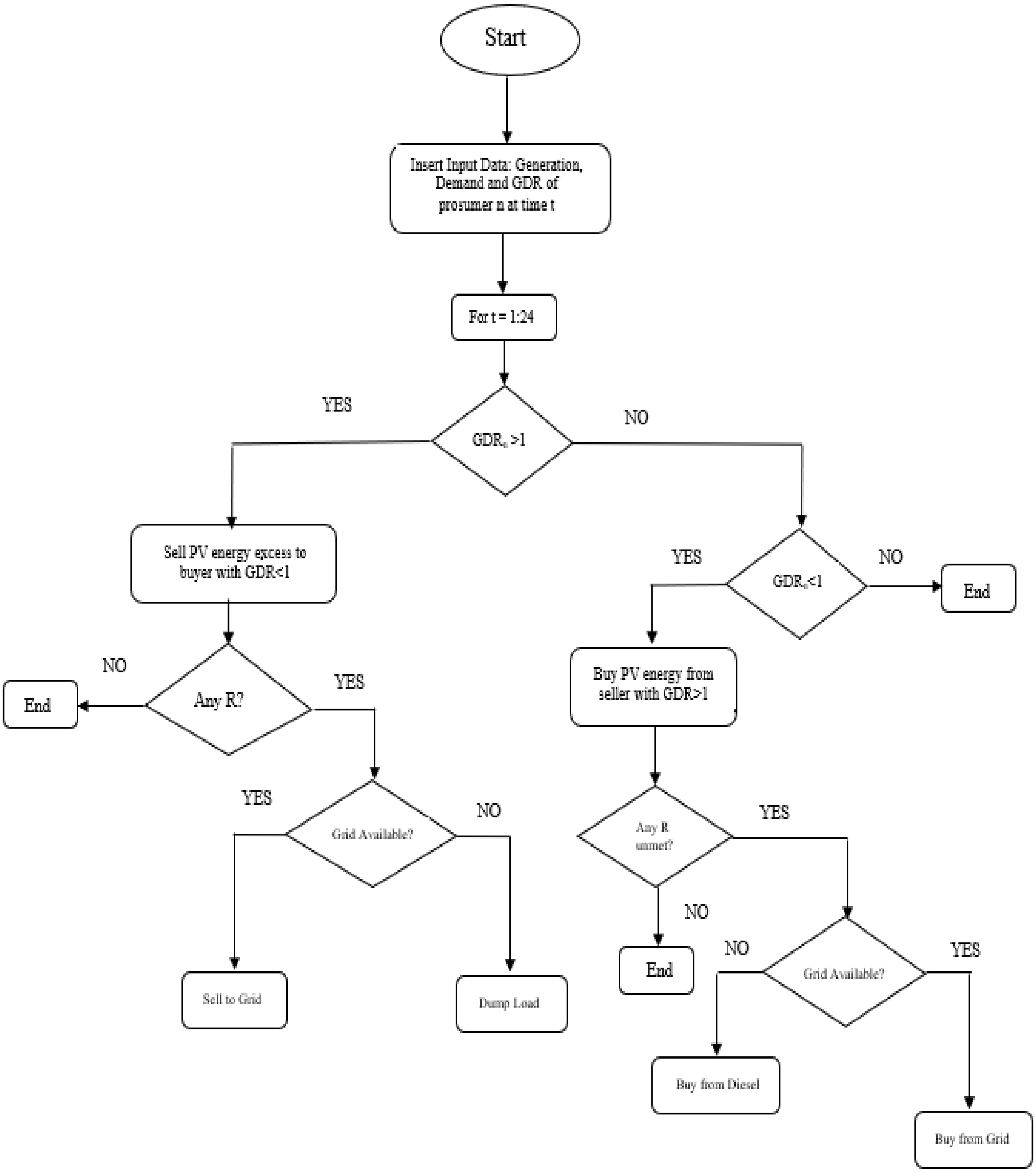


Figure 9: Proposed System Algorithm

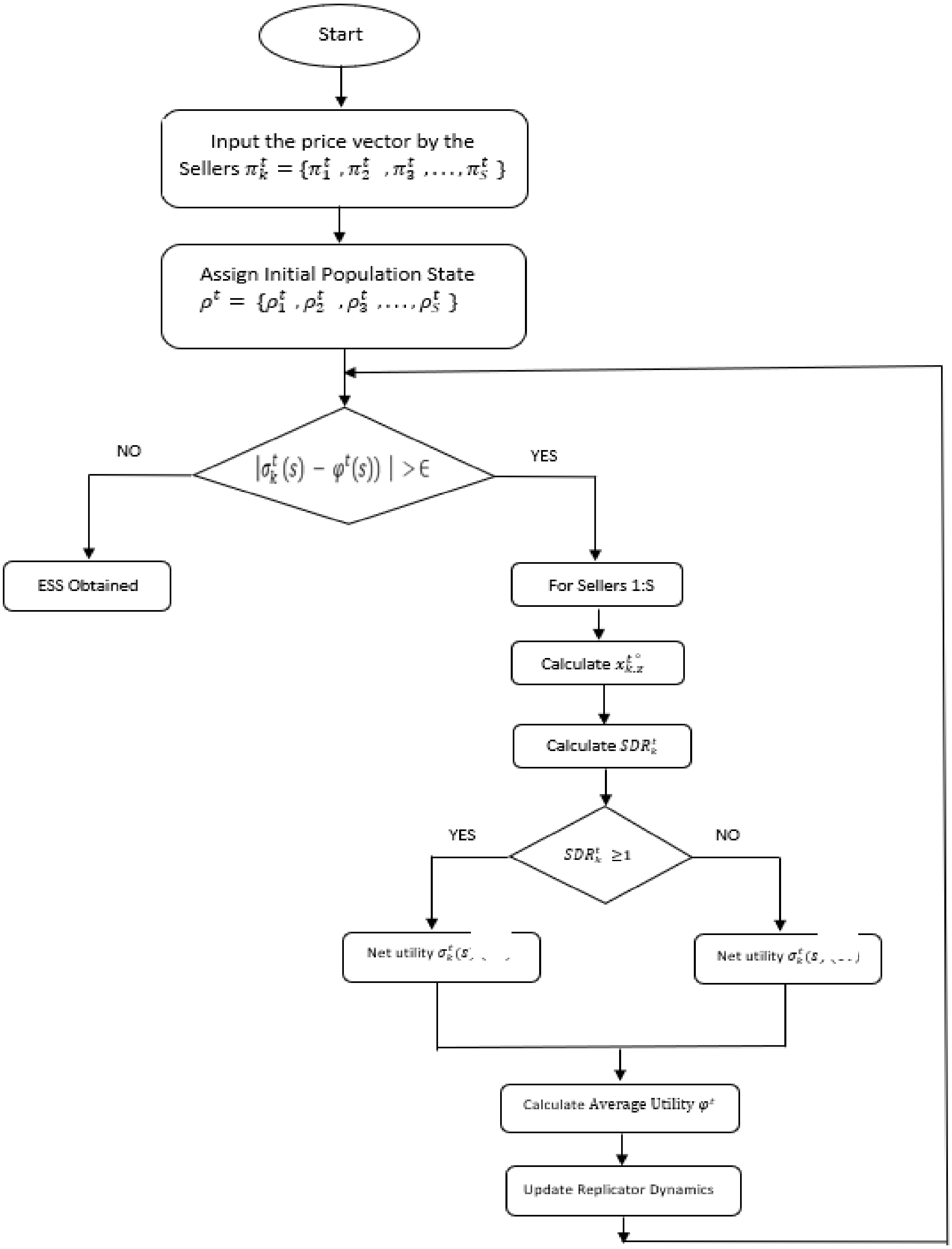


Figure 10: Evolutionary Game Algorithm

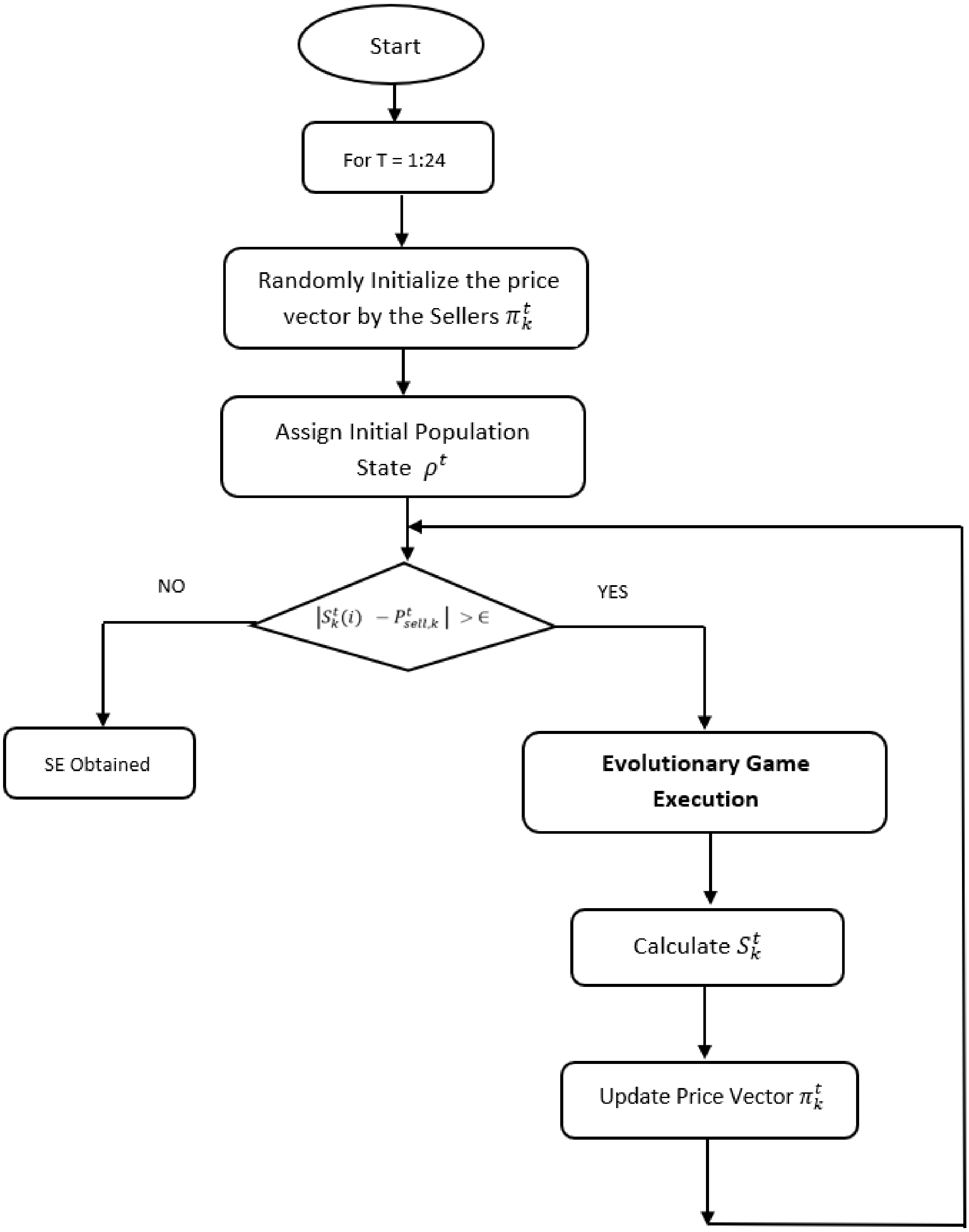


Figure 11: Stackelberg Game Algorithm

CHAPTER VIII

SIMULATION RESULTS

A. Input Data

This section presents the results of simulation studies to assess the performance of the proposed game-theoretic model for P2P energy trading in a prosumer-based community microgrid.

We consider a community microgrid that consists of five prosumers and the alternative sources which are the grid and the central diesel generation unit. The community microgrid is connected to the utility grid and the gensets unit, thus the prosumers can trade with one another as well as the retailers. Each prosumer has a solar PV system, so they are generating and consuming at the same time. Prosumers solar PV system is based on budgets and chosen randomly for all the prosumers in the microgrid. We assume that some prosumers chose a PV system based on their maximum consumption, and others choose the system based on their available budget considering a backup solar PV system. In any of the two ways switching to renewable energy shows remarkable savings in the system as proved in the results below.

On the other hand, prosumers may be sellers or buyers at each time instant of the day based on their generation to demand ratio “GDR” stated in figure 14. The generation and the demand profiles of each prosumer in the community are taken as real case prosumers in Lebanon as shown in figures 12 and 13 respectively. Since prosumers live in close proximity, communication and transmission losses are neglected. The simulation is done for one day.

The value of $\emptyset_n^t$ is selected randomly between 0 & 5 where according to simulations, increasing phi increases the utility function however taking phi to be a random number between 0 and 5 was the best choice, and $\propto_n$, a constant number in the utility function equation, is taken as 0.5.

1. System Assumptions

In our simulations, we consider the following important system assumptions:

- A lower bound on prosumers prices. If there are no lower bounds on the price, then whenever there is extra energy produced by the sellers $P^t_{sell,k} > S^t_k$ the price for these sellers will be moved down, eventually the prices will become negative. At that point, the "penalty" term on the buyer's welfare which is the "-price * x_{kz}" becomes a positive term and inverts from being a deterrent to consumption to an incentive to consumption and the buyers will buy extra energy, thus the solver will start oscillating and diverge. Consequently, a lower bound of at least 0 is necessary to keep the model mathematically sound, in proper terms, and a necessary condition for the problem to converge (not sufficient, but necessary).
- An upper bound on prosumers prices. If there are no upper bounds on the price, then whenever there is a general shortage of energy production for the sellers with respect to the demand from buyers, prices will go up again because the step direction for prices is " $S^t_k - P^t_{sell,k}$" and this is the mechanism that pushes buyers away from a seller that has too much demand relative to their production. However, when there is not enough total production and buyers must satisfy their demand, the mechanism fails since the S_k demand on the buyers won't get lower and the price hike will continue towards infinity. Consequently, an upper bound is a necessary condition for the problem to converge.

Based on the value of the generation to demand ratios shown in figure 14, the prosumers can behave as sellers or buyers during the same daytime. We choose time slot 9 to demonstrate the performance of the proposed game theoretical interaction among the prosumers. At time slot 9, Prosumers 2 and 4 are treated as sellers since their GDR is greater than 1, and the remaining three prosumers which are 1, 3, and 5 are buyers since their GDR is less than one. Prosumers in the community are assumed to be of the same nature and treated as residential prosumers with low demand that peaks at 5kW for prosumer 5. Table 4 shows the capacity of the installed solar system at each premise in comparison with the maximum prosumer consumption per day. Assume that we're using the 330Wp solar PV module with its characteristics stated in table 2 and output profile in figure 7. As a result, the total kWp is calculated after multiplying the number of panels with the selected panel watt peak.

A very important factor is to compare the system comprising of DGs with the conventional system which is done by calculating the PV cost of energy as depicted in table 5. This cost of energy is in dollars/kWh and is calculated based on equation (16).

To calculate the cost of energy per day, each prosumer is assumed to have taken out a bank loan with a specific interest rate, as shown in table 6. The annual payments of the prosumers differ because it is assumed that each of them is entitled to a different loan, interest rate, and, as a result, a different annual payment, resulting in a variety of simulation results.

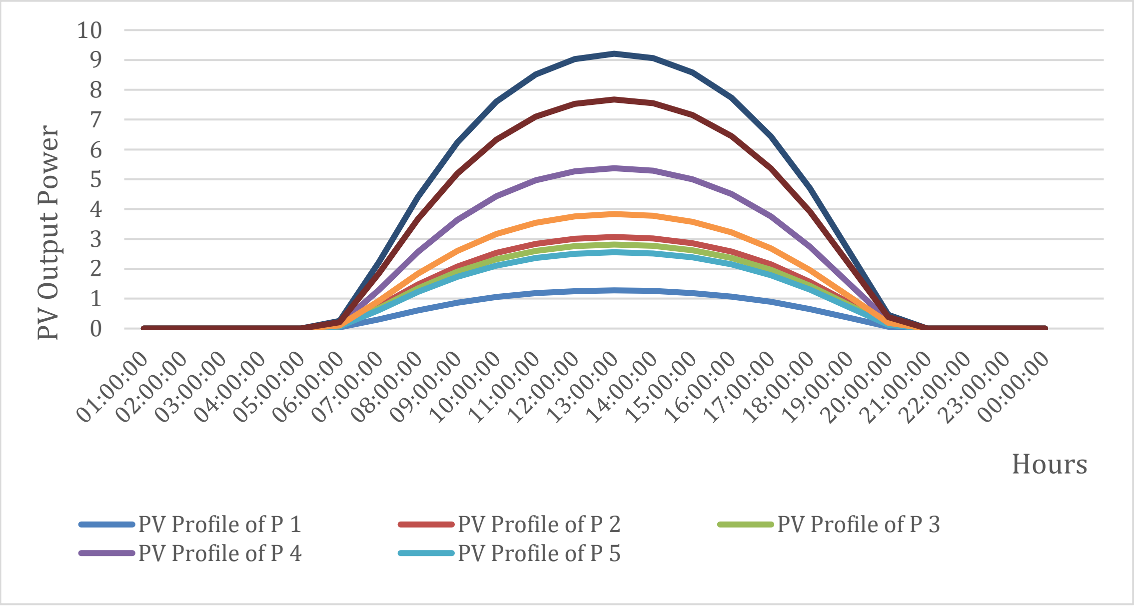


Figure 12: Prosumers PV Generation Profiles for one Day in April

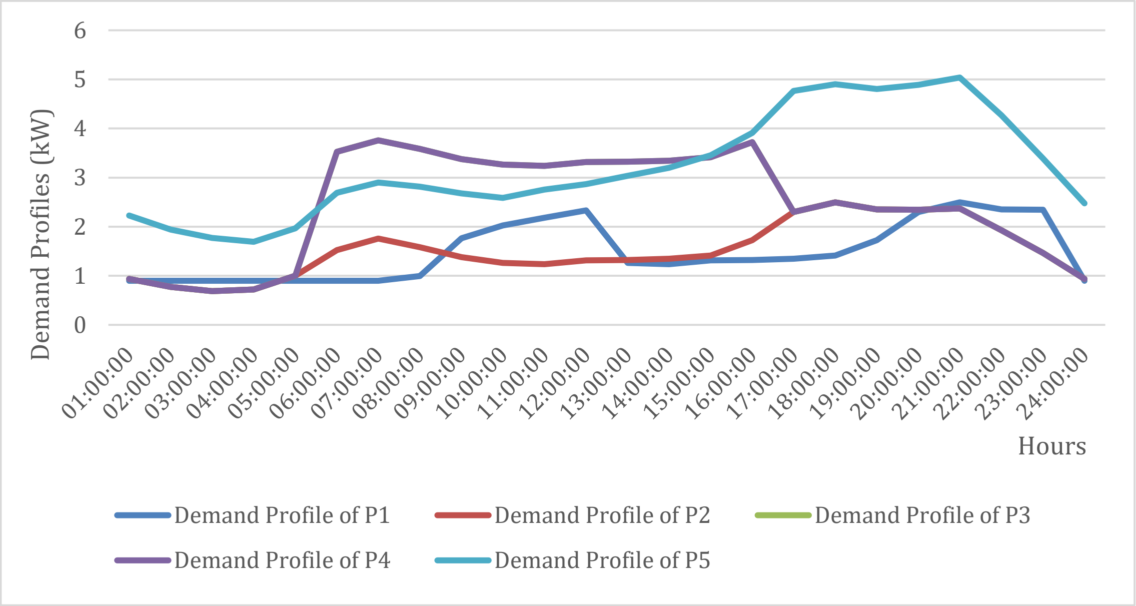


Figure 13: Prosumers Demand Profiles for one day in April

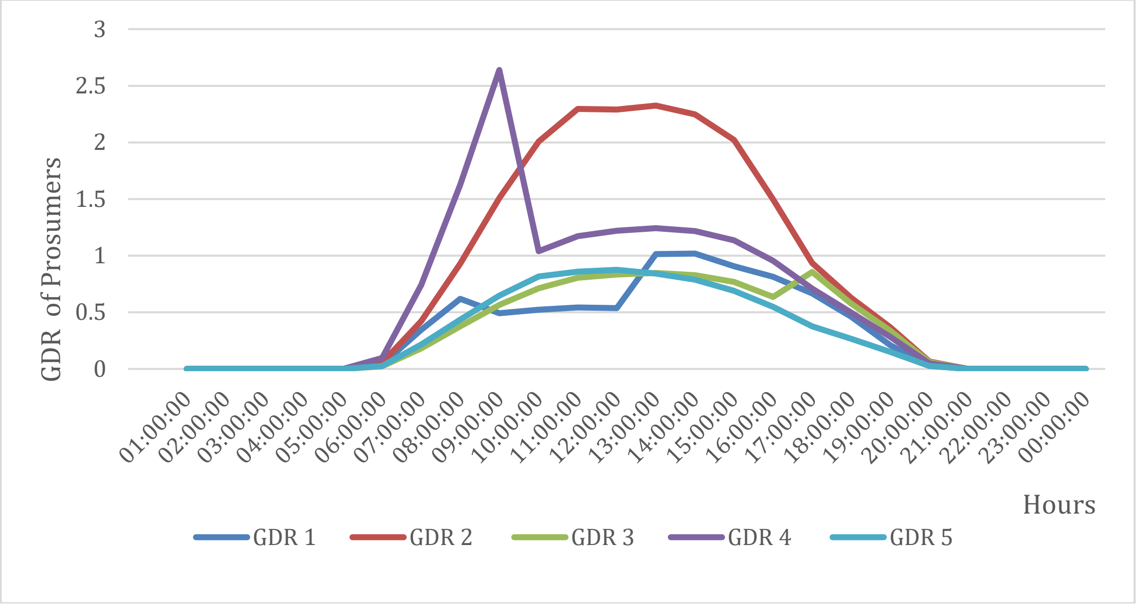


Figure 14: Generation to Demand Profiles of the Prosumers

Prosumer	**1**	**2**	**3**	**4**	**5**
Max Consumption (kW)	2.5	2.5	3.75	3.75	5
Installed PV System(kWp)	1.5	4	3.5	7	3.5
Number of Installed Panels	5	12	11	21	10
Used Panel	330Wp	330Wp	330Wp	330Wp	330Wp
Total kWp	1650	3960	3630	6930	3300

Table 4: Prosumers installed PV System

Prosumer	**1**	**2**	**3**	**4**	**5**
Average COE ($/kWh)	0.0756	0.0905	0.0943	0.1174	0.0945
Annual Payment($/yr.)	333.61	958.75	916.06	2177.15	834.43
Cost/ Day ($)	0.914	2.626	2.509	5.964	2.286

Table 5: Prosumers Generation Costs

Table 6: Prosumers Loans Information

PV (P1)		PV (P2)	
INPUT		**INPUT**	
Power (KW)	1.65	**Power (KW)**	3.96
Cost ($/KW)	874.285	**Cost ($/KW)**	874.285
O&M ($/year)	23.1	**O&M ($/year)**	49.5
Loan period (years)	5	**Loan period (years)**	4
Interest Rate (%)	0.025	**Interest Rate (%)**	0.02
Loan Percentage	100%	**Loan Percentage**	100%
Calculated Values		**Calculated Values**	
Capital Cost ($)	1,442.57	**Capital Cost ($)**	3,462.17
CRF	0.2152	**CRF**	0.2626
Annual payment ($)	333.61	**Annual payment ($)**	958.75
PV (P3)		**PV (P4)**	
INPUT		**INPUT**	
Power (KW)	3.63	**Power (KW)**	6.93
Cost ($/KW)	874.285	**Cost ($/KW)**	874.285
O&M ($/year)	41.745	**O&M ($/year)**	76.23
Loan period (years)	4	**Loan period (years)**	3
Interest Rate (%)	0.04	**Interest Rate (%)**	0.02
Loan Percentage	100%	**Loan Percentage**	100%
Calculated Values		**Calculated Values**	
Capital Cost ($)	3,173.65	**Capital Cost ($)**	6,058.80
CRF	0.275	**CRF**	0.346
Annual payment ($)	916.06	**Annual payment ($)**	2,177.15

PV (P5)	
INPUT	
Power (KW)	3.3
Cost ($/KW)	874.285
O&M ($/year)	39.6
Loan period (years)	4
Interest Rate (%)	0.04
Loan Percentage	100%
Calculated Values	
Capital Cost ($)	2,885.14
CRF	0.275490045
Annual payment ($)	834.43

B. Convergence of the formulated Evolutionary Game

Each buyer participates in the evolutionary game to find the probability of buying power from a particular seller, this is the evolutionary stable strategy.

To evaluate the performance of the iterative evolutionary algorithm, we perform the simulations, in which the users conduct algorithm 1 to achieve this equilibrium state. Figure 15 shows the convergence process of the residential users, and it depicts that the users can converge to equilibrium after several iterations

The population states of prosumers 2 and 4, which is the probability selected by buyers to choose the sellers at time instant 9, are depicted in figure 15. The converged probabilities' sum is equal to one. The probability of buying power from sellers 2 and 4 is represented by the converged purple and red graph lines, respectively.

We have two sellers in the game at that time, according to the GDR, other than one of the alternative sources, so as the evolutionary game begins to converge, buyers converge to stable population states for selecting the existing sellers.

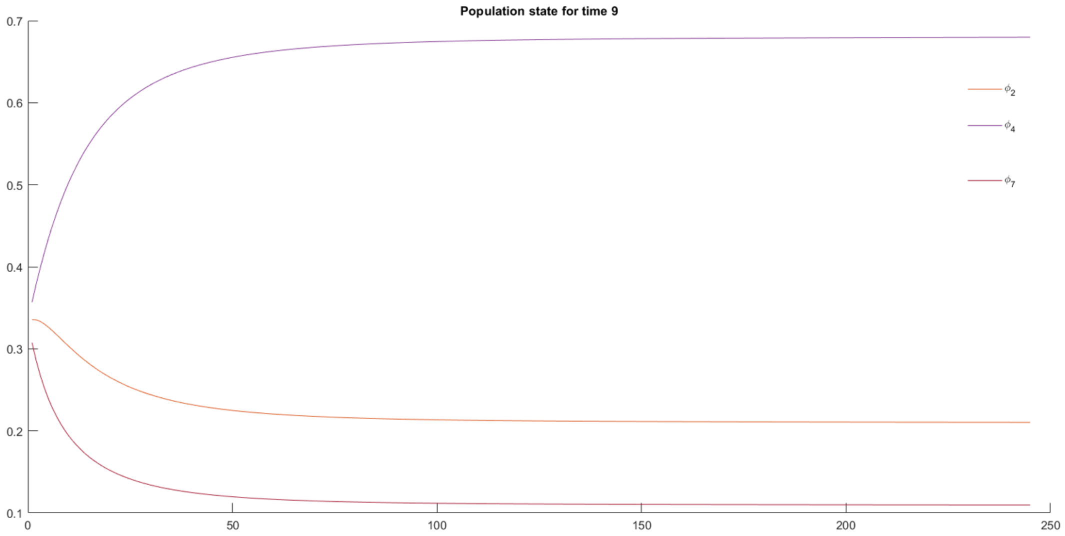


Figure 15: Probability of seller selection at t=9

The convergence characteristics of the average net utility is shown in figure 16. According to simulations, the ESS is obtained when the average net utility converges to a stable point. This point is the average of all utilities of sellers at time instant 9 that equals the utility of an individual seller. This result is what we aim for attaining the evolutionary stable strategy assuming that the net utility of seller k at time t can be defined as the accumulated welfare of all buyers obtained from seller k.

The average net utility is settled at a certain value after it reaches a maximum value. This value equals what we got from the individual net utility of the selected sellers. This result shows that the evolutionary game converges only when the individual net utility equals the average net utility of all the sellers.

The convergence process of the mismatch between the individual net utility and the average net utility is shown in figure 17. This dynamic process of the average and net utilities clearly shows that the residential users can obtain better welfare by executing algorithm 1.

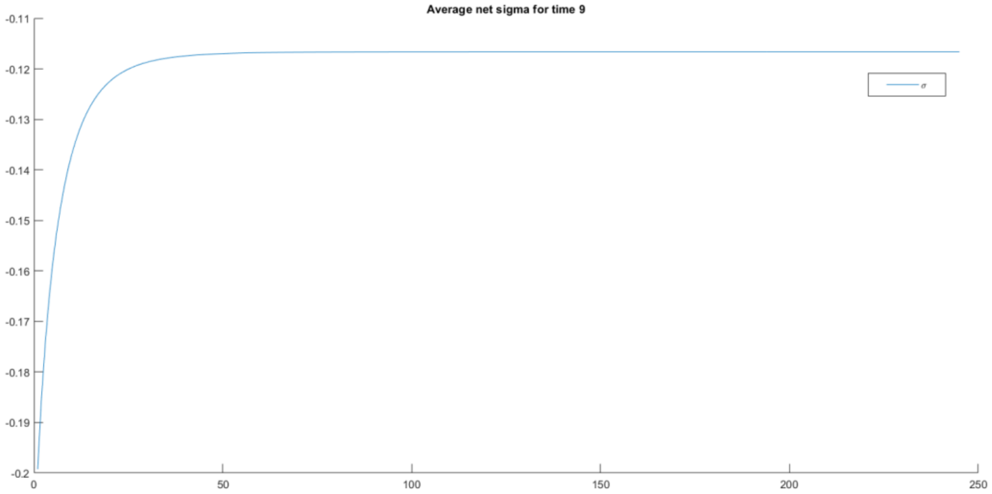


Figure 16: Convergence of average net-utility at t=9

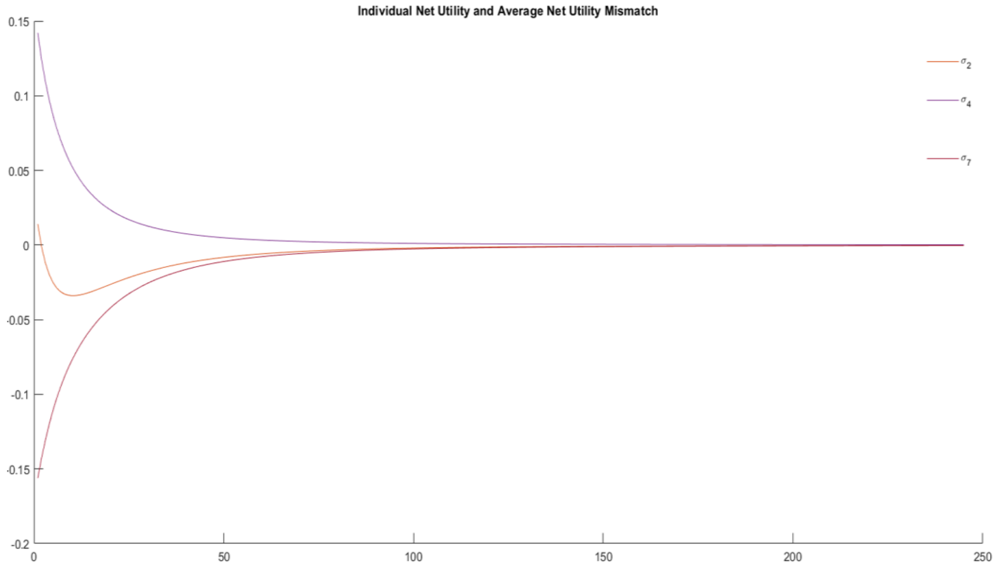


Figure 17: Convergence of mismatch between individual net utility and average net utility at t=9

C. Convergence of the formulated Stackelberg Game – Non-Cooperative Game

We proposed the Stackelberg, and the non-cooperative games defined in algorithm 2 of the previous section for two reasons:

1) To perform price competition among the sellers using the non-cooperative game.
2) To carry out the negotiation between the buyers and the sellers using the Stackelberg game.

Since the sellers are the leaders of the game, the solution (NE) of the Stackelberg game is an optimal response for the price announced by the sellers.

The price convergence characteristics of sellers to the Nash equilibrium are shown in figure 18.

To evaluate the performance of algorithm 2, an investigation of the competition among the sellers to reach convergence in the non-cooperative game is essential. Figure 20 shows the convergence process of the sellers in terms of their power price. The power price converges to a value only after the convergence of the algorithm.

The total power demand from buyers to sellers converges to a certain value as the price of sellers approaches NE, thus ensuring the existence of the Stackelberg equilibrium in the trading process as depicted in figure 18.

According to figure 19, the convergence characteristics of the supply to demand ratio show that power demand and supply after several iterations approach balance as required for the game convergence.

Figure 21 shows the welfare of the sellers that will gradually change and then converge. At the beginning of the process, the sellers collect information about the buyers and realize that the generation is much lower than the demand. Then, they adjust the amount of generation and power price to reach a balance between supply and demand. Finally, Nash equilibrium is achieved, and the welfare functions of the sellers are maximized.

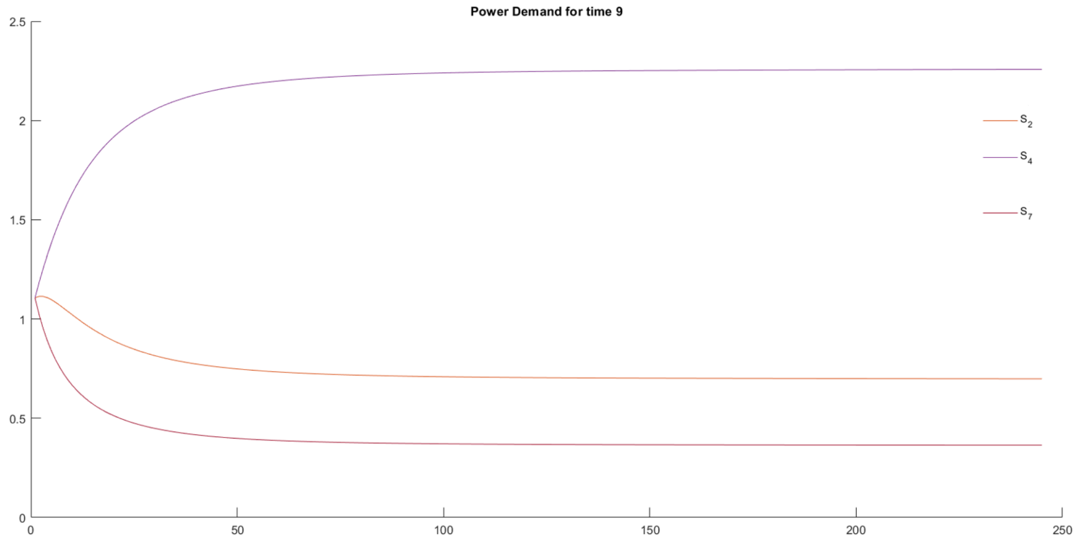


Figure 18: Power Demand of sellers at t=9

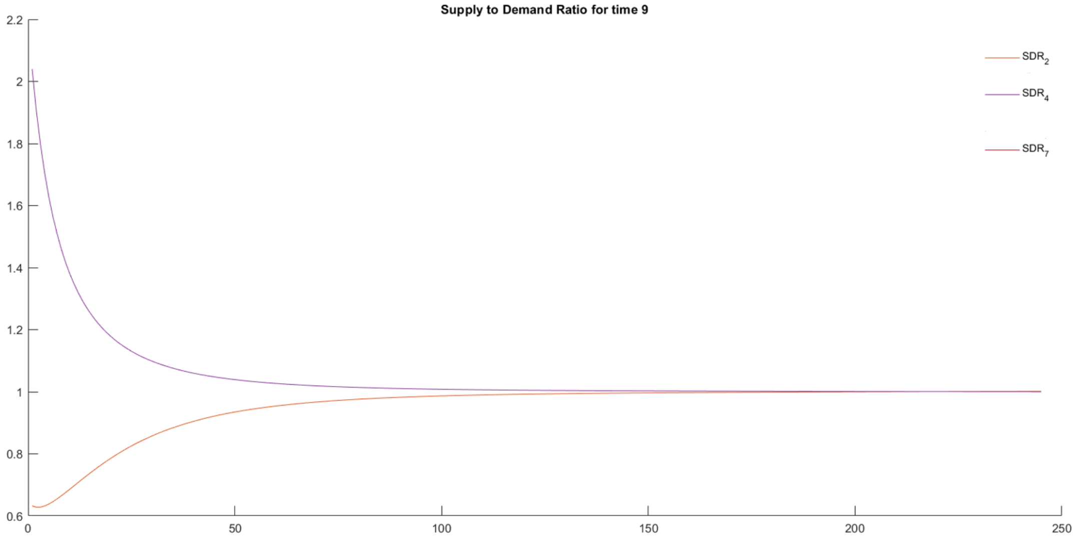


Figure 19: Convergence of supply to demand ratio at t=9

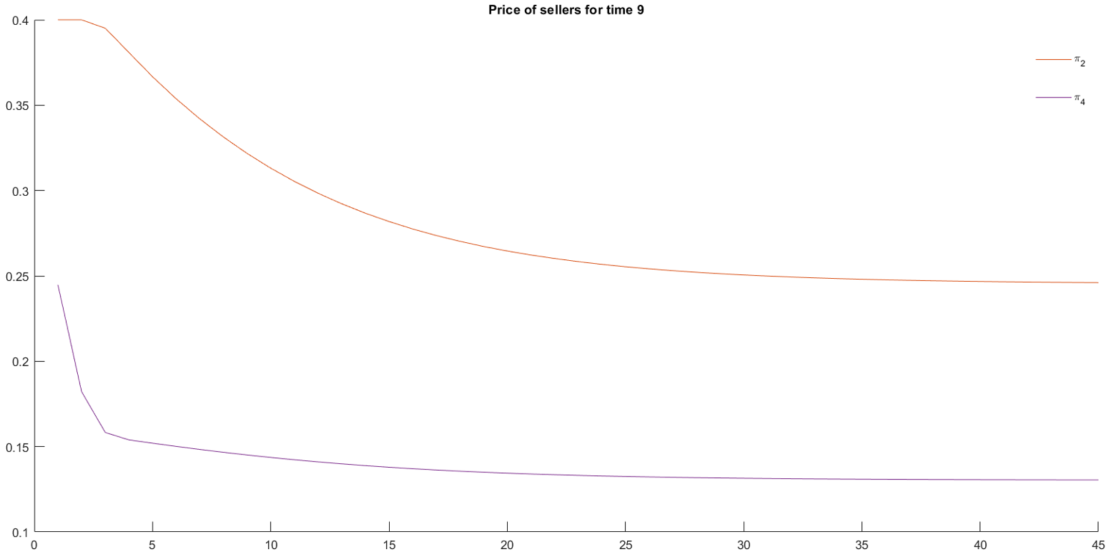


Figure 20: Convergence of seller’s price at time t=9

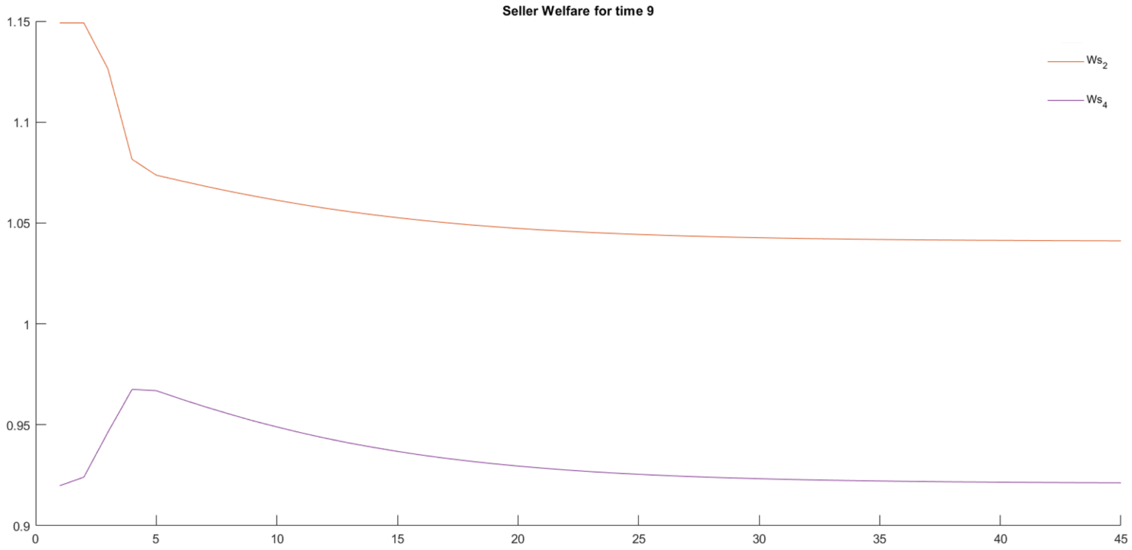


Figure 21: Convergence of welfare of sellers at t = 9

D. Trading simulation results

1. *Peer to Peer Trading*

The figures below show the trading results between the participating prosumers in the community. Each prosumer is configured as a buyer or seller at each time instant of the day according to his/her GDR. The sellers play the non-cooperative game, and the buyers play the evolutionary game. After convergence, results showing the trading process of each prosumer at each time instant of the day are shown in the figures below. Figure 22 shows the trading process of prosumer 1 throughout the day. As depicted, at the beginning and the end of the day the prosumer uses EDL to satisfy its demand since it's the only source present at these times with no other resource.

At time 6 the prosumer starts using the generator since EDL is off. In the middle of the day when the prosumer starts self-generating his own energy from the installed PV system, prosumer 1 starts consuming out from his own generation. For example, at time 11 prosumer 1 had to buy energy from EDL and from prosumers 2 and 4 which are sellers at that time instant to satisfy his own demand considering that the demand of the prosumer must be satisfied as shown in the black line of figure 22. At time t=13 prosumer 1 was able to satisfy his demand without the help of any prosumer or any alternative resource, where this depicts higher savings.

The purpose of showing the figures below is to demonstrate that prosumers in the proposed community can trade with one another and with alternative energy sources, and that P2P energy trading is a useful mechanism for such a business model.

As for prosumer 2 shown in figure 23, he’s able to satisfy his demand during the time between 9 till 16 without the need to buy energy from other prosumers in the community or from any other alternative resource.

The same goes for the other prosumers of the community in terms of energy exchanging process at each time instant of the selected day. The schemes of energy exchange between prosumers three, four and five is depicted in figures 24 to 26 respectively.

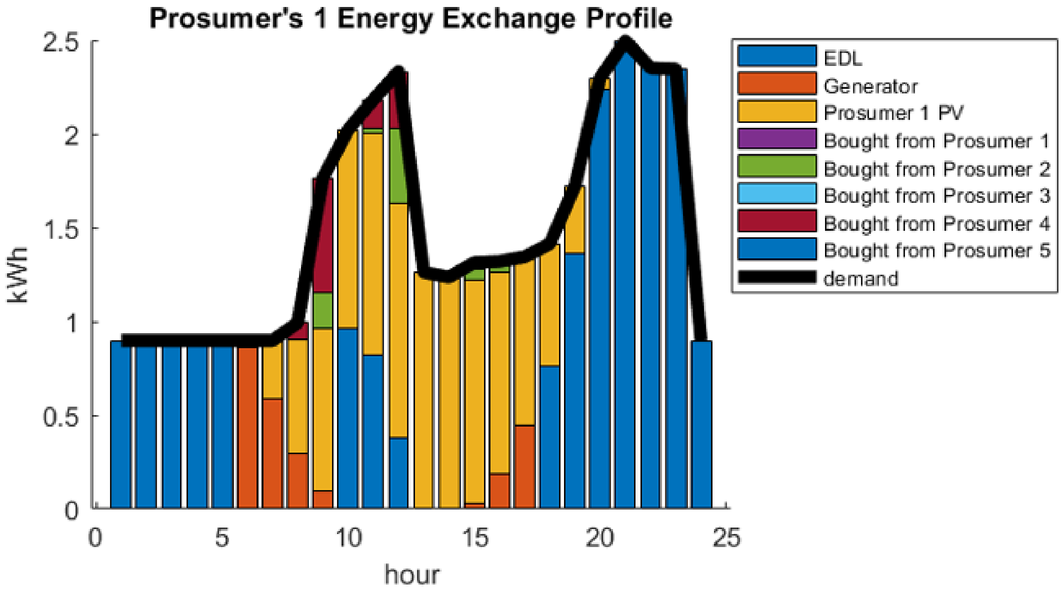


Figure 22: Prosumer 1 Exchanging Process

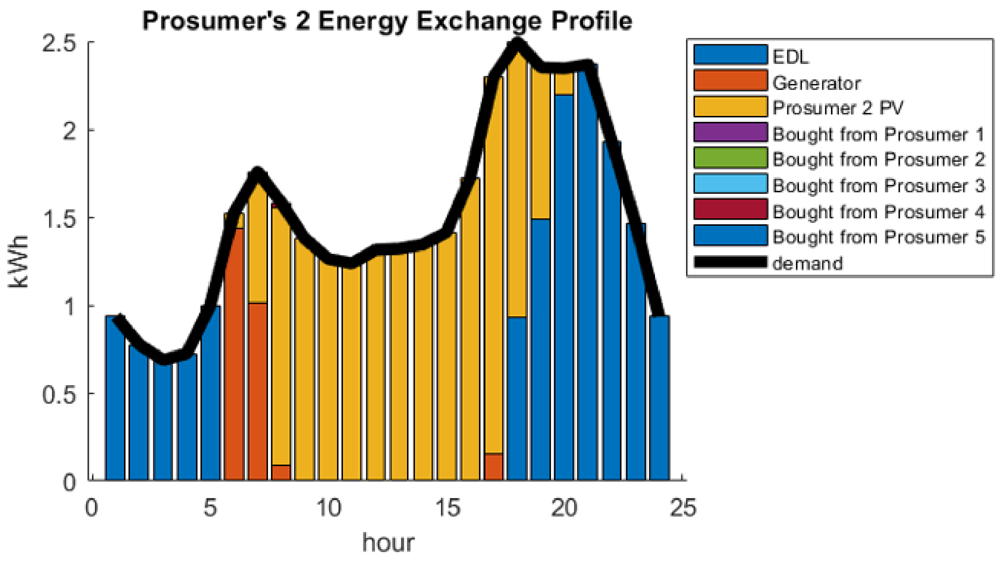


Figure 23: Prosumer 2 Exchanging Process

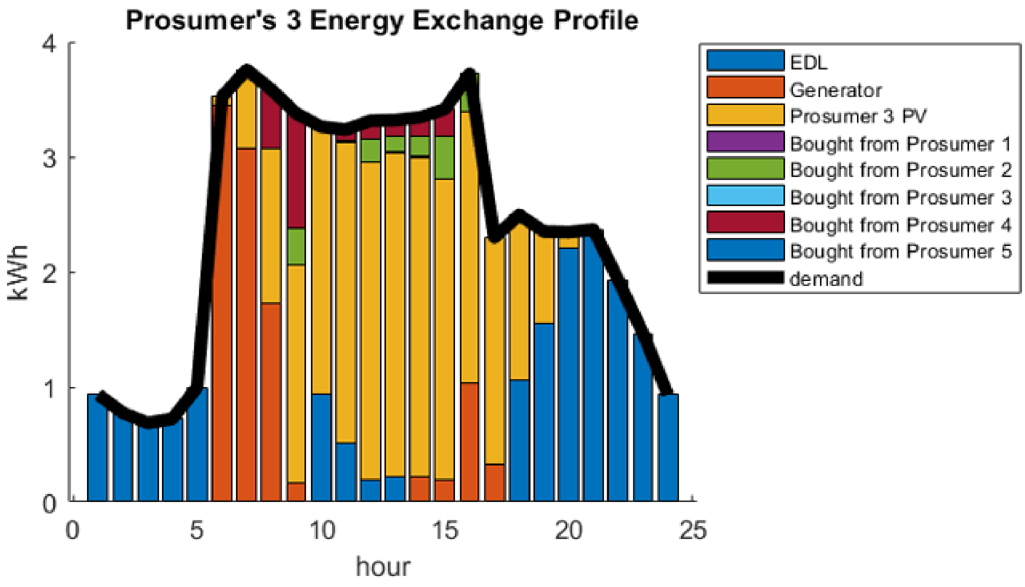


Figure 24: Prosumer 3 Exchanging Process

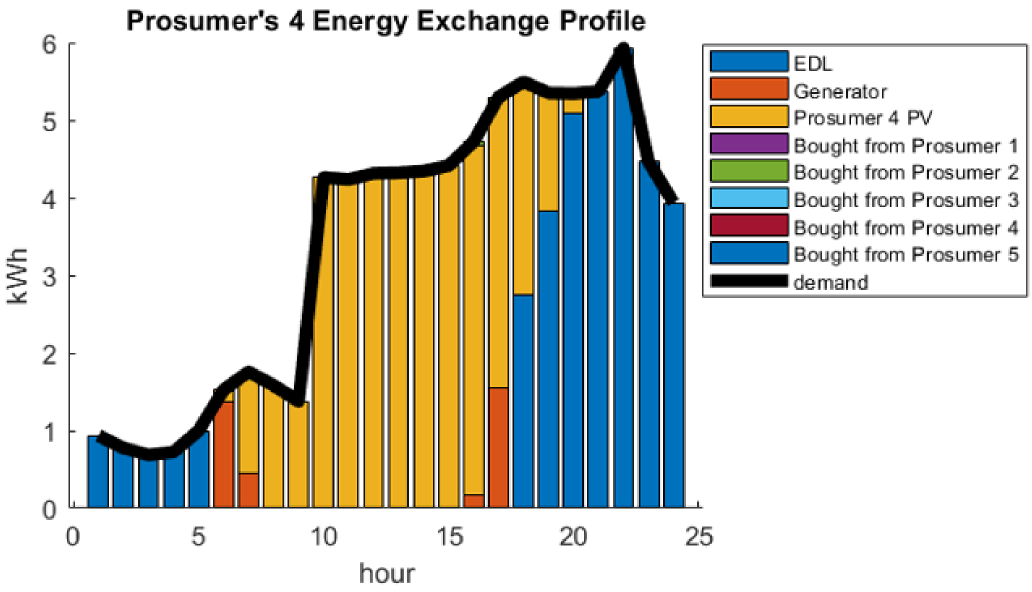


Figure 25: Prosumer 4 Exchanging Process

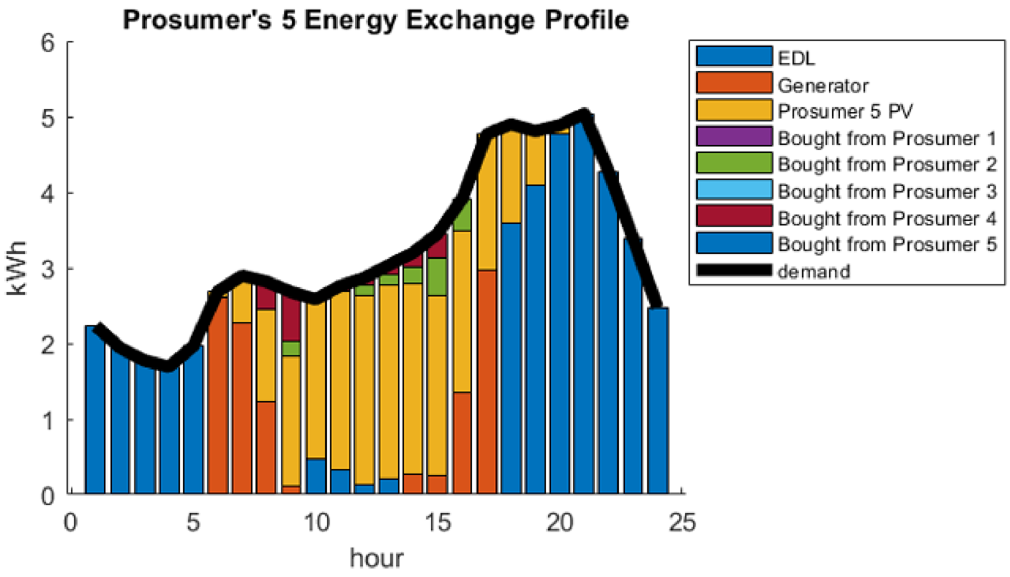


Figure 26: Prosumer 5 Exchanging Process

2. Prosumers Imported and Exported Energy from and to the Grid

As elaborated previously, the trading process occurs in a manner, when a certain prosumer has an excess of energy, he/she can then exchange this energy with other prosumers that have energy deficit at that time instant. However, when a prosumer at a certain time instant has an energy deficit and there are no prosumers with excess energy at that time, he/she must import from the utility company or from the diesel gensets available. When another prosumer has excess energy at another time instant and he/she also supplied all the needed energy and still has excess, he/she will then export this energy back to the utility company so that the prosumer can reduce his electricity bill and saves money in this scenario. Figure 27 shows the energy exported and imported to and from the grid at each time instant of the day. It shows that only prosumers 2 and 4 are exporting energy during the times between 10 and 15. The other prosumers are only importing energy or exporting to the community prosumers.

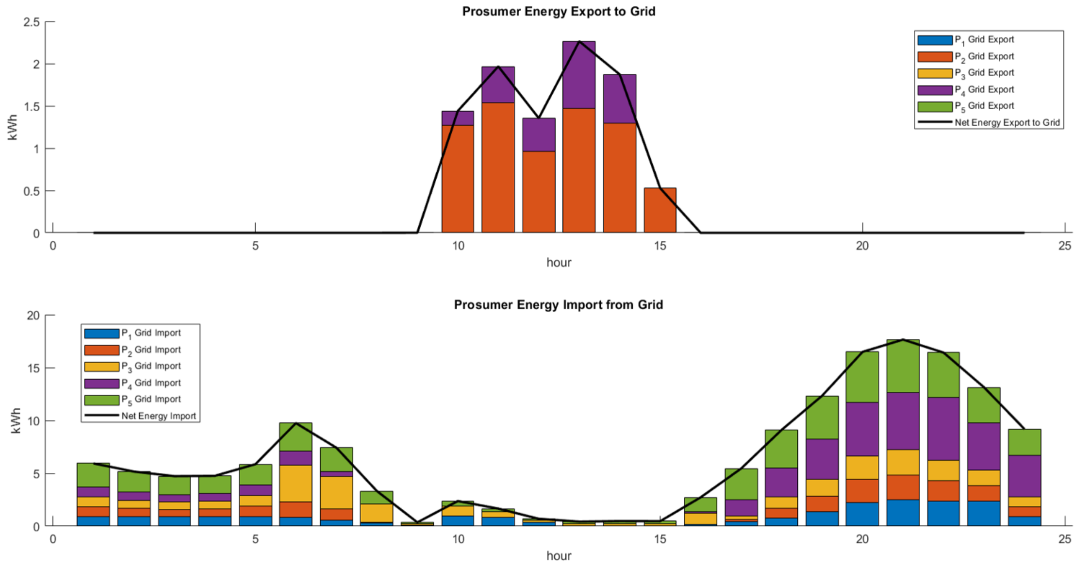


Figure 27: Energy exported to grid and imported from grid or diesel by each prosumer

3. Comparison with the Conventional System

In this section, we have analyzed and compared the results of the proposed P2P trading method with the conventional system highly depending on the alternative sources. As shown in figure 28 each graph shows the original system cost in comparison with the P2P system cost. For instance, prosumer 1 saves 1.44 dollars on a selected day on April 6 after participating in the P2P energy trading platform. However, prosumers 2, 3, 4, and 5 saved 2.69, 5.02, 7.83, and 4.36 dollars per day respectively.

The graphs in figure 28 show the importance of the proposed system in saving prosumer costs. Concerning the total costs between the original and the new system, it is shown that there is a difference of 21.34 dollars of cost per day. This is considered a significant amount and it financially shows the feasibility of the system.

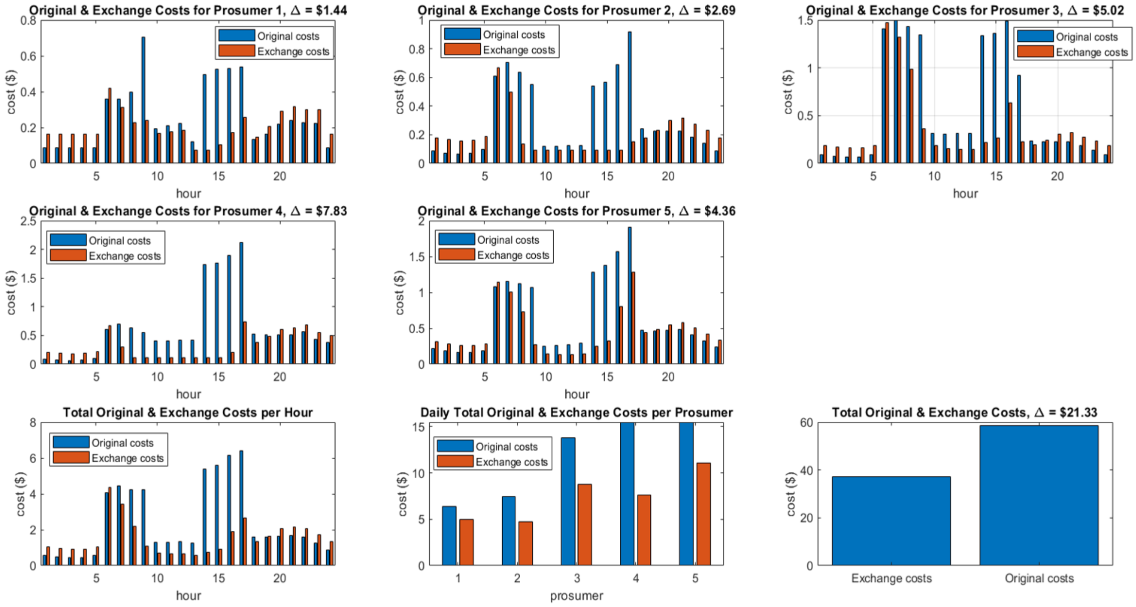


Figure 28: Comparison between original and new system for the five prosumers

CHAPTER VIII

CONCLUSION

This thesis presented a game-theoretical model for real-time P2P energy trading in a prosumer-based community microgrid. A prosumer in a P2P trading community is either a seller or a buyer. The interaction between sellers and buyers is modeled as a Stackelberg game, with sellers acting as leaders and buyers acting as followers. The buyer-seller selection competition is modeled as an evolutionary game, and an iterative algorithm is proposed to reach the game's stable state. Furthermore, seller price competition is modeled as a non-cooperative game. In a non-cooperative and Stackelberg game, a distributed iterative algorithm is used to reach the equilibrium states. The proposed method is used on a small community microgrid equipped with PV systems. The simulation results show that when using the proposed algorithms, each game converges to a stable state. The simulation results also show that the proposed model is capable of handling peer-to-peer energy trading in community microgrids. It also shows that peer-to-peer energy trading lowers the microgrid's overall cost. This study can be expanded further by considering the peer-to-peer network of several community microgrids and considering that groups of prosumers in an evolutionary game can play together increasing the number and the nature of the registered communities.

REFERENCES

[1] Hahnel, U. J. J., Herberz, M., Pena-Bello, A., Parra, D., & Brosch, T. (2019). Becoming prosumer: Revealing trading preferences and decision-making strategies in peer-to-peer energy communities. Energy Policy, 111098.

[2] Lüth A, Zepter J M, Crespo del Granado P, Egging R., Local electricity market designs for peer-to-peer trading: The role of battery flexibility, Applied Energy 229: 1233-1243, 2018.

[3] Zhang, C., Wu, J., Zhou, Y., Cheng, M., & Long, C. (2018). Peer-to-Peer energy trading in a Microgrid. Applied Energy, 220, 1–12.

[4] scihub.wikicn.top/10.1016/j.rser.2019.01.036

[5] Paudel, A. and Beng, G.H., 'A Hierarchical Peer-to-Peer Energy Trading in Community Microgrid Distribution
Systems', Proc. IEEE PES General Meeting, Portland, OR, USA, August 2018, pp. 1-5.

[6] Park, C., & Yong, T. (2017). Comparative review and discussion on P2P electricity trading. Energy Procedia, 128, 3–9.

[7] Long, C., Wu, J., Zhang, C., Thomas, L., Cheng, M., & Jenkins, N. (2017). Peer-to-peer energy trading in a community microgrid. 2017 IEEE Power & Energy Society General Meeting.

[8] Alam, M. R., St-Hilaire, M., & Kunz, T. (2019). Peer-to-peer energy trading among smart homes. Applied Energy, 238, 1434–1443.

[9] Awais, M., Javaid, N., Shaheen, N., Iqbal, Z., Rehman, G., Muhammad, K., and Ahmad, I. (2015, September). An efficient genetic algorithm-based demand-side management scheme for smart grid. In 2015 18th International Conference on Network-Based Information Systems (pp. 351-356). IEEE.

[10] Paudel, A., & Beng, G. H. (2018). A Hierarchical Peer-to-Peer Energy Trading in Community Microgrid Distribution Systems. 2018 IEEE Power & Energy Society General Meeting (PESGM).

[11] Zhang, C., Wu, J., Cheng, M., Zhou, Y., & Long, C. (2016). A Bidding System for Peer-to-Peer Energy Trading in a Grid-connected Microgrid. Energy Procedia, 103, 147–152.

[12] Luo, Y., Itaya, S., Nakamura, S., & Davis, P. (2014). Autonomous cooperative energy trading between prosumers for microgrid systems. 39th Annual IEEE Conference on Local Computer Networks Workshops.

[13] Nwulu, N. I., & Xia, X. (2017). Optimal dispatch for a microgrid incorporating renewables and demand response. Renewable Energy, 101, 16–28.

[14] Pouttu, A., Haapola, J., Ahokangas, P., Xu, Y., Kopsakangas-Savolainen, M., Porras, E., … Casado, S. (2017). P2P model for distributed energy trading, grid control, and ICT for local smart grids. 2017 European Conference on Networks and Communications (EuCNC).

[15] Logenthiran, T., Srinivasan, D., & Shun, T. Z. (2012). Demand Side Management in Smart Grid Using Heuristic Optimization. IEEE Transactions on Smart Grid, 3(3), 1244–1252.

[16] Xu, D., Zhou, B., Liu, N., Wu, Q., Voropai, N., Li, C., & Barakhtenko, E. (2020). Peer-to-Peer Multi-Energy and Communication Resource Trading for Interconnected Microgrids. IEEE Transactions on Industrial Informatics,11.

[17] Chen, T., & Bu, S. (2019). Realistic Peer-to-Peer Energy Trading Model for Microgrids using Deep Reinforcement Learning. 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe).

[18] Paudel, A., Chaudhari, K., Long, C., & Gooi, H. B. (2018). Peer-to-Peer Energy Trading in a Prosumer Based Community Microgrid: A Game-Theoretic Model. IEEE Transactions on Industrial Electronics, 1–1.

[19] Zhang, Z., Wang, H., Qin, Y., Gu, C., Chen, D., & Yin, K. (2019). An Optimization Strategy of Microgrid Energy Market Based on Scenario Method. 2019 IEEE 3rd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC).

[20] Meena, N. K., Yang, J., & Zacharis, E. (2019). Optimal Planning and Operational Management of Open-Market Community Microgrids. Energy Procedia, 159, 533–538.

[21] Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., Sorin, E., 2019. Peer-to-peer and community-based markets: a comprehensive review. Renew. Sustain. Energy Rev. 104, 367–378.

[22] Zion Market Research. Smart home market (smart kitchen, security and access control, lighting control, home healthcare, HVAC control, and others): global industry perspective, comprehensive analysis, and forecast, 2016-2022; 2017.

[23] A D, Yang Q, Yu W, Yang X, Fu X, Zhao W. Soda: strategy-proof online double auction scheme for multi microgrids bidding. IEEE Trans Syst, Man, Cybernet: Syst 2018;48(7):1177–90.

[24] Burgwinkel D. Blockchain technology. Berlin (Boston): De Gruyter; 2016

[25] Long, C., Wu, J., Zhou, Y., & Jenkins, N. (2018). Peer-to-peer energy sharing through a two-stage aggregated battery control in a community Microgrid. Applied Energy, 226, 261–276.

[26] 26 M. Ramli, H. Bouchekara, A. Alghamdi, “Optimal sizing of PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm,” Renewable Energy, vol. 121, pp. 400-411, June 2018.

[27] M. Hussien, I. Chung, “Optimal design and financial feasibility of a university campus microgrid considering renewable energy incentives,” Applied Energy, vol. 225, pp. 273-289, September 2018.

[28] Zhou, Y., Wu, J., Long, C., Cheng, M., & Zhang, C. (2017). Performance Evaluation of Peer-to-Peer Energy Sharing Models. Energy Procedia, 143, 817–822.

[29] F. Wei, Z. X. Jing, P. Z. Wu, and Q. H. Wu, "A Stackelberg game approach for multiple energies trading in integrated energy systems," Applied Energy, vol. 200, pp. 315-329, 2017/08/15/ 2017.

[30] S. F.M., "Heinrich von Stackelberg’s Marktform und Gleichgewicht," Journal of Economic Studies, vol. 23, no. 5/6, pp. 58-70, 1996.

[31] W. Tushar et al., "Energy Storage Sharing in Smart Grid: A Modified Auction Based Approach," IEEE Transactions on Smart Grid, vol. 7, no. 3, pp. 1462-1475, 2016.

[32] Z. Zhou et al., "Game-Theoretical Energy Management for Energy Internet with Big Data-Based Renewable Power Forecasting," IEEE Access, vol. 5, pp. 5731-5746, 2017.

[33] S. Maharjan, Q. Zhu, Y. Zhang, S. Gjessing, and T. Baar, “Demand response management in the smart grid in a large population regime,” IEEETrans. Smart Grid, vol. 7, no. 1, pp. 189–199, Jan. 2016.

[34] Y. Parag and B. K. Sovacool, "Electricity market design for the prosumer era, "Nature Energy, Perspective vol. 1, p. 16032, 03/21/online 2016.

[35] E. Sorin, L. Bobo, and P. Pinson, "Consensus-based Approach to Peer-to-Peer Electricity Markets with Product Differentiation," IEEE Transactions on Power Systems, pp. 1-1, 2018.

[36] Beitollahi H, Deconinck G. Peer-to-peer networks applied to the power grid. In: Proceedings of the international conference on risks and security of internet and systems (CRiSIS); 2007

[37] Parag Y, Sovacool BK. Electricity market design for the prosumer era. Nat Energy 2016; 1:16032. https://doi.org/10.1038/nenergy.2016.32.

[38] Mostyn T, Teytelboym A, McCulloch MD. Bilateral contract networks for peer-to-peer energy trading. IEEE Trans Smart Grid PP 2018;99. https://doi.org/10.1109/ TSG.2017.2786668. [1-1].

[39] Sorin E, Bobo LA, Pinson P. Consensus-based approach to peer-to-peer electricity markets with product differentiation; IEEE Trans on Power Syst PP 99, 2018. ⟨https://doi.org/10.1109/TPWRS.2018.2872880⟩, [1.1].

[40] Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C. Designing microgrid energy markets: a case study: the brooklyn microgrid. Appl Energy 2017;105:870–80. https://doi.org/10.1016/j.apenergy.2017.06.054

[41] Alvaro-Hermana R, Fraile-Ardanuy J, Zufiria PJ, Knapen L, Janssens D. Peer to peer energy trading with electric vehicles. IEEE Intell Transp Syst Mag 2016;8(3):33–44. https://doi.org/10.1109/MITS.2016.2573178.

[42] Mohsen Khorasany, market design for peer-to-peer energy trading in a distribution network with high penetration of distributed energy resources, School of Electrical Engineering and Computer Science Science and Engineering Faculty Queensland University of Technology,2019.