User-centric peer-to-peer energy system for residential microgrids

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USER-CENTRIC PEER-TO-PEER ENERGY SYSTEM FOR RESIDENTIAL MICROGRIDS

A thesis in fulfilment of the requirements for the degree of
Master of Philosophy

By

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Thesis/Dissertation Sheet

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The development of distributed energy resources (DERs) and the increasing affordability of residential solar power has meant that more and more families are now supplying their own domestic electricity with small-scale generating systems. This brings enormous opportunities and challenges to the energy market. The chance to develop new business models that give residential customers different options to deal with their excess generation, is one such opportunity. At this point, the choice made by most is to sell the residual energy back to the grid in return for payment of a feed-in-tariff by the network, even though the current level that tariff is only 1/4 or 1/3 of the cost of buying electricity from the grid. This means the potential benefit of installing a domestic solar system has not yet be fully realised and, in the absence of any financial motivation to install solar, it is likely to slow down the speed at which the market transforms to clean energy. It is therefore critical to find a way to maximise the financial efficiency of residential microgrids. A potential and promising solution is peer-to-peer (P2P) energy trading in a residential microgrid.

This thesis introduces, explains and compares three different structures for a peer-to-peer energy trading system. The main focus is on finding a solution that maximises both the financial incentive and social welfare. The thesis presented user centric peer to peer energy system and proposed modelling ways. In this model, potential P2P energy trading mechanisms are introduced and two innovative pricing strategies are evaluated. Based on end-user actual net-power demand, a case study is conducted to calculate, analyse and compare the impact of the P2P pricing strategies on a traditional electricity bill. To explore the effect of the two pricing strategies on the decision making of different customers, a P2P energy trading option based on prosumer profile is discussed.

In summary, the proposed methods have been successfully demonstrated and compared with existing works. Simulated results were able to verify the efficiency and superiority of the proposed mechanism over other approaches.

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Abstract

The development of distributed energy resources (DERs) and the increasing affordability of residential solar power has meant that more and more families are now supplying their own domestic electricity with small-scale generating systems. This brings enormous opportunities and challenges to the energy market. The chance to develop new business models that give residential customers different options to deal with their excess generation, is one such opportunity. At this point, the choice made by most is to sell the residual energy back to the grid in return for payment of a feed-in-tariff by the network, even though the current level that tariff is only 1/4 or 1/3 of the cost of buying electricity from the grid. This means the potential benefit of installing a domestic solar system has not yet be fully realised and, in the absence of any financial motivation to install solar, it is likely to slow down the speed at which the market transforms to clean energy. It is therefore critical to find a way to maximise the financial efficiency of residential microgrids. A potential and promising solution is peer-to-peer (P2P) energy trading in a residential microgrid.

This thesis introduces, explains and compares three different structures for a peer-to-peer energy trading system. The main focus is on finding a solution that maximises both the financial incentive and social welfare. The thesis presented user centric peer to peer energy system and proposed modelling ways. In this model, potential P2P energy trading mechanisms are introduced and two innovative pricing strategies are evaluated. Based on end-user actual net-power demand, a case study is conducted to calculate, analyse and compare the impact of the P2P pricing strategies on a traditional electricity bill. To explore the effect of the two pricing strategies on the decision making of different customers, a P2P energy trading option based on prosumer profile is discussed.

In summary, the proposed methods have been successfully demonstrated and compared with existing works. Simulated results were able to verify the efficiency and superiority of the proposed mechanism over other approaches.

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List of Publications

A complete list of publications during my Master project is provided below.

1. "User-Centric Peer-to-Peer Energy Trading Mechanisms for Residential Microgrids" *Proceedings of the 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*, Beijing, China, 20-22 Oct. 2018. DOI: 10.1109/EI2.2018.8582548

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Chapter 1 Introduction

1.1 Problem Statement

Driven by the fundamental challenges of energy shortage and climate change, the modern power grid is shifting from centralised generation to distributed generation, largely because of the increasing popularity of Distributed Energy Resources (DERs). For example, more than one in seven Australian households have installed solar panels, a penetration of more than 15%. Some green suburbs in Brisbane and Adelaide have recorded penetration levels as high as 50% [1][2]. The installed capacity of distributed renewable energy across Australia is expected to reach 165,500 MW by 2023 [3]. Considering this background, it has been recognised that energy management techniques are critical to improving the energy efficiency of the demand side as well as saving bills for end users.

In economic terms, electricity (electricity and energy) is a commodity that can be sold and traded. An electricity market is a system enabling: purchases, through bids to buy; sales, through offers to sell; and short-term trades, generally in the form of financial or obligation swaps. A traditional electricity market has two parts, wholesale and retail. Competing generators provide power output to the wholesale power market, from which retail companies purchase, re-price and market the electricity. The wholesale power transaction is conducted as a spot market for supply and the supply needs real-time matching of requirements through centralised coordination dispatch procedure. In Australia, end-users have to purchase their electricity from a retailer, though they can choose their own power supplier in a competitive market.

Distributed energy refers to a comprehensive energy utilisation system that is built near the user load centre, as opposed to centralised energy in which power is generated, co-generated or stored, remotely. Distributed energy resources (DER) have become a global trend. It is a term used to describe various forms of energy management systems and common examples include home solar power systems or residential wall-mounted gas heating systems. In Australia, solar power is the main DER option for residential customers.

The country's unique solar PV market has become really popular for several reasons: 1) most parts of Australia have a pleasant climate and abundant sunshine, ideal for a photovoltaic system; 2) most of Australia's homes are independent houses with a relatively large roof space, suitable for photovoltaic systems; 3) compared with many other countries, Australian households have to pay very high residential electricity rates on electricity bills. A Photovoltaic (PV) system is a very economical and effective way to reduce household electricity charges; 4) Australia's relatively high homeownership rate allows homeowners to benefit from investments in photovoltaic systems; 5) policy support from federal and state governments has traditionally focused on photovoltaic systems below 10 kW, including the solar credit multiplier, provided through the renewable energy target revised by the former Labour government in 2009-2012. At the same time, there were various state-based grid-connected tariffs, which were usually applied limitedly to small photovoltaic systems.

Australia has virtually the highest proportion of households with roof photovoltaic systems in the world (excluding small countries like Kiribati). Nearly 15% of Australian households have installed solar panels on their roofs, a number which may actually be a slight underestimation.

A feed-in-tariff is a credit customers can get that is applied to any unused electricity from their solar power system and sent back to the grid. It is usually a fixed rate per kilowatt-hour and is paid through the electricity bill.

Australian state governments used to fund power tariff schemes, but they have since closed them down for new customers. Retailers still offer some online tariffs, depending on the customer's location and size of their system. The rates vary by state: in Victoria it is 9.9 cents per KWh; in New South Wales 12.5 cents per KWh; in South Australia 15 cents per KWh; and in Queensland 16.1 cents per KWh.

In regards to the calculation of the electricity bill, the most popular method uses peak/off-peak/controlled load electricity rates. Excluding the daily supply charge, the average charge per KWh is 28.9 cents.

What is clear is that there is a big disparity between the feed-in tariff and the amount customers pay for electricity from the grid. Because of this, a more promising method and business model is needed to encourage end-users to participate in the renewable energy market.

1.2 Research Contributions

The research contributes to the electricity market in the following aspects. Firstly, it expands on the concept of peer-to-peer (P2P) energy trading, in which each peer (consumers, prosumers, generators—even suppliers) can choose a way in which to trade energy with the other peer, according to their own individual goals. These could include minimising costs, maximising social welfare, a certain volume of transactions, minimising pollution, etc. One of the advantages of this promising P2P electricity market is the opportunity for customers to express these preferences. They may prefer to purchase more green energy, such as power from offshore wind farms or local solar power etc. To provide a more efficient trading platform, prosumers need to form communities in which to trade at a larger scale.

In comparison to the traditional electricity market, peer-to-peer(P2P) energy trading would cut out the fees paid to 'middle-men', such as retailers, and turn this into a saving for the customer. In the future, as distributed energy resources increase in volume, the expectation is for P2P to become the major market and, although the traditional wholesaler and retailer market would still exist, they would merely supplement the P2P energy market. In this case, the value of P2P energy trading is clear.

The business model is key to peer-to-peer energy trading. It could help residents with renewable energy resources get more benefits and help end-users benefit from the development of renewable energy. The extent to which P2P trading reduces electricity bills would depend on the pricing methods that are adopted, and two different pricing methods are explored in this paper.

Finally, this paper includes a case study that applies different customer profiles to two pricing strategies to investigate the advantages and disadvantages of each. It also discusses which type of customers would prefer each pricing strategy, and why.

1.3 Thesis Outline

Chapter 2 reviews the literature on the development of the electricity market and details the various models used in different countries. The literature review also includes the perspectives of other researchers on P2P energy trading and the methods they are proposing.

Chapter 3 gives an overview of the architecture and a comparison of a user-centric energy trading system. A detailed modelling method is given and a method for calculating the electricity bill is proposed.

Chapter 4 explains the trade mechanism of the P2P energy market in detail. Pricing strategies for prosumers to get high social welfare are discussed and recommended. Two pricing strategies—unified and identified—are introduced.

Chapter 5 discusses the determination of P2P energy trading options based on the prosumer's profile. This includes a case study that applies two pricing strategies for a peer-to-peer trade mechanism, based on the real solar data of 15 prosumers, extracted from solar home electricity data sourced from Ausgrid. The two pricing strategies are compared, and a recommendation is given.

Chapter 6 outlines the conclusion drawn on how the peer-to-peer energy market can improve financial efficiency for both prosumers and the whole community.

Chapter 2 Literature Review

2.1 Power Energy Market History

For a long time, the energy market has been a centralised industry with a top-down approach in which power is transmitted and distributed from central plants to consumers, under strict government regulation. At the turn of the twenty-first century, the energy markets in Europe and Belgium changed dramatically, built on three important pillars: liberating the market; securing the supply of energy; and protecting the environment.

In the 20^{th} century, the Belgian energy market was featured that the energy market is monopolistic since most of the activities in the energy sector were manipulated by some small amount of people. Because of this, the European Commission was worried it was at odds with the drive towards innovation and efficiency. More importantly, it needed to make sure that electricity remained affordable for every consumer. Therefore, the EU passed a law to free up the energy market and this let to full liberalisation of the Flanders energy market in 2000 and the Brussels and Wallonia market in 2007.

In order to improve the operational efficiency and supply of power, in the early 1990s the United Kingdom privatised its electricity industry; separating transmission and distribution, and establishing competition in generation. It implemented price control and unified operation in transmission and distribution. The power system reform gradually began to open up the electricity market. In the mid-1990s, some countries in South America and Northern Europe, as well as Australia and some states in the United States, also carried out reforms which included the separation of power generation and transmission, the introduction of competition mechanisms in the power generation field, the opening of the national grid, and the establishment of an electricity market. The wave of power system reform aimed at breaking monopoly and implementing competition continues to expand.

In 1996, the European Union issued a mandatory guide to open natural gas and electricity markets, requiring its 15 member states to open the electricity market in phases within a prescribed time and scope. Taking into account that there had been a general decline in electricity prices in the EU after marketization, in 2003, after years of negotiations, the EU adopted guidelines to further open up the electricity and gas market. The guidelines required the opening of the electricity market to all business users by July 2004, the opening of the electricity market to all residential users by July 2007, and the separation of power distribution.

The 1996 Guidelines set forth the principle requirements for power reform in EU countries, mainly related to the degree and duration of electricity market opening (minimum progress requirements), the organisation of large-scale trading markets, the independence of grid operators, the calculation of network fees, and supervision, duties and so on. The decree only stipulated the overall framework for market opening and the specific open mode. The specific progress is stipulated by the countries to develop their own power opening laws in light of their national conditions. By 2003, the electricity market in the EU was around 80% open. The electricity markets in Germany, Sweden, Austria, Finland, the United Kingdom, Denmark and Spain were fully opened. The electricity market in Belgium was 80% open, and those of Italy, the Netherlands, Luxembourg and Ireland were more than 50% open—66%, 63%, 61% and 56% respectively. Portugal, France and Greece had the lowest openness, with 45%, 37% and 34% respectively.

2.2 Electricity Market and Metering Development

Figure 2.1 shows how power is delivered to a customer's home: including generation, transmission and distribution. The electricity generated by the power plant is delivered to the customer through the transmission and distribution lines. High-voltage transmission lines, such as those suspended between tall metal towers, carry electricity over long distances to where consumers need it. For long-distance transmission, high-voltage electricity is more efficient and less expensive. Low voltage power is safer to use in homes and businesses. Transformers in substations increase or reduce voltages as necessary to manage the different stages in the journey from power plants to homes and businesses.

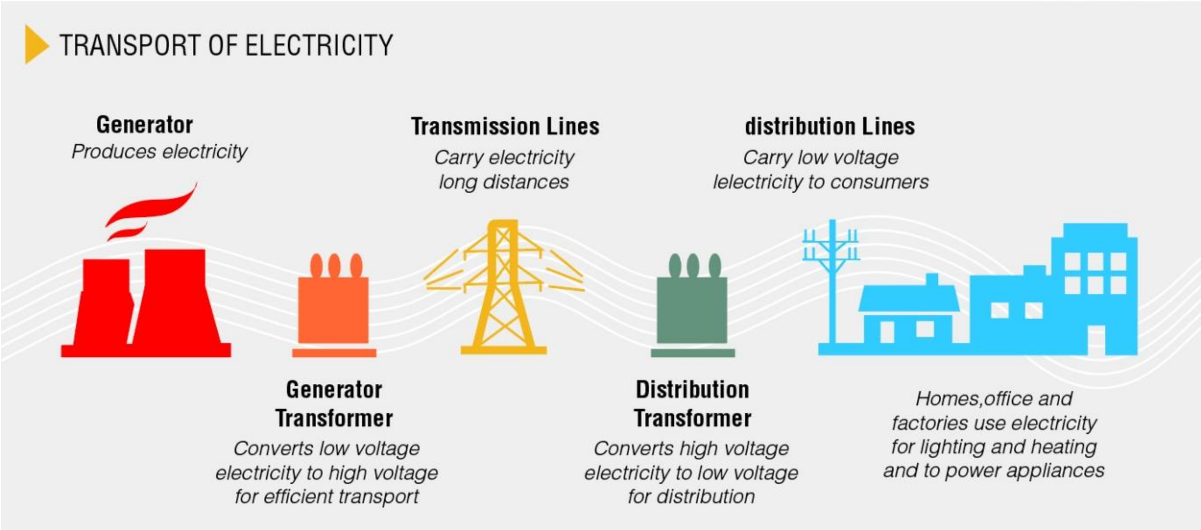

Figure 2.1 Power generating, transforming and distribution[1]

When the power is delivered to an end-user's home, power or electricity is regarded as a commodity that can be bought, sold and traded.

In terms of commodity, the establishment of market is indispensable. Electricity market therefore is essential for managing electricity and power. Generally speaking, the electricity market is in two parts: the retail electricity market and the wholesale electricity market and their relationship is shown below as Figure 2.2:

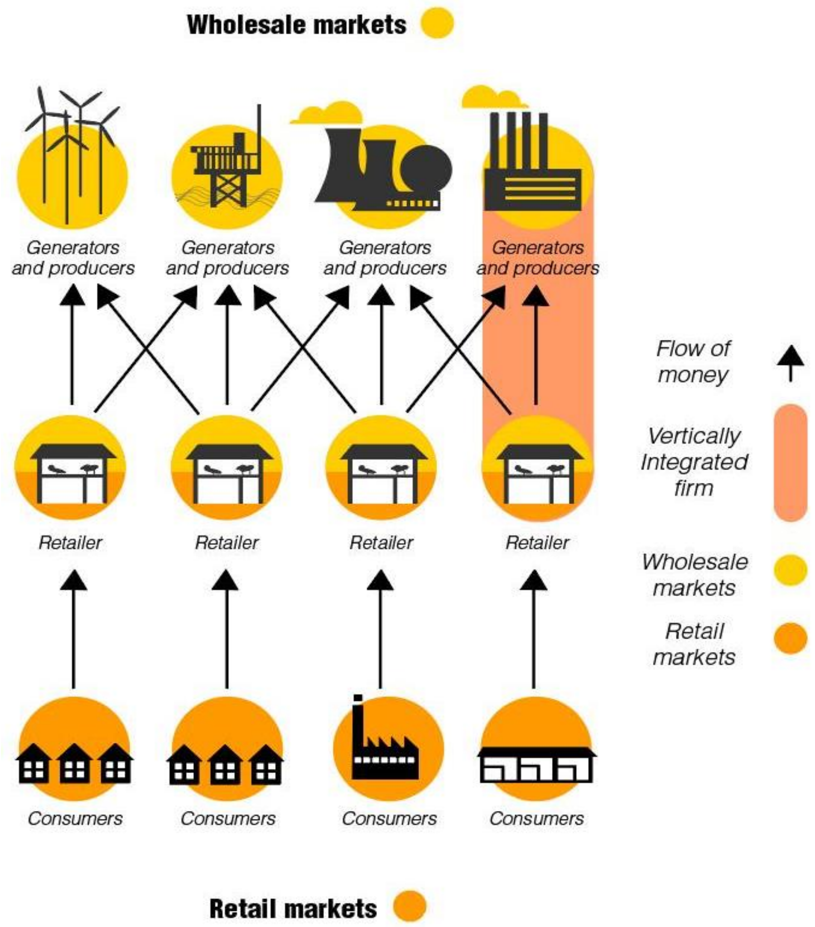

Figure 2.2 The relationship between wholesale electricity market and retail market[3]

The essence of the electricity market is to improve the economic efficiency of the entire power industry by establishing a power system operating environment full of competition and choice. These are two aspects of market mechanism interdependence. According to the different degrees of competition and choice, the electricity market model is divided into four types, which correspond to the phased goals of power industry reform, so this classification method is called the power market target model (referred to as the target model).

(1) Complete monopoly mode

Sometimes called a monopoly or monopoly model at all stages. It is monopolized in the fields of generation, transmission, distribution and power supply. Its basic feature is that the entire power industry is a vertically, highly integrated system; a model commonly used by power companies before the emergence of the electricity market. In small systems where economies of scale are still likely to be of benefit, there is a tendency to maintain the monopoly. It is also argued that in large systems consisting of standardised and centralised nuclear power projects, the economies of scale using the monopoly model outweigh the benefits of competition.

(2) Power market competing on the power generation side (buy mode)

This is the initial mode of introducing competition into the power industry. In this mode, the power system power plants are separated from the power grid and become independent legal entities. The power generation market has the only power purchase mechanism. Each power generation company competes with each other but does not allow electricity to be sold directly to end users through the transmission grid.

Its main features are: 1) the introduction of competition mechanism in the field of power generation allows the existence of power plants of various economic components and multiple forms of ownership; 2) the grid operation management organisation becomes the power grid operation centre; 3) distribution companies have two modes of operation: competition and franchise; 4) power trading between power grids through grid operations management agencies; 5) introducing the bidding mechanism and national macro-control.

It is generally believed to be a good model for developing countries, in the early stages of power industry reform or where the power system is too small and the competition is naturally restricted, the relevant regulations are still not perfect, and there is no experience in the operation of the electricity market.

(3) Wholesale competition mode

Also known as the wholesale market competition model or wholesale competition, transmission grid opening, and multiple buyer models. Main features: 1) the introduction of competition mechanism in the power generation field is reflected in the construction and operation of power plants and the electricity they generate can be directly sold to distribution companies (or large users; 2) the transmission network is open to users and provides transmission services; 3) the distribution company (or large user) has the option, but the distribution network is still not open; 4) both buyers and sellers share market risks; 5) regulation is more important. In short, at this stage, the market is more likely to allow generators and sales companies to achieve transactions through contracts.

The wholesale competition model is considered to be a transitional model. For developed countries with complex power systems, the wholesale competition model will be adopted before adopting the retail competition model, and will transition when the time is right.

(4) Retailer competition mode

Energy retail markets provide the interface between retailers and their customers. They allow energy retailers to sell electricity, gas and energy services to residential and business customers. Retail markets provide: 1) the framework for retailers to offer energy services to energy customers. 2) retail competition - allowing consumers to choose between competing retailers. 3) balancing and reconciliation services - for instance, managing the daily allocation of gas usage to retailers to enable the settlement of gas supply contracts. Competitive retail markets with appropriate consumer protections provide a basis for innovation, product choice and competitive pricing. The cost components of the electricity supply chain contribute to the overall price paid by residential consumers

In terms of the end-user, there are different ways to calculate an electricity bill, depending on what electricity plan and what metering are being used. For a single-rate meter, only a single price and daily supply charge is applied to calculate electricity bills. A two-rate meter is able to charge at two prices: peak and off-peak plus a daily supply charge. A time-of-use meter can charge at three prices: peak, off-peak and shoulder plus a daily supply charge.

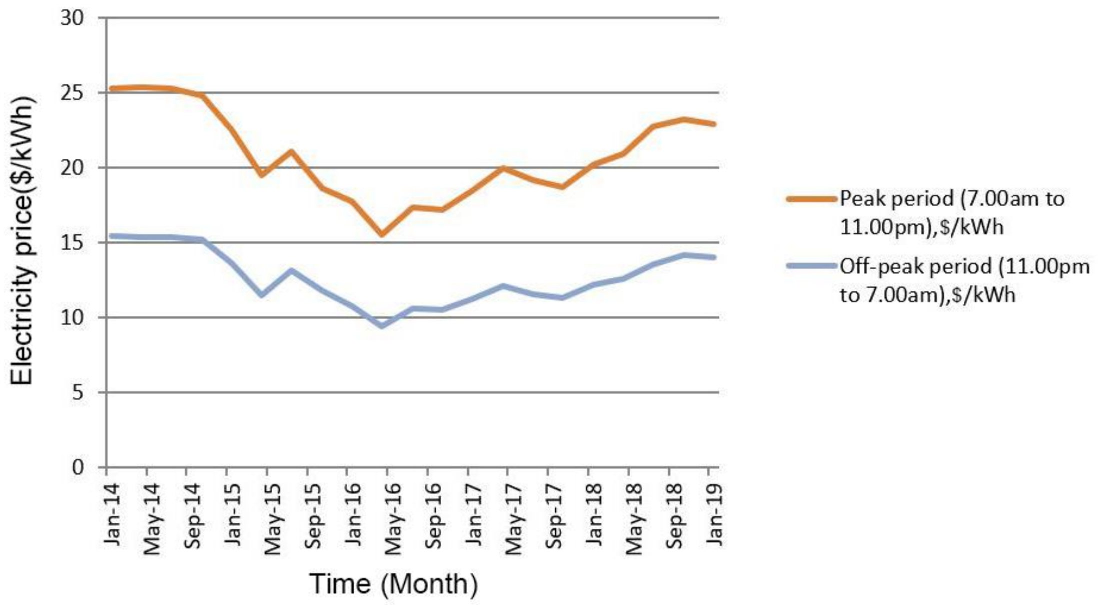

Figure 2.3 Historical domestic electricity tariff prices (2014-2019)

With the development of advanced metering technology, smart meters—a special type of electricity meter—have been created. In contrast to other meters, they can record how much electricity a house or business is using in 30-minute intervals. The smart meter sends the readings directly to the energy distributer electronically instead of needing a door-to-door reading. With the smart meter, in-home display units and web portals that monitor home usage can be delivered. A web portal allows the customer to see their usage across different periods and gives them the option to adjust the time at which they use certain appliances. When these meters are integrated with distributed energy resources, the meter is designed to be bi-directional. Not only can it monitor the customer's consumption, it can also record how much excess solar power is fed-back into the grid. This local generation is rewarded by way of a feed-in-tariff which represents the amount the energy provider pays for every KWh of excess solar energy that is fed-in to the grid. For example in table 2.1, the electricity bill of a customer with a solar system will list general usage, supply charge and provide a credit for feed-in tariff. The rate of feed-in-tariff differs from every energy provider.

Table 2.1 The form of electricity bill of one resident with AGL who has solar system at home

New charges and credits				
Usage and supply charges	**Units**	**Price**	**Amount**	
General Usage	$1443.222 KWh	$0.289	$417.09	
Supply charges	90 days	$0.84	$75.60	
Total charges				+$492.69
Credit				
Standard Feed-in-Tariff	1201.462KWh	$0.111	$133.36cr	
Total Credits				-$133.36cr
Total new charges and credits				=$359.33
Total GST				+$49.27
Total due(include GST)				=$408.60

Some of the customers make profits from solar rebates, including the feed-in tariff, while others with solar power systems still receive high electricity bills. This is because a customer who is working does not consume much power during the day when the solar system is generating a high volume of electricity. As a result all this excess energy is sold back to the grid at a low price. In contrast, the same customer's peak consumption usage is in the evening, when they have to purchase electricity from the grid at a high price, since renewable solar does not generate after sunset.

2.3 Peer-to-peer Energy Market History

Because of the big gap between the feed-in-tariff and the cost of electricity usage, peer-to-peer energy trading represents a promising solution to provide high financial efficiency for solar residential customers in the future. A peer in the P2P energy trading is one, or a local group of, energy customer(s) who can be prosumers and consumers. In recent years, this topic has been studied in both academia and industry. [4] reviewed some peer-to-peer energy trade trail projects worldwide that were in progress and listed the comparison between them. In [5], the concept and seven components for the efficient design and operation of microgrid energy market, were introduced. As a case study, Brooklyn microgrid, with a virtual community platform and physical microgrid, was discussed and evaluated. It was proposed that the feasibility of peer-to-peer energy trading was proven in technical stage in [6] by clustering the smart meter data. By analysing the historical demand data, local demand and generation balancing was achieved. Energy sharing inside a microgrid of P2P prosumers was proposed in [7] in which the internal price was formulated by supply and demand. Technically, a hybrid cyber-physical P2P energy-sharing framework for nano-grid clusters (NGC) was explained in [8]. Blockchain was recommended as a promising technique that can be applied for security and efficiency within an energy trade system; it was mentioned in [9] and [11] that blockchain will provide a reliable and feasible solution in terms of decentralised smart grid energy trading at a higher of privacy and security. A Stacklberg game approach was applied in energy sharing management and a billing mechanism was designed to deal with the uncertainty of PV energy and load consumption in [10]. Chao Long etc [12] proposed three representative market paradigms (bill sharing, mid-market and an auction-based pricing strategy) for Distributed Energy Resources among local customers and discussed the cost reduction, while flexible demand response in the community was not considered [84].

A P2P energy system will bring challenges as well as opportunities. An analysis on the strengths, weakness, opportunities, threats (SWOT analysis) of peer-to-peer energy trading is important and shown as below:

Table 2.2 SWOT analysis on P2P energy trading

Strengths	Weaknesses	Opportunities	Threats
1) Consumers got better choice of supply and supply production possibilities and can sell surplus energy 2) Empowerment, transparency and more open 3) Eliminate potential market strength of	1) Possibly too crowded and frequent transition 2) Hard to define energy prices of all energy sources 3) Lots of hardware & infrastructure requirements	1) Create new business models for market 2) Increasing consumer awareness and cooperation 3) Democratis ation of energy power resources	1) Energy poverty of some consumers 2) Consumer participation and involvement willingness 3) Technology needs to be developed (e.g. block chain)

some players in the wholesale market 4) Increase elasticity and reliability of the system	4) Need to collaborate with existing electricity market 5) Complex negotiation mechanisms	4) Promoting the retail market due to the lack of competitio n 5) Delaying grid investment from system operations	4) Data security and privacy 5) Possibility of market failure if whole structure not designed well 6) Potential grid operation mess 7) Legal obstacles and regulation which affect transactions

2.4 Chapter Summary

In the past few decades, in order to improve the operational efficiency and supply of power, the energy market has experienced transformation from monopolistic to liberalistic. A few countries reformed and implemented separation of power generation and transmission which brings the introduction of competition mechanisms in the power generation field, the opening of the national grid, and the establishment of an electricity market. According to the different degrees of competition and choice, the electricity market model is divided into four mode types: 1) Complete monopoly mode 2) Power market competing on the power generation side (buy mode) 3) Wholesale competition mode 4) Retailer competition mode. Due to advanced metering technology, richer consumption information and more service are provided in latest electricity market. Distributed energy generation allows people to generate their own electricity and sell energy they do not use back into the market, which makes customers more possibilities and brings the potential to peer-to-peer electricity market in the future. A peer who can be prosumers and consumers will be able to participate the energy trade with different peer. Some academic and industry studies have been started and the SWOT analysis has been done in specific to the peer-to-peer energy trading.

Chapter 3 User-Centric Peer-to-Peer Energy System

3.1 Overview of The Concept on Peer-to-peer(P2P)

The Emergence of the concept of a sharing and cooperative economy (including platform) are the driving factors of P2P infrastructure, which started from decentralised, commons-based production and the basic concepts of information distribution used in computer science [20]. This concept is defined as a decentralised system in which all agents (or peers) collaborate and negotiate what they can provide for production, distribution and then trade an asset (which can be commodities, tools or services, etc.) [21]. The P2P concept will allow peers to exchange facilities with each other, which is distinct from the centralised organisation used in traditional economic sectors. From the 19th century, some organisations adopted this P2P concept to distribute different sorts of data, e.g. video, documentation, information etc. Several different application domains have proved that can be achieved with the P2P method [22].

These days, with the technological development of small scale DERs, IoT and the energy market, end-users are more aware of their predicted and actual energy consumption. Though 20 years ago it was only a concept to assess the features of centralised versus decentralised market structure, these factors make the user-centric electricity market more realistic [23]. A user-centric electricity market needs the collaboration and communication of all the energy users in the community, which may let the customer choose or suggest which other customers to trade with in community. No one can promise a user- centric electricity market can be exactly the same as a P2P sharing market due to a lot of factors including carbon reduction, different size of DERs, etc.

A user-centric electricity market can be split into three different peer-to-peer structures: 1) full decentralised P2P market 2) community-based P2P electricity market 3) hybrid P2P electricity market.

In a peer-to-peer energy market, a peer can be defined as any consumption, production or storage unit. Generally speaking, it can be any end-users who are willing to participate in the market.

Figure 3.1 a) shows the structure of a full peer-to-peer market, which is defined as any unit (could be prosumer, producer, consumer) that can directly interact or make a trade with other unit without any intermediary (eg. retailers). More specifically, two units can make a transaction on a certain energy amount with the price they agree on, without the participation of any centralised entity. The advantage of this structure is that the end-user is free to decide their energy purchases or sales, while the drawback is that, without the supervision of a centralised department, the transaction could become disorderly, as end-users will only consider the maximisation of their own benefits. Thus, after comparison, the second structure of a community-based P2P market is more realistic and easier to operate. Figure 3.1 b) illustrates that, with a third-party entity (community management system), the user group is classified as different small communities. The community management system is in charge of managing and operating the transaction to make sure a better manner and order of energy trade can be achieved. A community management system can achieve different transactions because the third party entity could operate the whole community with a different goal (e.g. maximisation of social welfare, maximisation of carbon reduction, maximisation of benefits for producers). For this reason, a reasonable and economic trading mechanism is indispensable for community management so that they will achieve a good transaction that satisfies every participant. The hybrid P2P electricity market combines two structures and integrates different layers for trading energy.

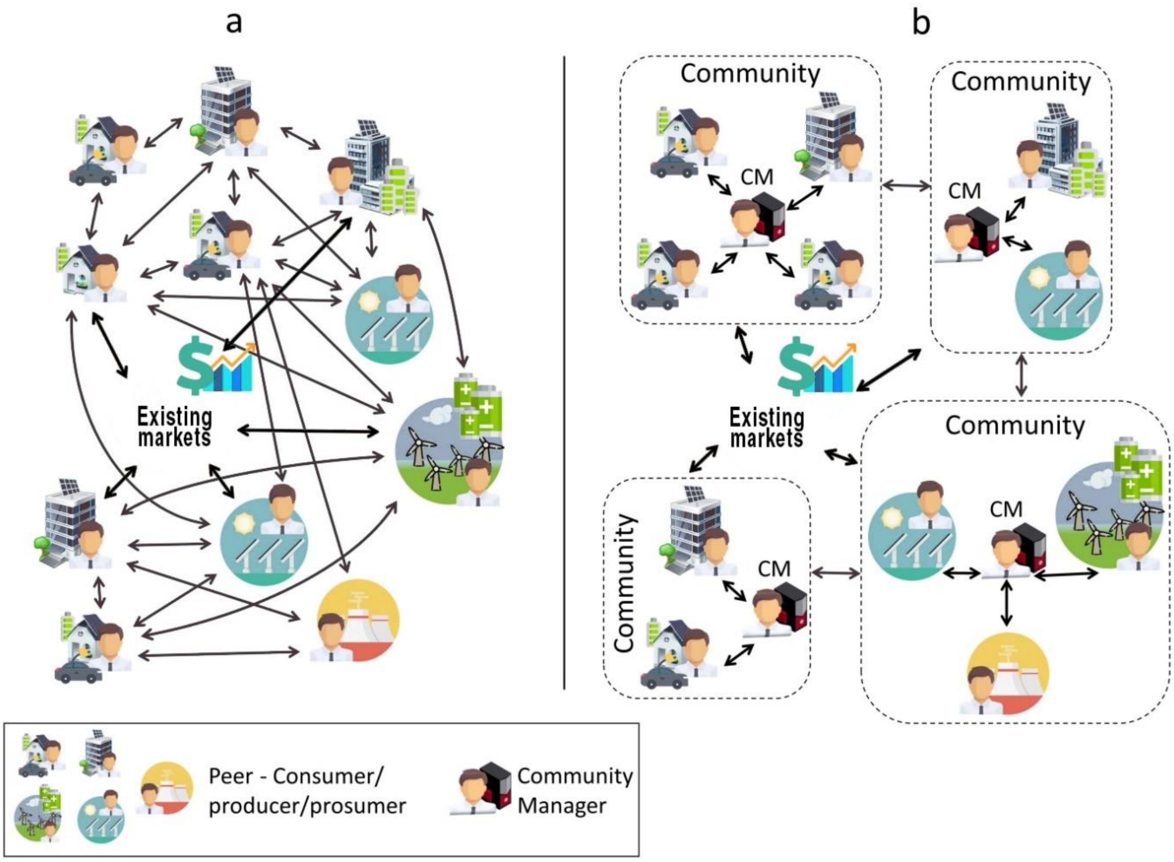

Figure 3.1 Peer-to-peer community a) full P2P market b) community-based P2P market[25]

Some practical application examples are applied to the operation of peer-to-peer energy trading which shares the local energy in the community. For example, the most famous project in this area is the Brooklyn Microgrid which applies the P2P idea to a practical test project. Although most of the countries have not completely opened the direct energy exchange and trade between end-users and small DER players, the innovation and development of peer-to-peer energy trading is a trend. The user-centric energy market's future depends on the advancement of regulation and legislation. More importantly, the deployment of a new peer-to-peer market needs to be compatible with the current electricity market to prevent conflict between the energy transaction and the existing market. Coupled with the technology of DERs, the user-centric energy market concept will provide a great opportunity to the electricity market and power management.

3.2 Premises and Technology Requirements for Peer-to-peer Energy Trading

3.2.1 Microgrids

The microgrid is a set of local power supply and sink (load), usually connected and synchronised with a traditional centralised grid (main grid), but that can be automatically disconnected and maintained according to physical and/or economic conditions. The US Department of Energy's standards define microgrids as follows: a microgrid is a set of interconnected load and distributed energy sources, which act as a single controllable entity relative to the grid within a clearly defined electrical boundary. The microgrid can be connected and disconnected with the power grid to enable it to operate in grid-connected or island mode. Note that there are no other DER technologies actually generated or involved. In fact, many microgrids will involve a combination of resources, sometimes very complex resources. There is no specific guidance for the size of the microgrid. On the contrary, the definition of microgrid mainly focuses on two characteristics: 1) a microgrid is a local control system and 2) a microgrid can be connected to either a traditional grid (megagrid) or as an electrical island.

These include microgrids which are completely on one site, similar to traditional utility customers—commonly referred to as customer microgrids or real microgrids—and microgrids that involve a part of traditional regulating grids. The development of microgrids bring obvious advantages to customers, such as increasing efficiency, reducing carbon pollution, improving the environment, raising the reliability of power supply, improving the flexibility of the grid, and providing an emergency solution. Another philosophical aspect is that local control systems are more likely to choose smart options, such as power supply technology and efficient investment. Microgrids will try to coordinate the assets and scale consistent with the existing current grid operation, thus reducing the costs of new investment when it comes to integrating decentralised resources. In a smart grid concept, a microgrid with a new structure of distribution network is proposed which combines a lot of small-scale DERs into a low-voltage distribution system. More specifically, a smart grid has the following advantages: 1) by using synchronisation, it improves the performance of traditional high-voltage power grids; 2） by using intelligent metering and real-time pricing, the grid-customer interaction is enhanced; 3) new distributed entities, such as microgrids and network, are created.

3.2.2 Grid operation

In general, when new peer-to-peer energy markets try to integrate into the electricity market there are still some concerns about the operation of the grid. The major one is that the new P2P market would work under existing power grid constraint conditions, on which the impact has not been completely assessed. If the P2P market is not well applied, there is also the threat of grid congestion. However, on the other hand, to apply P2P market provides some challenges and opportunities to improve the common existing grid infrastructures as well as services.

To achieve the P2P market design, the direct exchange and trade between different agents needs to be monitored and mapped on the grid. For instance, the grid tariff may need innovative regulation due to the mapping of peer-to-peer trade. The grid tariff is dependent on which strategy is applied, the distance from electrical transmission and the usage of the grid, and is relevant to every peer-to-peer transaction. These factors need to be considered in P2P energy trade as well. A full peer-to-peer energy trade market design that takes into account the price differentiation in order to help integration to influence the trade, is proposed in order to solve this. Baroche et al. [52] proposed a way with different factors to calculate the grid cost e.g., cable distance, location, etc. This cost-allocation policy preserves the transactions in an exogenous way to keep them lower than the line limit. In this way, agents are motivated to respect the grid operation instead of causing potential congestion. Baroche [53] proposed an endogenous method for integrating grid operations in a complete P2P market. The full peer-to-peer market design incorporates DC-OPF to satisfy the grid constraints. Recent breakthroughs in distributed optimisation with regard to operating in power grids [54,55] can also stimulate innovative work on power grids.

Future research in assessing the effect on power grid operation is required. In addition, grid constraint problems related to voltage regulation in P2P market should be considered in future work. New business models need to be considered for deployment in grid operations, in places where community or personal agents are involved in flexible services. Raising awareness could be another opportunity for mobilising customers' resilience and flexibility.

3.2.3 Bilateral contracts

With the deregulation of the energy sector, bilateral contracts can increase competition in the electricity market[56][57]. A bilateral contract is a consensus contract with an agreement in regard to energy trade within a certain period of time. Gui et al [58] analysed the impact on bilateral contracts affecting a microgrid community under the decentralised system. Their research showed that in the microgrid environment, service providers and customers establish a strong relationship to stimulate incentives and business models. Back in the 1990's, a coordinated, multilateral and bilateral trade model was proposed by Wu and Valaia [61][62] as a reliable alternative to the pool structure for wholesale electricity markets. The model was suitable for large enterprises operating in the market but not perfect for small-scale distributed energy resources, it did, however, lay the foundation for the P2P market. In the simplest form, an agreement between different agents on the P2P market means a multilateral bilateral, in which peers can exchange energy, resources, or services.

3.2.4 Smart contract and blockchain technology

Blockchain can be seen as a distributed network of agents in which each occupies a node that represents a resource, address etc. [59]. When it is on the blockchain, all activities need to be certified by different parties. This can eliminate the possibility of fraud and protect the security for all energy trade because all financial transactions occur using blockchain as well as a smart contract [60].

As a decentralised, distributed shared ledger, the blockchain realises chain storage through the one-to-one hash-value one-way connection of neighbouring blocks [68]. Each node of the blockchain has a copy of the complete book, and any node can view and proof the transaction data in real time. The advantage of distributed storage is not only the openness of the transaction to effectively maintain data security [69], but also the use of the server for purchasing and the cost of providing service. All distributed energy transaction data will be stored on the block body, and the hash algorithm automatically generates a Merkle tree that stores the hash value of the transaction data [70]. The blockchain structure containing the Merkle tree is shown in Figure 3.2.

It can be seen from the figure that if the transaction data has been maliciously tampered with, the corresponding Merkle tree root hash value will change [71]. The distributed energy transaction information utilises the Merkle tree storage of the blockchain, so that each transaction can be traced back, preventing problems such as "receiving accounts" and "false accounts" in the transaction process [72].

Using blockchain technology, the identity desensitisation process of each node in processing the distributed energy transaction, anonymous transaction and dataless cache feature, provide an important guarantee for the P2P transaction and two-way interaction. The decentralised verification transaction process is separate from the central rights system such as those of government agencies and banking organisations [73]. Therefore, a distributed energy transaction system based on the blockchain can realise the immediate settlement of benefits and immediate payment of subsidies, while P2P direct transactions are also greatly reduced intermediate fees required [74].

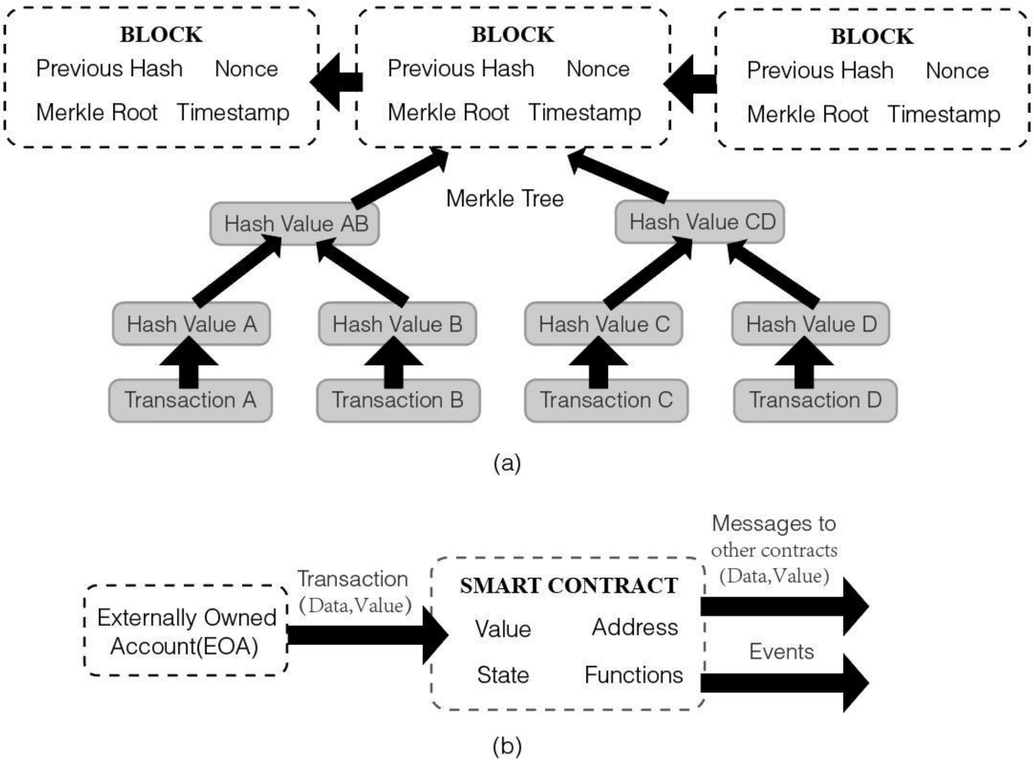

Figure 3.2 The structure of blockchain[68]

The smart contract was first introduced in 1994. After the concept was proposed it was buried, in the absence of a completely independent platform to execute the contract. The emergence of blockchain technology provides an ideal platform for smart contract operations, while blockchain-based smart contracts give new definitions of smart contracts, giving them the general characteristics of blockchain data, such as distributed records and storage, verification as well as preventing tampering, etc.

Traditional legal contracts define rules around agreements between multiple individuals or parties, while intelligent contracts go further and actually enforce these rules by controlling money or asset transfers under specific conditions. In the approach of a smart contract, the currency and asset are included and transferred into the program that runs the code. At some point or certain condition, it will trigger the completion of the trade, or transfer the asset to someone automatically, or return others. This feature of a smart contract would simply guarantee outcomes, eliminate confusion and remove any need for litigation. In a similar way to a traditional contract, a smart contract would become standardised. Much of it would not be the type of contract two parties negotiate from scratch. The standardised contract is expected to be a template of choice for the user. Smart contracts not only have the potential to perform automated processes, but also have the potential to limit behaviour. They will bring huge benefits too, closing the gap between events and auditor verification. More specifically, once you have a machine-executable smart contract that can be verified by a computer, the auditor can also observe at a level of 50,000 feet and review it almost in real time every minute, rather than every quarter or month. For each transaction, both internal and external real-time risk assessments and real-time audits would be conducted.

In general, blockchain-based smart contract construction and execution steps are shown in Figure 3.3. First, the two or more parties jointly develop an energy trading contract as needed. After that, the parties signing the contract agree on the content, the conditions of default, the liability for breach, the external verification data source and, if necessary, after checking and testing the contract code, spread through the P2P network to the entire network node and store; Finally, when the parties complete the task according to the agreed conditions, the smart contract stored in the blockchain is automatically executed.

At the same time, energy trading in the energy Internet involves a large number of energy entities, including a large number of smart devices with advanced sensors, so a smart contract client for energy trading is developed, and the client can embed any trading system and participate in transactions according to demand. Smart devices have a great impact on improving transaction efficiency, managing a large number of smart contracts and improving transaction automation. Both parties to the transaction establish a smart contract through the client and send it to the blockchain for storage and execution, while depositing a certain margin. The smart contract client periodically checks the contract execution status, traverses the status, transactions, and trigger conditions contained in each contract one-by-one, and pushes the conditions that satisfy to the queue to be verified, waiting for the node consensus. If the contract fails to perform, the defaulter will not be able to get back the deposit, making the cost of the transaction default much higher than the cost of executing the contract to achieve the purpose of mandatory trust.

In the energy trading process, after the participants reach a bilateral and multilateral transaction through the game, the platform automatically generates a smart contract, which writes the attributes of the trader, energy quota, price, trading time, default amount, etc., and finally uses the private key for multiple signatures. The guarantee contract cannot be tampered with. The smart contract generated by the transaction is defined by the code. The smart contract parties do not need to trust each other, nor do they need the supervision of the trust intermediary. They are completely automatic and unable to intervene, which reduces the extra cost of the transaction. At the same time, once the smart contract determines its funds, they are allocated according to the terms of the contract. Only when the pre-set conditions of the contract are met, can the funds be used. To ensure the security of its transactions, during the contract period and after the contract is concluded, neither party can control or misappropriate funds. Also, the smart contract stored in the blockchain is guaranteed by the entire network node and cannot be arbitrarily tampered with, its content can be changed only after obtaining the consent of all contract signing parties. The addition of smart contracts makes the transaction have the advantages of distributed trust autonomy, fairness and justice, lower cost, high efficiency, and no tampering.

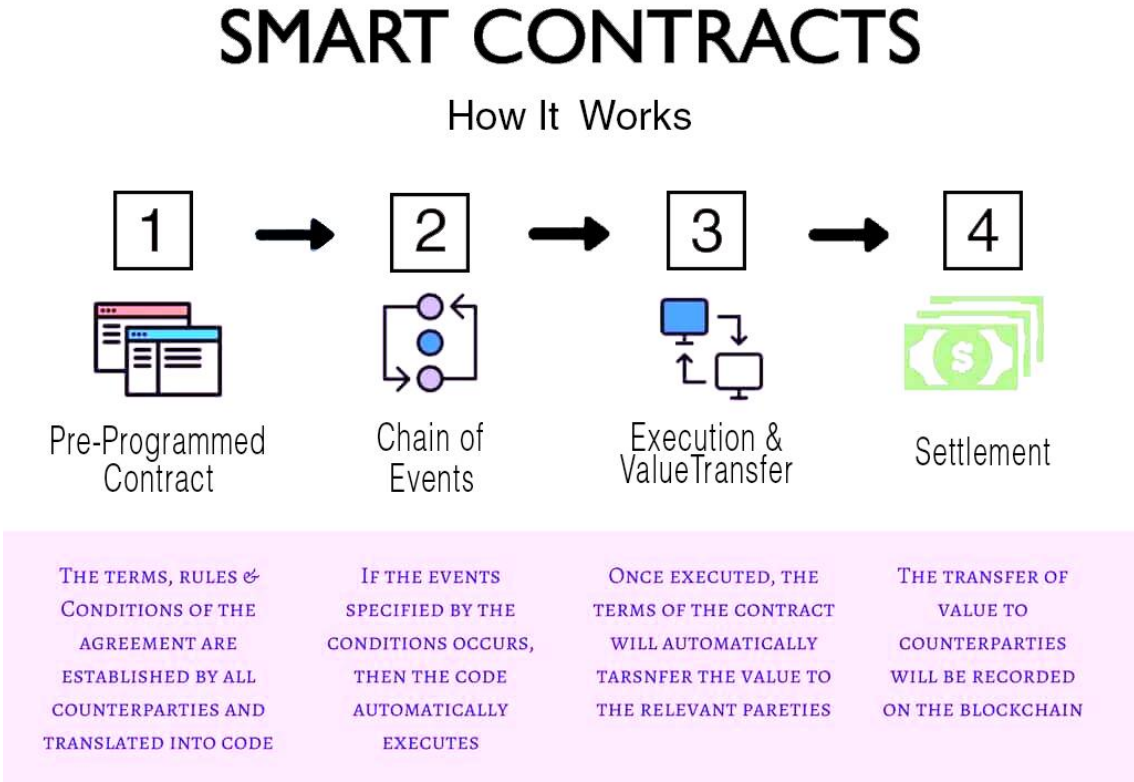

Figure 3.3 Smart contract working principal[35]

3.3 Research and Experimental Projects Regarding Peer-to-peer Energy Trading

Many experimental projects regarding peer-to-peer energy trading in recent years have been carried out to explore the potential of the P2P market. Two main subjects for the P2P research project to achieve are: 1）design the business model structure and market design for better financial efficiency; 2）apply control and communication with regards to ICT for the P2P market platform. These two aims are the most important for the P2P market research. One of the approaches for peer-to-peer energy markets is an applied transaction between small DER prosumer agents to achieve maximum financial efficiency. Several projects have been recently applied to demonstrate advanced ICT on the distribution grid.

Piclo is a UK platform designed for the purpose of peer-to-peer electricity trade. It is operated by "Open Utilit" and supported by "Good Energy" as its supplier. In regards to the profits, its main income is from government investment (DECC) and venture capital. Its major clients are commercial electricity users, including industrial factories, offices, etc. rather than individual customers. All the power supplied is renewable energy. The methodology is to match the consumer's preference and generate a price for the customer to choose. The data is based on information from Good Energy which provides the cost of power generation every 30 minutes, including information on customer preference. The smart contract, billing and customer service are all provided by Good Energy. Piclo is an online service which power suppliers and end-users can achieve transaction through the data assistance. [26]

Vandebron[27] is a website through which customers can buy electricity directly from the DER producers. The small DER producers are, in the most part, farmers who have their own wind turbines. The project is based in the Netherland where there are a lot of wind turbine farms. It was started in 2014 to great effect. Similar to traditional contract generation, customers can input their contract duration preference and the amount of power they need. From these options they can see from different producers which matches their generation. As an agent, Vandebron charges $12 a month as a subscription fee and no other transaction fee. In this case, the more transactions consumers can achieve, the more benefits they can get. Vandebron is beneficial to both consumers and wind turbine energy providers since they can reduce bills for users as well as increase the income for wind farmers.

SonnenCommunity[28] is a project operated by Sonnenbatterie. Sonnenbatterie is a German storage company that applies a storage system into peer-to-peer energy trading. The owners in SonnenCommunity can share their self-generated energy with other members in the community. With a photovoltaic solar system and battery storage system, the users can cover all their electricity bills. The surplus self-produced energy feeds into a virtual pool instead of feeding into the traditional grid. Similarly, the software in regards to monitoring users' supply and demand data is applied in this project. In this project, the major advantage is to emphasise the importance of a battery storage system in P2P energy trade to increase the efficiency of renewable energy use.

Yeloha is a project that lets clients who have a photovoltaic solar system rent their solar system to customers who do not have one. The project lets customers who cannot install solar panels have the opportunity to access renewable energy as well as save money on their electricity bills.

The providers of the photovoltaic systems are largely huge industrial sites. They can not only supply the electricity they need for their own industrial demand, they can also make some money from renting them to separate electricity consumers. According to the record, the electricity consumers in this project can save around 10% on their monthly electricity bills.[29]

Smart Watts was a project in Germany. Its idea was to use ICT to control consumption in a secure manner. These ICTs were tested and proved effective in the project, which explored the potential of security ICT in peer-to-peer energy trading.

PeerEnergyCloud[31] was a cloud-based technology project which aimed to deal with surplus local production from the community. It was developed to investigate and record historic patterns and forecast future electricity consumption. The virtual marketplace and added service in the local microgrid were a highlight.

Brooklyn recently launched a new project called Sandbox. Brooklyn Microgrid is a pilot project that applies the blockchain technology, Etherum, to reduce intervention in the transaction. The project proves that blockchain technology gets the best effect on the P2P trade both securely and effectively. It is a potential solution for future microgrids, especially on the peer to peer energy trade.[32]

Table 3.1 R&D projects

Project Name	Start Year	Country	Objectives	P2P Layers	Highlight
Piclo	2014	UK	Peer-to-peer energy trading platform from supplier	Business	Matching the preference of renewable energy and consumers
Vandebron	2014	Netherland	Peer-to-peer energy trading platform from supplier	Business	Establish the local clean energy community

SonnenCommunity	2015	Germany	Peer-to-peer energy trade with storage system	ICT, Energy network	Stable power supply with storage battery system
Yeloha	2015	USA	Solar sharing network for lower electricity bills	Business	Installation of solar panels by owner and rent to consumer
Smart Watts	2011	Germany	Optimizing energy via ICT	ICT, Energy Network	Smart meter access to Internet of energy
PeerEnergyCloud	2012	Germany	Cloud-based peer-to-peer trading platform	ICT	Cloud-based platform for smart home
Microgrid Sandbox	2017	USA	Reduce intervention by blockchain technology	ICT	Blockchain technology Etherum

Transactive Grid, a distributed photovoltaic power-selling blockchain platform jointly established by US energy company LO3 and Bitcoin-development company Consensus Systems, developed the world's first energy blockchain market [66], combining blockchain technology with a microgrid to give users the right to return excess photovoltaic power to the grid. The Energo project creates a system of decentralised autonomous energy community (DAE), establishes an automatic energy trading platform based on Qtum's quantum chain, and implements clean energy metering, registration, and management of microgrids with digital currency TSL, trading and settlement [67]. Although the Energo project was founded by local Chinese company Energolabs, the current energy industry in China is basically monopolized by giants, and the entire energy market is very saturated. Therefore, the layout of the company is focused on the Southeast Asian market.

3.4 Architecture and Design for Peer-to-peer Energy Market

The architecture design for peer-to-peer energy can be divided into two parts: power flow and cash flow. Power flow represents the physical electricity operation process, in which cash flows represent where customers buy electricity from. Fig.3.4 depicts the operational mechanism of the state of the traditional electricity retail market. End users purchase electricity from market retailers. For users who have small DERs (e.g. rooftop solar panel), they buy electricity from suppliers when renewable energy is insufficient. When there is sufficient renewable energy, users can sell the surplus energy to the grid and get paid by certain feed-in-tariff prices [84].

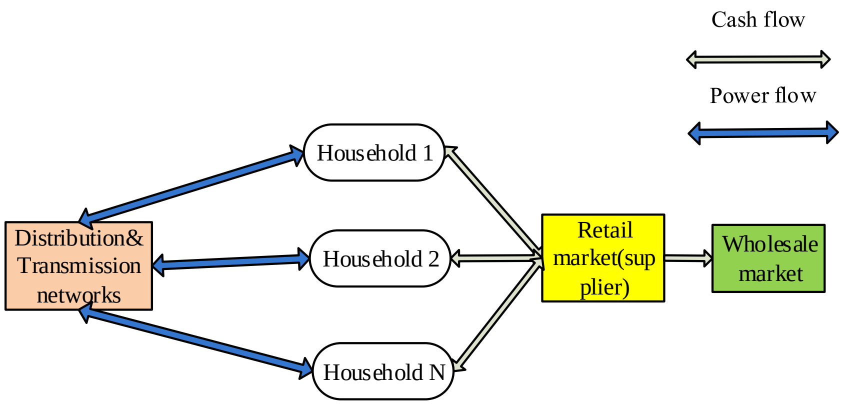

Figure 3.4 Traditional architecture of electricity market

Compared with the conventional electricity retail market, P2P energy trading in the community-scale provides a promising solution for enhancing energy sharing among small DER owners. Fig. 3.5 shows a conceptual architecture for P2P energy trading in a community. In this vision, end users can not only purchase electricity from retailers, but also have the option to trade their energy with their neighbours. The community energy management system takes the role of balancing local energy. In this study, P2P energy trading pricing mechanisms are developed based on the business model which decides the trade energy price and energy allocation, achieving the maximum social welfare for the community [84].

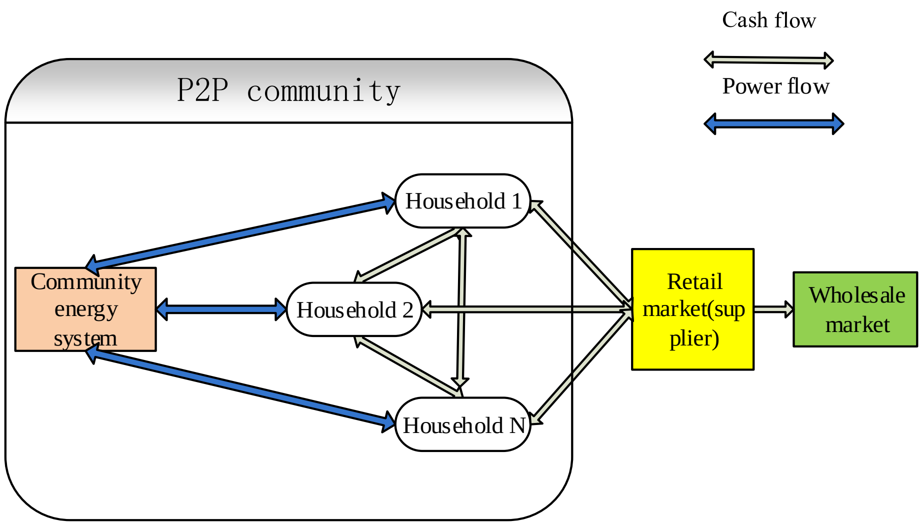

Figure 3.5 Peer-to-peer architecture of electricity market

3.4.1 Design and model of P2P electricity market

This part will list and introduce different market design models for peer-to-peer energy trade. The following section will focus on three major different peer-to-peer energy market designs: 1) full peer-to-peer energy market; 2) community-based peer-to-peer energy market; 3) hybrid peer-to-peer energy market.

Full peer-to-peer energy market

The idea of full peer-to-peer energy market is that any participants in P2P trade can directly communicate and trade energy with other participants without the intervention of any third party or agents. The full peer-to-peer energy market highlights that there cannot be any third party supervision in the trade process. Sorin et al.[33] introduced the idea of full P2P electricity market design between prosumers and consumers, which depends on multi-bilateral smart contracts. More details for this model are explained in [34] that product differentiation depends on the customer's preference. The existing pool market with this P2P market design was analysed to compare as well. Morstyn et al [35] stated a peer-to-peer electricity trade based on real-time and apply the strategy on the case study for prosumers.

In the Brooklyn Microgrid project, a microgrid energy market was introduced and the way it works will be presented in [5] It developed a local microgrid energy market between small agents who trade with each other locally. All these transactions were applied without the intervention of any central unit utility. Alvaro-Hermana et al [36] proposed the idea of peer-to-peer trade with electrical vehicles. It assumed each electrical vehicle as a prosumer so that it could trade its energy instead of charging from the central electricity pool. More specifically, it assumed that each electrical vehicle charged fully based on the wholesale electricity market price. With the car fully charged, each became a single prosumer unit and was able to trade electricity by negotiation without central agents. It was able to achieve the effect of electrical vehicles transacting with other participant EVs to share the energy, rather than buy electricity from wholesale market again. In [37], it gave the mathematical formula in regards to the P2P trading, it can be concluded as below:

$$\min_{D} \sum_{n \in \Omega} C_n \Big(\sum_{m \in w_n} P_{nm} \Big) \tag{3.1}$$

$$s.t. \underline{P_n} \le \sum_{m \in w_n} P_{nm} \le \overline{P_n} \qquad \forall n \in \Omega \tag{3.2}$$

$$P_{nm} + P_{mn} = 0 \qquad \forall (n,m) \in (\Omega, w_n) \tag{3.3}$$

$$P_{nm} \ge 0 \qquad \forall (n,m) \in (\Omega_p, w_n) \tag{3.4}$$

$$P_{nm} \le 0 \qquad \forall (n,m) \in (\Omega_c, w_n) \tag{3.5}$$

Where $D = (P_{nm} \in \mathbb{R})_{n \in \Omega, m \in w_n}$, Ω, Ω_p and Ω_c represents agent, producer and consumer respectively. Due to the relationship between them, we can conclude that $\Omega_p, \Omega_c \in \Omega$, $\Omega_p \cap \Omega_c \in \varnothing$, which P_{nm} represents the transaction between n and m, from which that production or selling use positive value and generation or purchasing using negative value. Figure 3.6 gives the conception illustration representing the mathematical formula. In this example, 1 and 4 are prosumers, 2 is producer and 3 is consumer. Full P2P means it is allowed to trade with any prosumer or customer while not having to do that all the time. The formula can be more generalized as they can be seen as prosumers which they are able to both produce and sell energy.

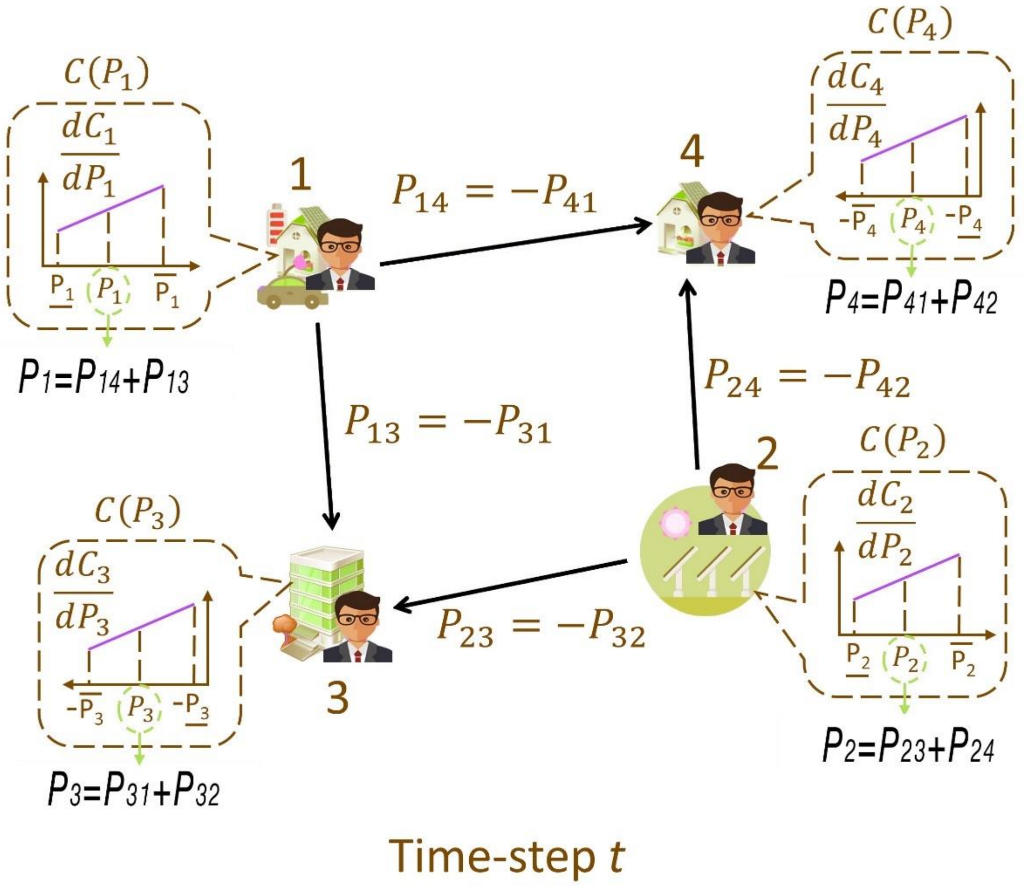

Figure 3.6: The example of a full peer-to-peer energy market[37]

Set w_n represents the units that include all agents that certain agent n can trade with. In terms of the consumers, they can trade with either producer or prosumer. In the same way, the producer can sell his energy either to consumers or prosumers. In the example of this figure, consumer 3 purchased the energy from prosumer 1 and producer 2. P_{nm} is a bilateral trade contract with an interaction effect. For instance, the potential trade between prosumer 3 and consumer 4 decides that P_{34} and P_{43} are the same value with different directions. In general, the negotiation process can differ each trade and transaction, which means every trade yield can be different.

The function C_n majorly depends on the cost of production and cost of bilateral trade. In literature e.g. [38] use a quadratic function to represent the cost of production and consumption, with parameters a_n , b_n and c_n . The [35] proposed the other approach to model the contract prices with the upper limit and lower limit. One model with combined parameter r_{nm} and trade amount P_{nm}

for agent w_n is introduced in [37]. The parameter represents the trade cost between agent n and agent m, which can be seen as the preference from local agent or green agent. The other approach to represent the preference is to set up the upstream and downstream, which introduced in [35]. The product differentiation in multi-bilateral trade regards tradeable energy as a heterogeneous commodity instead of a homogeneous commodity, which is a product in the pool with the uniform price.

In order to optimise this problem, a centralised manner is normally applied. While the concept of full peer-to-peer energy trading is to eliminate the factor of centralised manner, a decentralised approach is required for this issue. In [35][37], it was proposed that a coordinated manner be applied within each agent. The reciprocity constraints are likely to ensure the coordination. Decentralised optimisation techniques by decomposition are used in [35][37]. More specifically, Consensus Alternating Direction Method of Multipliers (ADMM), Lagrangian relaxation, etc. techniques were applied to achieve the optimisation effect on a decentralised solution. These ensured that each agent solved their own problem as well as protected their privacy. The aim was to promise every agent is willing share the energy and price on their own, while protecting their privacy on their utility curve, cost or preference. The solution was to iteratively work on the problem based on each agent's power and price, until the collaboration of consensus was achieved.

Community-based peer-to-peer energy market

In regards to the community-based peer-to-peer energy market, a community manager is required to coordinate electricity trading activities for the community members within the community, which is more suitable for microgrids. A group of customers can share the energy in the community as long as they have electrical appliances, electrical vehicles or small DERs. In the background of smart city, the building or some blocks of apartments can be seen as a community. In some situations, the users need to undertake the cost of investment on the DER utility and communication network. In other words, the community can constitute any member who is willing to share the energy and the utility cost. The community members cannot be in the same location although they have the aim of sharing energy with each other.

[39] pointed out that most of the research relevant to community was focused on the problem of methodology to solve the investment problem on DERs utility and raised the involvement of willing participants. Example recent works for market design were proposed in [7][40][41] which discussed simplifying the community-based market design. Since the project of EMPOWER, [42][43] gave the work a community-based market design which is for smart energy service provider(SESP). In the same way as the wholesale electricity market, the agent played the role of an aggregator who communicated the demand or surplus energy to a community. The SESP received more flexibility on power system services due to the regulation.

[44] introduced a trading mechanism in regard to sharing the power in the community which provides the service for electrical vehicles. The mechanism applied one third-party entity as an agent. Each car gave its best price and the agent decided the power between the different electrical vehicle members. Moret and Pinson [45] proposed one community-based power market in which different prosumers collaborated together to achieve the trade. Similarly, the community manager was set up to complete the trade and collect the information if there was a lack of, or excess energy from the trade. Morstyn and McCulloch [46] introduced one new multi-class energy management for peer-to-peer energy markets in the community. Three different classes of energy were formulated to represent the preference of prosumers. The utility function was established by the prosumer in the community and the preference defined on each class. An auction scheme was implemented by [47] for sharing energy in a local community. The participants were the agents with storage devices and the customers were willing to use the energy from storage devices as well. A third party was required as auctioneer to implement the auction between different groups.

There was more literature discussing the market design on community-based peer-to-peer market design than full peer-to-peer energy market. More work in regards to control and aggregator-based operation was discussed in [48][49], which required consumers to transfer to an active manner in a customer-centric energy market.

A general formula for community-based peer to peer energy market is written by [45] as below:

$$\min_{D} \sum_{n\in\Omega} C_n(p_n, q_n, \alpha_n, \beta_n) + G(q_{imp}, q_{\exp}) \tag{3.6}$$

$$s.t.\quad \mathrm{p}_n + q_n + \alpha_n - \beta_n = 0, \qquad \forall \mathrm{n} \in \Omega \tag{3.7}$$

$$\sum_{n\in\Omega} q_n = 0 \tag{3.8}$$

$$\sum_{n\in\Omega} a_n = q_{imp} \tag{3.9}$$

$$\sum_{n\in\Omega} \beta_n = q_{\exp} \tag{3.10}$$

$$\underline{P_n} \le P_n \le \overline{P_n} \tag{3.11}$$

where $D = (p_n, q_n, \alpha_n, \beta_n \in \mathbb{R})_{n\in\Omega}$, Ω is the set all agents within the community. To better understand the structure, the figure 3 is shown and 1 represents the prosumer, 2 represents the producer and 3 represents the consumer in this small community. Community manager is set up to control and operation and optimize the trade.

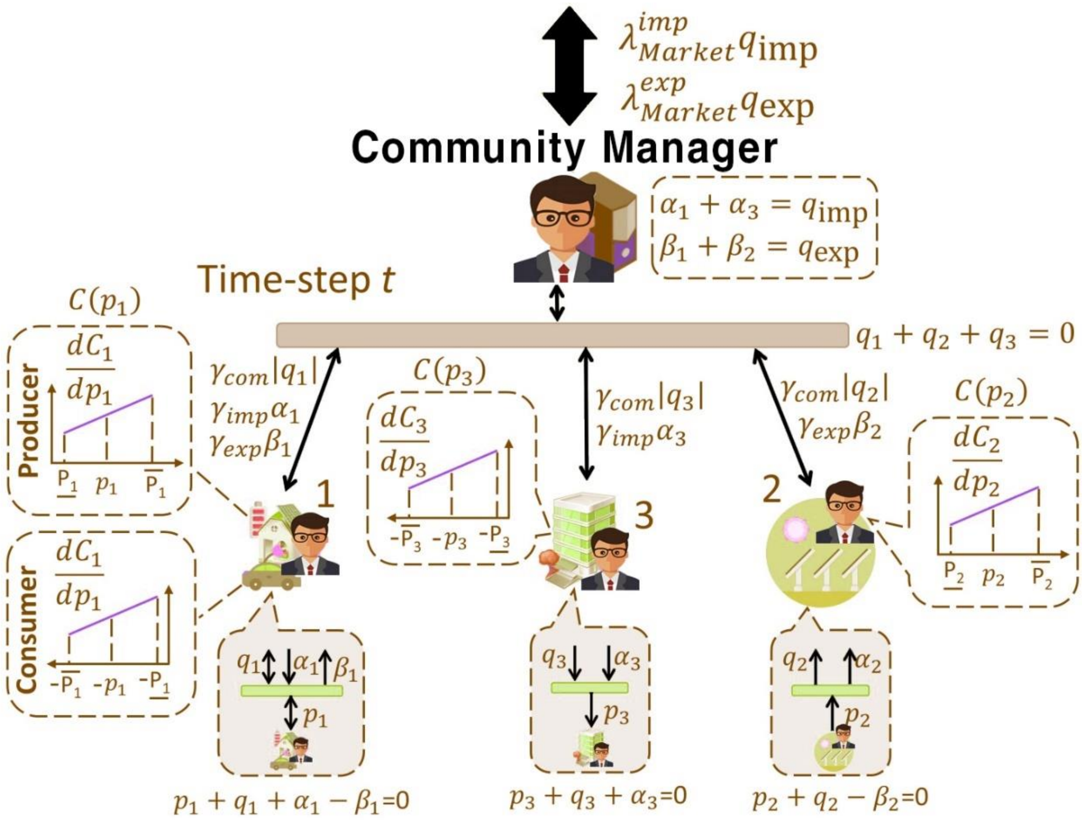

Figure 3.7: The example of a community-based peer-to-peer energy market[37]

p_n is the production or consumption for agent n, which can be selling energy or purchasing energy. The prosumers can either sell or purchase energy, just not at the same time. q_n represents that agent n completed the transaction in certain community. For instance in the graph, q_1 is bi-directional which means 1 is prosumer who sell and purchase both. q_3 is single directional which means consumer 3 is purchasing the energy from the community. However, due to the mechanism of community-based peer-to-peer energy market, none of them would know who or which member they are having trade with, which is operated by the community manager. The energy amount from different directions with trade in total requires to be zero that needs power balance, while it can output the grid if it is a grid-tied system. In a more general concept, the agents from the community can trade with other communities or the main grid if they have unbalanced power within the community. α_n represents the power input and β_n represents the export for agent n trade with outside community. The sum of import and export is the amount that community trades with other communities in regards to the power trading. q_{imp} and $q_{\exp}$ have the constraint which are the power constraints for agent n. λ_n means the price agent n is willing to pay.

A quadratic function is used as production or consumption cost for p_n. γ_{imp} and $\gamma_{\exp}$ are the coefficients that weigh the willing to the trade from the agent in the community. A function of $G(q_{imp}, q_{\exp})$ is modelled to describe energy transaction with outside agents (including main grid or other community). More specifically, it is more likely to have the link with the wholesale electricity market.

Hybrid peer-to-peer energy market

Hybrid peer-to-peer energy can easily be understood as the combination of full P2P market and community-based P2P market. A "Russian doll" approach is applied for this market design. As introduced and explained in [50], this approach highlights the scalability for peer-to-peer participants in the energy and electricity market. Figure 3.8 shows one hybrid P2P energy market design.

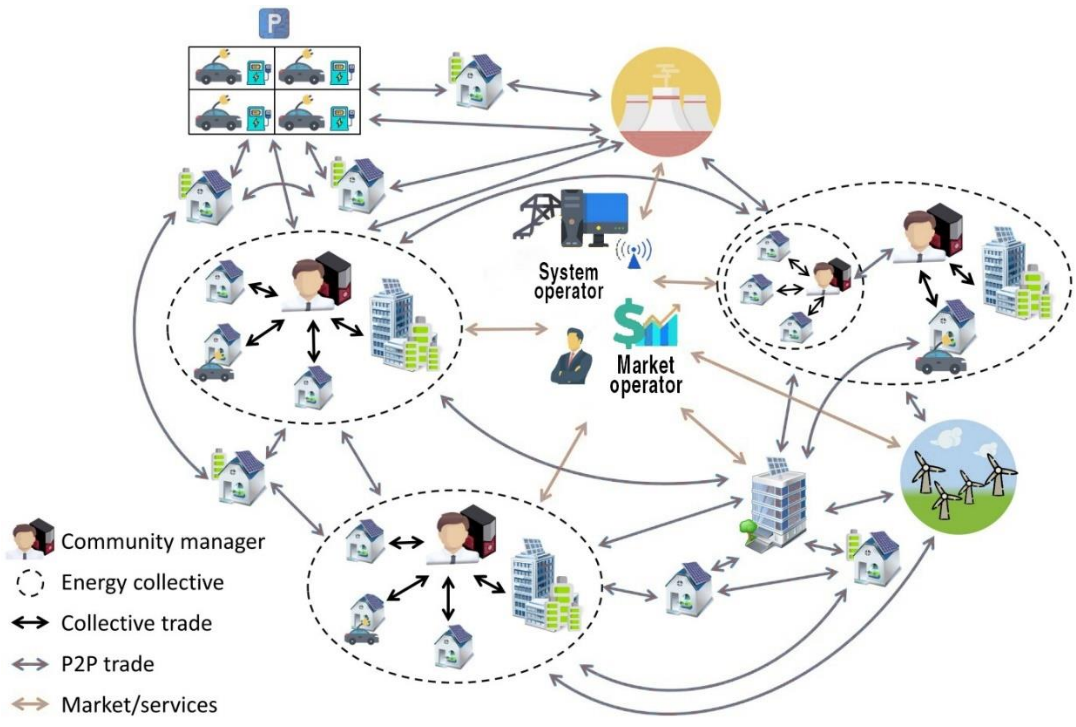

Figure 3.8 Hybrid peer-to-peer energy market[41]

At the top level, it is found that individual resources or energy collectives conduct P2P transactions between them and interact with existing markets. At the bottom, energy collectives behave similarly to the previously introduced community-based approach in which community managers supervise transactions within their communities. More specifically, energy collectives can nest with each other (for example, buildings and their inhabitants form energy collectives and become part of another energy collective of their neighbours). One nested approach proposed and explored by Long et al[6] discussed a hybrid design with three peer-to-peer levels. In the top level, the different grids were able to trade with each other. In the second level, power trade was executed between microgrids which had similar sized cells. At the bottom level, a community-based P2P cell comprised the microgrid. All the energy trade or transactions only happened at the same level.

A hybrid approach was introduced in [51] for microgrids. Each microgrid played the role of a community in which members traded. In this case, the costs for importing energy from the grid, power efficiency loss, operation fee, storage costs and energy trade within microgrids these problems need consider to be optimized.

It is believed that in the future, hybrid P2P market design will coexist with either full peer-to-peer energy market design or community-based market design. The design is believed to be compatible with the existing wholesale electricity market. Different level hybrid P2P market design requires the definition of splitting cells in each level accurately.

There is comparison between three peer-to-peer market designs shown as table 3.2

Table 3.2 Advantages VS challenges on different types of P2P energy market

P2P market design structure	Advantages	Challenges/Disadvantages
Full P2P market design	1) Complete “Democratization’ energy use 2) Consistency in energy use with agent preferences(e.g. costs, local etc) 3) Total freedom choice and autonomy, empowering active power consumer	1) Predicting system behaviour by the grid operator. Since lack of centralized control 2) Investment on infrastructure and maintenance on ICT network for all systems

		3) Guarantee safety an high quality on energy delivery 4) Potential slow convergence to reach a consensus in providing energy
Community-based P2P market design	1) Potential new services and operated by the community manager 2) Strengthen relations and participation community members due to sharing common interest (renewable energy) 3) Mobilizing society cooperation and resilience for community members	1) For community managers, data from all members is being aggregated and expectations is managed 2) Achieving preferences energy use for community members and available at all times 3) Fairness and impartiality on energy sharing within all community members
Hybrid P2P market design	1) More predictable grid operations 2) ICT infrastructure and the calculation can be extended to all systems 3) Most compatible system	1) Internal coordination trading in the community transaction with agents(e.g. community manager)

3.5 Prosumer in User-centric Residential Microgrid

A prosumer is a producer as well as a consumer in the energy market, playing the role of selling and buying energy. A residual microgrid is set up by many factors such as smart devices, bi-directional communication, software infrastructure, etc. However, besides the above factors mentioned, the most important factor to keep energy sharing sustainable is dynamic prosumer participation. For instance, if the prosumers in a residential microgrid suddenly disagree about sharing with each other or with the utility grid, the demand on customers may not be satisfied. In this case, the consistency of prosumer agreement should be complied with. [63][64][65] revealed that some of the research work that had been done on smart devices, software infraction and ICT communication application, while not enough work had been done on the investigation of prosumer management strategies in regards to sharing energy.

3.5.1 Modelling for prosumers

To describe prosumer in the residual microgrid, a mathematics equation needs to be set up to model the prosumers.

Prosumer refers to the energy entity that is able to generate and consume energy simultaneously. The power consumption profile of an arbitrary prosumer (denoted as i) in the community is expressed as [84]:

$$TP_i \triangleq [TP_i^1, TP_i^2, TP_i^3, ..., TP_i^H] \ \text{ i} \in [1, 2, ..., n] \tag{3.12}$$

where n is the amount of PV prosumers in the community; n is the total number of time intervals. The power generation profile of prosumer i is represented as:

$$P_i \triangleq [P_i^1, P_i^2, P_i^3, ..., P_i^H] \ \text{ i} \in [1, 2, ..., n] \tag{3.13}$$

The net-power consumption of the prosumers is the difference between consumption and generation:

$$NP_i^h = TP_i^h - P_i^h, h \in [1, 2, ..., H] \tag{3.14}$$

In regards to the cost model of prosumers, they are assumed to have a certain of shiftable load. Because of the price incentive, the power consumption can be deviated from its original TP_i value and form new adjusted power consumption as:

$$x_i \triangleq [x_i^1, x_i^2, x_i^3, ..., x_i^H] \ \text{ i} \in [1, 2, ..., n] \tag{3.15}$$

where x_i^H is adjusted power profile of prosumer i at time slot H.

As an important factor in the energy management of demand side, the customer’s willingness to shift load needs to be considered. Due to the response to the P2P price, the customer might change their usage pattern of appliances and the load would be shifted, which brings inconvenience. In respect to this factor, the value cost of inconvenience is defined as in [84]:

$$c_i = \alpha_i \sum_{h=1}^{H} (x_i^h - TP_i^h)^2 \tag{3.16}$$

where c_i is the equivalent inconvenience cost of prosumer i, α_i is the sensitivity coefficient of PV prosumer i, the larger α_i means the prosumer is more sensitive to the inconvenience caused by the shift loading. Combining the electricity or income and inconvenience cost, therefore, the optimal cost function can be denoted as:

$$\sum_{h=1}^{H} C_i^h (x_i^h) = c_{p2p} (x_i^h - P_i^h) + \alpha_i (x_i^h - TP_i^h)^2 \tag{3.17}$$

where cost function can be divided into two parts: $c_{p2p}(x_i^h - P_i^h)$ represents the cost for electricity use, and $\alpha_i (x_i^h - TP_i^h)^2$ represents the adjusting flexible power, considering both economic and user's willing factor [84].

3.5.2 Actual demand and consumption within DER end-users

We use the data which was shared by Ausgrid in regards to solar home customers. Half an hour of electricity data is available for 300 homes with rooftop solar systems, which use aggregate measurements to record the total amount of solar energy produced every 30 minutes. The data came from 300 randomly selected solar customers in the Ausgrid power grid area, who were billed at domestic tariffs and installed the total-metering solar system. The real data is 268559 rows with 54 columns in Excel.

The solar home generation capacity is increasing which means prosumers are getting more from the data, which goes from an average of 1253 in 2010 to an average of 1297 in 2013.

Table 3.3 Solar home summary

Year	2010-11		2011-12		2012-13	
Description	Mean	Median	Mean	Median	Mean	Median
Solar home customers- summary(300 samples)						
Annual consumption; KWh per year	6,980	6,362	6,596	6,017	6,387	5,867
Annual gross generation; Kwh per year	2,119	1,764	2,083	1,708	2,181	1,814

Solar system size(KWp)	1.68	1.50	1.68	1.50	1.68	1.50
Annual gross generation; KWh/KWp	1,253	1,280	1,231	1,253	1,297	1,326
Ausgrid residential customers – summary*(>1.4 million)						
Annual consumption; Kwh per year	6,611	-	6,224	-	5,954	-

To get more meaningful data and analysis, the calculation is applied on to get the average value for 300 prosumers in gross generation, gross consumption, gross generation minus consumption, which can represent the supply, demand and actual demand for the prosumers. For the prosumers in a residual microgrid, the most important factor is the actual demand because it will affect the bidding price of prosumer as well as the whole community financial efficiency.

Table 3.4 Solar gross generation VS consumption in 24 hours

	GG(Gross generation/KWh)	GC(Gross consumption/KWh)	GG-GC(Kwh)
0:30	0.0001	0.2488	-0.2487
1:00	0.0002	0.2287	-0.2285
1:30	0.0003	0.2136	-0.2133
2:00	0.0004	0.2019	-0.2015
2:30	0.0004	0.1958	-0.1954
3:00	0.0006	0.1899	-0.1893
3:30	0.0006	0.1876	-0.187
4:00	0.0006	0.1829	-0.1823
4:30	0.0006	0.1845	-0.1839
5:00	0.0006	0.188	-0.1874
5:30	0.0006	0.2003	-0.1997
6:00	0.0007	0.2161	-0.2154
6:30	0.0029	0.2466	-0.2437
7:00	0.0136	0.294	-0.2804
7:30	0.0398	0.3253	-0.2855
8:00	0.0832	0.3387	-0.2555
8:30	0.1379	0.3353	-0.1974
9:00	0.1965	0.3247	-0.1282
9:30	0.2553	0.3121	-0.0568
10:00	0.3062	0.301	0.0052
10:30	0.3514	0.2978	0.0536
11:00	0.3862	0.2952	0.091
11:30	0.4107	0.2948	0.1159
12:00	0.4252	0.2975	0.1277
12:30	0.4319	0.3019	0.13
13:00	0.4292	0.3019	0.1273
13:30	0.4204	0.2989	0.1215

14:00	0.399	0.2966	0.1024
14:30	0.3673	0.2929	0.0744
15:00	0.3304	0.2936	0.0368
15:30	0.282	0.299	-0.017
16:00	0.228	0.3117	-0.0837
16:30	0.1732	0.3324	-0.1592
17:00	0.123	0.3726	-0.2496
17:30	0.0833	0.4385	-0.3552
18:00	0.0524	0.4997	-0.4473
18:30	0.0283	0.5237	-0.4954
19:00	0.012	0.5204	-0.5084
19:30	0.0034	0.5026	-0.4992
20:00	0.0004	0.4909	-0.4905
20:30	0.0001	0.4848	-0.4847
21:00	0.0001	0.468	-0.4679
21:30	0.0001	0.4431	-0.443
22:00	0.0001	0.4128	-0.4127
22:30	0.0001	0.3892	-0.3891
23:00	0.0001	0.3538	-0.3537
23:30	0.0001	0.3129	-0.3128
0:00	0.0001	0.277	-0.2769

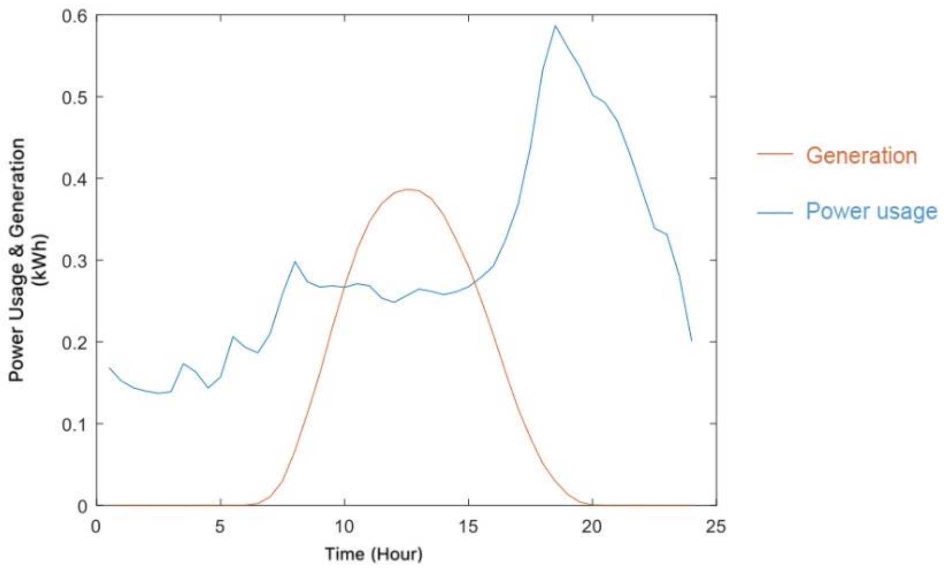

Figure 3.9 Comparsion between gross generation VS gross consumption

More vividly speaking, from figure 3.9, we can see that the sunshine generation power period can range from 7:00~19:00, the demand period is continuous all through the day for the full 24 hrs because some electrical appliances remain on. In terms of prosumer actual demand, the 10:00~15:00 period is positive and the other period is negative, which means during the

10:00~15:00 period, the average supply from the prosumers in the community is more than the demand of the prosumers.

3.6 Chapter Summary

In this chapter, detailed peer-to-peer energy system was introduced and explained. The components including the premise infrastructure and advanced technology provide the possibility to achieve the P2P energy system in real. These important factors include the development of microgrid, grid operation, bilateral contracts and blockchain technology. With these premises and technology, a few industry experimental projects were applied in different countries, which gives us more ideas what feature and potential peer-to-peer energy system will bring to us. The main focus on the details of peer-to-peer energy market is the architecture and design. Three major different peer-to-peer energy market designs are explained and stated: 1) full peer-to-peer energy market; 2) community-based peer-to-peer energy market; 3) hybrid peer-to-peer energy market. The advantages and disadvantages of these three different designs are discussed and compared. In regards to the end-users in the peer-to-peer energy market, the mathematics equation is set up to describe the modelling for the prosumers. To investigate the relationship between actual demand and generation of the prosumers, the comparison of solar gross generation VS consumption in 24 hours is applied based on the 300 randomly selected solar customers in the Ausgrid power grid area.

Chapter 4 Trading Mechanism and Pricing Strategy

4.1 Internet of Energy Industry Development

As an important means to promote the energy revolution, the emergence of the energy Internet is the marketization, liberalisation and flexibility of multi-energy trading and the provision of a new opportunity. Energy Internet can be understood by using advanced power electronics technology, information technology and intelligent management technology to interconnect a large number of new power network nodes consisting of distributed energy harvesting devices, distributed energy storage devices and various types of loads. From the perspective of government administrators, an energy Internet is a new energy system that is compatible with traditional power grids and can fully, widely and effectively utilise distributed renewable energy to meet the diverse power needs of users; from the perspective of operators, Look, the energy Internet is an energy consumption market that can interact with consumers and compete. Only by improving the quality of energy services can market competition be won. From the perspective of consumers, the energy Internet not only has the power supply function of the traditional power grid, it also provides a common energy exchange and sharing platform for all types of consumers. An energy Internet has the following five characteristics: 1) Renewable: renewable energy is the main source of energy for the energy Internet. Renewable energy generation is intermittent and volatile, and its large-scale access has an impact on the stability of the grid, thus transforming the traditional energy network into an energy Internet. 2) Distributed: due to the decentralised nature of renewable energy, for the most efficient collection and use of renewable energy, a network of in-situ collection including storage and use of energy is required. These energy networks are small in size and widely distributed, each micro-energy network constitutes a node of the energy Internet. 3) Interconnectivity: a large-scale distributed micro-energy network cannot guarantee self-sufficiency. It is necessary to combine energy exchanges to balance energy supply and demand. An energy Internet is concerned with interconnecting micro-energy networks consisting of distributed generation devices, energy storage devices and loads, while traditional grids are more concerned with how these elements are “connected”. 4) Openness: the energy Internet should be an energy-sharing network with equal, flat energy flows in both directions. Power generation devices, energy storage devices and loads can be “plug and play”. As long as the interoperability standards are met, this access is autonomous. From the perspective of energy exchange, no network node is more important than other nodes. 5) Intelligence: the generation, transmission, conversion and use of energy in the energy Internet should be intelligent.

The energy Internet is the product of the deep integration of energy and the Internet. It has become the new focus of the current international academic community and industry. Following the smart grid, it is also an important topic and the direction in which the energy industry is developing. In the early international period, relevant research on the theme of “Energy Internet” was carried out. In 2008, the National Science Foundation of the United States funded the FREEDM project [75], proposed the construction of Internet of Energy, and established a research center. In the same year, the German Federal Ministry of Economics and Technology and the Ministry of the Environment launched the E-Energy project [76], proposed the construction of Internet of Energy, and implemented six demonstration projects. In 2011, Rifkin’s "Third Industrial Revolution" [77] made the energy Internet a core of the third industrial revolution and had a wide impact. The feature of Internet of Energy is as followed:

(1) Energy synergy and coordinated scheduling, the synergies of multiple energy chains such as electricity, heat, cold, gas, oil, coal, and transportation complement each other, improving the overall efficiency of energy systems, capital utilisation efficiency and asset utilisation.

(2) Energy efficiency is mainly focused on the efficiency and effectiveness of energy systems. Make the environmental and social benefits through access to a variety of clean energy sources such as wind and solar energy; based on energy producers, consumers, operators and regulators, etc. to promote energy the overall performance of the system.

(3) Energy commodification means that energy has commodity attributes, stimulates the vitality of all participants through marketization, and forms innovative business models such as energy marketing e-commerce, transaction finance, investment marketization, and financing network. Exploring new energy consumption models, building an energy sharing economy and creating freedom trade with energy promote the construction of an energy consumption ecosystem.

(4) Energy is concentrated in the ubiquitous realization of energy production from centralised to decentralised, energy unit plug-and-play, peer-to-peer interconnection, energy equipment and energy-using terminals can be two-way communication and intelligent regulation.

The sharing and cooperation of all participants' resources will promote the timely transformation of cutting-edge technologies and innovations, realise an open innovation system, and promote the transfer of technological achievements and collaborative innovation across regions and fields.

(5) Energy virtualisation refers to the use of virtualisation technology in the Internet domain to abstract the energy system infrastructure into virtual resources through software, revitalise the stored resources of lead-acid batteries, and break through the geographical distribution restrictions to effectively integrate various forms and characteristics of energy infrastructure to improve energy resource utilisation.

(6) Energy informatisation refers to physically discretizing energy, and then imparting energy information attributes through computational power, enabling energy to be transformed into computational resources, bandwidth resources, storage resources, and through the field of information communication, control to achieve personalised energy operation services in the future.

The Internet of Energy is an advanced concept of smart grid. The smart grid is an important concept proposed in the early 21st century and has been rapidly developed in recent years. It is the product of the convergence of information and communication technology (ICT) and power grid. The Internet of Energy is the product of the Internet concept and the integration of technology and energy systems. It is the development and innovation of the smart grid.

Compared with the smart grid, the Internet of Energy is more open and more interconnected. It is reflected in the change of focus: 1) from a single power system to a focus on integrated energy systems such as power supply, heating, cooling, gas supply, and electrified transportation, to achieve multiple energy sources and the open interconnection of the system; 2) from the integration of ICT to the integration of the Internet, the use of Internet thinking and technology, transformation of the existing energy industry, formation of new business models and new formats, promotion of public innovation and entrepreneurship, its social influence and greater public interest than the smart grid.

4.2 The Operating Mechanism of the Energy Internet Market

The operational mechanism is the fundamental guarantee for realising the optimal allocation of resources in the energy Internet market. It consists of price, supply and demand, competition, settlement and incentives. Among them, the price mechanism is at the core.

1) Price mechanism. The price mechanism is a concentrated expression of the market regulation, and is related to the transaction method and energy type. For bilateral transactions, the pricing is mainly negotiated between the two parties; for centralised trading, different pricing mechanisms such as matching price, system marginal price, partition marginal price and node marginal price can be selected according to the energy type. At present, it is generally recognised in the electricity market that the marginal price of nodes is superior in price guidance and congestion management [82]; the marginal cost pricing method has been applied in regional thermodynamic markets such as Sweden and Finland [83]. Considering the network economic nature of the energy Internet market, the pricing mechanism for ancillary services and distribution costs is indispensable. The current international transmission and distribution price is mainly based on the "cost + income" pricing method, and there are also the highest ceiling and results-based incentive control measures; the method of determining the natural gas pipeline price is mainly service cost pricing, price cap pricing method, etc.

2) Supply and demand mechanism. In the traditional energy market, energy demand is generally considered to be rigid and not sensitive to changes in energy prices. The formation of multi-energy complementary systems in the energy Internet, the access of a large number of distributed devices, and the emergence of production and consumption users has promoted energy substitution and sharing, which has increased the flexibility on the demand side. In addition, with the strengthening of market concepts and energy-saving awareness, users will actively change the energy consumption type and energy consumption time according to market prices, and actively participate in the demand side response, thereby further enhancing the elasticity of energy demand and facilitating the balance of market supply and demand.

3) Competition mechanism. The competitive mechanism is the means of survival of the fittest in the energy Internet market and generates great social value. For example, the regional electricity market in the United States has effectively reduced retail prices by introducing a competition mechanism for electricity retail services, thereby saving users a huge total expenditure [22]. Therefore, in order to improve their competitiveness, energy retailers need to increase their energy choices, such as providing different combinations of energy sources such as electricity, gas, and heat, while carrying out personalised value-added services to enhance user stickiness. Big data processing, analysis and mining capabilities in the energy Internet environment will become one of the core competencies of market players.

4) Settlement mechanism. The transaction time of energy commodities is different from the actual delivery time, and the emergence of large-scale distributed transactions leads to two-way energy transmission. Therefore, establishing a reasonable settlement mechanism plays an important role in maintaining the interests of market entities and regulating market transactions. For example, the US PJM power market has a good reference value by establishing a double settlement mechanism between the day market and the real-time market, effectively regulating settlement work, improving settlement efficiency and reducing settlement risk [23].

5) Incentive mechanism. In order to mobilise market enthusiasm and promote social energy conservation and emission reduction, it is necessary to formulate corresponding incentive mechanisms. For example, a reasonable user-side subsidy policy can stimulate users to install distributed new energy, use electric vehicles, and participate in demand-side management such as central air-conditioning centralized control. Large-scale utilisation of renewable energy depends on the introduction and implementation of incentive policies; the United States and countries such as Norway and Sweden have ensured the market share of renewable energy generation by adopting a combination of renewable energy quota system and green certificate trading.

4.3 Business Model and Power Optimization

The construction of the P2P energy trading system steady-state analysis model mainly solves the following three key problems.

(1) From the perspective of power flow: under the distributed architecture, the power flow in the system is also distributed. Which power dispatching strategy can reduce transmission loss and maximise user benefits, is a key issue in a P2P energy trading system.

(2) From the perspective of information flow: due to the uncertainty of the DER position and the uncontrollability of DER power generation, the communication network of the microgrid will be challenged. Therefore, researching efficient two-way communication systems will help improve grid system performance with reliable, real-time information.

(3) From the perspective of currency flow: the P2P energy transaction process involves user payment problems; blockchain technology can be used to achieve distributed accounting, and the characteristics of blockchain technology are used to protect user privacy and transaction security. The challenge and opportunity to achieve these requires improving network reliability.

The increase in penetration rate of DER in the microgrid makes the power flow in the microgrid more diverse. Users no longer just buy electricity from the grid, they can also get power from their own DER and, through P2P energy trading systems, from other users with excess power. Distributed grid power dispatching is more complicated than traditional centralised grids. The P2P energy trading system can be regarded as a kind of adaptive distributed network. Such networks are characterised by self-learning, self-organisation, and self-optimisation. The first two features are self-adaptive distributed networks, and the third feature requires a corresponding distributed optimisation algorithm. Compared with the traditional distributed optimisation algorithm, game theory considers the factors of multi-party confrontation or cooperation in the optimisation goal. Based on the game theory model, the main body of the distributed generation market can be closer to the actual situation, reflecting the independent decision-making process between the network side and the user side. Avoiding subjective prejudice, reflecting the subjective initiative and individual rationality of participants well, can help solve the conflict between different stakeholders in the distributed generation market, and improve the flexibility and intelligence of the microgrid to some extent.

4.3.1 Distributed energy scheduling model based on game theory

In a cooperative game, players with similar objective functions can communicate with each other to form an alliance. Due to the intermittent and random nature of renewable energy supply, these power supplies are difficult to meet the load power balance by relying on their own regulation capabilities. Based on the application of cooperative game theory in the field of distributed energy dispatching, different literatures have different focuses. This paper divides the application based on cooperative game theory in the literature into three fields: source, storage and Dutch. In the source literature [9] based on the cooperative game model to optimise the energy demand and supply structure of consumers in the community, the literature [10] proposed a micro-cooperative game strategy, in order to meet the requirements of each MG energy demand, and minimise the total cost of power generation and transportation. At the energy storage end, the literature [11] proposes to reduce the user's demand for large-scale energy storage systems through cooperation between distributed generation and energy storage owners, and to stimulate the micro-network through Nash equilibrium theory. The electric transaction is achieved between them, thus saving the cost for the participating consumers [12-14]; On the load side, the literature [15] is based on cooperative game theory for optimising user load. In the literature [16], it focused on cooperative game model for exchanging electrical energy, which mitigates the dependence of the load on the main grid by the MG within a cooperative strategy and minimises the power loss costs associated with the distribution line.

In the non-cooperative game, each participant focuses on the influence of other participant strategies on their own strategy. In the distributed generation market, the original intention of each of the sellers is to maximise their own benefits [17]. However, in the competitive power market, the final decision of the sellers is affected by factors such as electricity price and power generation cost, and is also affected by the behaviour of other sellers [18]. Therefore, the competition for electricity sales can be regarded as a typical non-cooperative game problem. Its distinctive feature is that it has multiple decision-making bodies, and the decision-making between subjects affects has a mutual impact [19].

At present, there have been many studies on the issue of energy trading through non-cooperative game theory. In [20], the production and consumption type power users with DER and schedulable demand response load in the energy Internet were regarded as power units. Under the condition of local and global grid constraints, non-cooperative game theory was used to build the electricity market between users. The transaction model and simulation results verified the effectiveness of the non-cooperative game model. In the study of the non-cooperative game of energy storage units between producers and consumers, the literature [21] developed a non-cooperative game theory model for energy storage energy between MGs. Reference [22] considered the interaction between all parties involved, including grid companies, MGs, and power users, and proposed a two-stage Stackelberg game: Phase 1, grid companies and MGs as leaders of the game will decide electricity price as a function of power generation cost, power loss and electricity sales revenue, the game solution was the set price; in the second stage, consumers adjusted their demand according to the set price. Through the game model, the utilisation efficiency of distributed energy was effectively improved.

For different application scenarios, the designed game model provides an effective solution framework for distributed power optimisation scheduling problems in microgrids [23]. However, how the participants in the game model converge to the equilibrium state during the dynamic decision process of the game stage is the second aspect of game design: design strategy learning algorithm. This section describes two common strategy learning algorithms.

In any case, if the benefits of other strategies are greater than the strategy, then the strategy is a disadvantage strategy. Nash equilibrium is the best result after gradually removing the inferior strategy. Literature [24] identifies the planning problems of distributed energy such as wind, light, storage and combustion in the microgrid as the decision-making and equilibrium problem between power generation equipment investors, establishes the game planning model of DER, and finds Nash by eliminating the inferior strategy method. The equilibrium point is as follows: by fitting the gain function curve of each micro power source, it can be observed that the gain is a continuous concave function of the configured capacity. For the complete information static game, the information is transparent. In order to get the maximum benefit, different investors will constantly adjust their own configured capacity according to the strategies of other investors, and continuously eliminate the strategy of less profit according to the size of the income, and continuously iterate, and finally get Nash equilibrium. Each investor chooses the configured capacity corresponding to the maximum revenue.

Assume that the optimisation result of the i-th round is $(P_{w\cdot i}, P_{s\cdot i}, P_{R\cdot i}, P_{B\cdot i})$ where $P_{w\cdot i}$ $P_{s\cdot i}$ $P_{R\cdot i}$ $P_{B\cdot i}$ representing wind power, photovoltaic, and micro gas. The capacity of the turbine and energy storage investors. In the i + 1 round optimisation, get the optimal strategy $(P_{w\cdot i+1}, P_{s\cdot i+1}, P_{R\cdot i+1}, P_{B\cdot i+1})$ comparing the two strategies, gradually eliminating the inferior strategy, when the following conditions are met, then get the optimal configuration result $(P_w^*, P_s^*, P_R^*, P_B^*)$ which is $(P_{w\cdot i+1}, P_{s\cdot i+1}, P_{R\cdot i+1}, P_{B\cdot i+1}) = (P_{w\cdot i}, P_{s\cdot i}, P_{R\cdot i}, P_{B\cdot i})$.

4.3.2 Iterative search method

The literature [25] is based on the power market power balance constraint, microgrid alliance and other power supplier output upper/lower limit constraints and other constraints as a one-round iteration end condition of the iterative search method. The iterative process is a dynamic process that ends the iterative search process until the market bidding game reaches the Nash equilibrium state or the maximum number of iterations. The specific iterative process is as follows: in the first iteration, each bidder submits initial bidding information to the bidding system according to its own state information. The bidding system obtains the first round of iterative results according to the relevant optimisation algorithm under the premise of satisfying the system security level and other constraints. And the relevant result information is fed back to each bidder through the interaction between the bidders, and each bidder modifies and bids the bid information according to the feedback information, and completes one iteration.

For the generality of the narrative, n bidders in the electricity market are numbered sequentially from 1 to n. Assume that the bidding power of each bidder in the k-th iteration is $\{q_{G1}^k, q_{G2}^k, ..., q_{G(n-1)}^k, q_{Gn}^k\}$,the bidding power of each bidder in the k + 1 iteration is $\{q_{G1}^{k+1}, q_{G2}^{k+1}, ..., q_{G(n-1)}^{k+1}, q_{Gn}^{k+1}\}$, $U_{Gi}q_{Gi}$ represents the i-th power producer's return, which is a quadratic function with the bidding power as the independent variable. $\arg\max\limits_{q_{G1}^k} U_{Gi}\{q_{G1}^k, q_{G2}^k, ..., q_{G(n-1)}^k, q_{Gn}^k\}$ indicates the bid power corresponding to the i-th bidder in the kth round, and the k-th round represents the iteration equation as follows:

$$\begin{cases} q_{G1}^{k+1} = \arg\max\limits_{q_{G1}^k} U^{Rf}{}_{Gi}\{q_{G1}^k, q_{G2}^k, ..., q_{G(n-1)}^k, q_{Gn}^k\} \\ q_{G2}^{k+1} = \arg\max\limits_{q_{G2}^k} U^{Rf}{}_{G2}\{q_{G1}^k, q_{G2}^k, ..., q_{G(n-1)}^k, q_{Gn}^k\} \\ ..... \\ q_{Gn}^{k+1} = \arg\max\limits_{q_{Gn}^k} U^{Rf}{}_{Gn}\{q_{G1}^{k+1}, q_{G2}^{k+1}, ..., q_{G(n-1)}^{k+1}, q_{Gn}^{k+1}\} \end{cases} \quad (4.1)$$

When the bidding powers of the two rounds of iteration are equal,

$$\left\{q_{G1}^{k+1}, q_{G2}^{k+1}, \ldots, q_{G(n-1)}^{k+1}, q_{Gn}^{k+1}\right\} = \left\{q_{G1}^{k}, q_{G2}^{k}, \ldots, q_{G(n-1)}^{k}, q_{Gn}^{k}\right\} \tag{4.2}$$

At this time, no bidder is willing to change his bidding power. The solution at this time can be regarded as the game Nash equilibrium solution

A P2P communication system is a complex distributed communication system consisting of a large number of heterogeneous and interdependent components operating in a dynamic environment [26]. However, the system size of each user in the piconet can only observe and measure the local information of the network, and it is difficult to achieve global optimisation through distributed control. If you want to obtain real-time and reliable data information of each device, you need efficient information exchange strategy support between users. To date, one of the main ways to integrate multiple distributed communications is through multi-agent system (MAS) technology.

[30], in which each participant can be modelled as an autonomous agent capable of interacting through messaging. A multi-agent system (MAS) is a collection of software agents that work in conjunction with each other by multiple intelligent agents and reacts to environmental changes to complete a given task. Considering that the system scale of each agent can only observe and measure the local information of the network, each agent in the micro-network must make local decisions autonomously, and coordinate with each other to achieve distributed management, thus ensuring the flexibility and stability of the MG. Literature [33] uses a distributed P2P multi-agent framework to manage power sharing in MG. A graph-based model is proposed for the Ziegler-Nichols algorithm for electric vehicles. Performance analysis shows that information exchange improves system performance. In the study of [80], the loop technique was used to simulate the communication between agents. However, the main obstacle of the loop technology is that as the number of agents increases, the number of communications increases sharply and the system is not scalable. In addition, researchers in [79] used MG-controlled minimum spanning tree (MST) algorithms to implement agent-based communication. In MST, the communication path through which information is propagated between agents is a function of minimum path formation.

However, the disadvantage of the MST algorithm is that communication between agents can only begin after the tree is formed, and each additional agent must rebuild the MST, which greatly reduces the system effectiveness. In view of this, the literature [78] proposed a new communication algorithm based on intelligent physical agents (IPA). Compared with other existing P2P structures (such as loop technology and MST), the algorithm had fewer communication steps and responses. Fast speed and low complexity are more suitable for information flow optimisation of P2P energy trading system in microgrid.

4.4 The Trading Mechanism for Peer-to-peer Energy Market

In order to ensure the fairness and openness of the market, it is necessary to formulate a reasonable trading mechanism based on the energy Internet market system. According to the preliminary definition of the energy Internet market, the energy Internet market trading mechanism mainly studies the application of multiple types of energy such as electricity, gas and heat.

4.4.1 CDA auction mechanism

Continuous double auction (CDA)

As an auction mechanism, through the quotation of buyers and sellers to match the deal, it is explained distributed energy P2P transactions in this paper. When this paper adopts this mechanism, we need to consider the issue of maximising benefits. As the main body, grid users , service providers have their interests in the distributed energy trading market. For equivalence, a non-cooperative static game model needs to be established [80]. In the transaction process, the grid is selected as the game subject, and the two games are separated from each other. Users and distributed energy service providers. The game model established by the counterparty and the advantage of reducing transaction costs will consider the benefits of distributed energy service providers to sell electricity and minimise the cost of purchasing electricity with users.

Game strategy: Grid companies decide to maximise subsidy payments to motivate market transactions. Each distributed energy service provider determines its own sales vector to maximise revenue, and each user determines its own purchase vector to minimise costs [81].

In terms of constraints, the grid needs to ensure that the electricity market is active and orderly, the user bid must be higher than the lowest price in the previous cycle, and the price of the distributed energy service provider must be lower than the user's bid.

According to the definition of the above game strategy, the game subject will choose the most beneficial market subsidy distribution strategy, and the game will choose the most favourable way to trade, that is, the user chooses the distributed energy service provider with the lower quotation. The service provider selects users with higher quotations. However, the constraint of this bilateral auction offer is that if the selling price is greater than the bid, the platform judges that the transaction cannot be carried out and closes the trading path. Nash equilibrium based on benefit maximisation means each game participant can accept the bilateral auction game strategy [82].

4.4.2 Innovative pricing strategy introduction for peer-to-peer energy trade

Trade mechanism in residential communities is essentially a kind of business model, while the power balancing is handled by the community energy management system. The P2P pricing frame is defined between the buying price from grid and selling price to grid. The constraint for the P2P price $C_{P2P}{}^{i}(t)$ for prosumer i is $[C_{stg}, C_{bfg}]$ to ensure to social welfare of whole community [84], where C_{stg} is the price selling to the grid (feed in tariff) and C_{bfg} is the price buying from the grid.

Pricing mechanism plays a critical role for P2P energy trading mechanism [15],[16]. In this study, we propose two P2P energy trading pricing strategies: Unified Pricing (UP) and Identified Pricing (IP) [84].

A. Unified Pricing

In this proposed unified market clearing price mechanism, the market clearing price is decided by the actual demand based on historical local knowledge. For the time period t, the whole community P2P trade price would be unified, which means any P2P transaction during this period would be based on this price. The P2P trade price is determined by the follows:

$$C_{P2P}(t) = \lambda \bullet C_x(t) \tag{4.3}$$

where λ is learning factor which is decided by the weather influence and day consumption, $C_x^{\,i}(t)$ is the electricity price determination by the historical generation and consumption records of the users.

$$C_x(t)=\begin{cases}[1-\dfrac{p_g(t)]}{P_d(t)}]\bullet C_{bfg} & \text{if } P_d^{\,i}(t)>p_g^{\,i}(t)\\ C_{stg} & \text{if } P_d^{\,i}(t)\le p_g^{\,i}(t)\end{cases} \tag{4.4}$$

where $p_g(t)$ is the estimated generation of the community at time *t*; $P_d(t)$ is the estimated demand of community based on historical consumption and generation at time *t*.

The P2P energy allocation in method Unified Pricing is distributed followed by the descending order for the P2P customers in community.

The electricity bill of the user *i* is calculated as [84]:

$$\sum_{h=1}^{H} B_i^h = \sum_{h=1}^{H} C_i^h(x_i^h) + \sum_{h=1}^{H} G_i^h,\ h\in[1,2,....,H] \tag{4.5}$$

where $\sum_{h=1}^{H} B_i^h$ is the electricity bill of user *i* for 1 day (24 hours); the summation of $C_i^h(x_i^h)$ is the cost function of user i to trade energy in the community; the summation of G_i^h is the cost of user i to trade energy with the grid [84].

Alogrithm: Unified P2P price strategy and electrciicty bill

```
Arrange end user profiles in the community at time period t
    for consumers i from 1 to M
        for producers j from 1 to N
            if ∑Pd(t)> ∑Pg(t)
                Calculate P2P price Cp2p(t)
                Calculate electricity bill(t)= P2P bill(t)+ traditional bill(t)
                end if
            else if ∑Pd(t)<=∑Pg(t)
                Calculate P2P price Cp2p(t)
                Calculate electricity bill(t)=P2P bill(t)
            end if
        end for
end for
```

B. Identified Pricing

In this section, we propose another pricing strategy, Identified Pricing. In the identified market clearing mechanism system, every user bids a different trading price based on their demand and community offered. In such a process, the customer gets one customised price for their P2P trading in the real time P2P market [84].

The price for every user is determined by the demand, supply, and the wealth of whole community. In the auction-based pricing strategy [13], it is obvious that the strategy of resource consumers is to decrease the price when supply is relatively high, and increase their bidding price when the supply is relatively low. The customers start the bid with an initial price for the market and update the price over the period based on their local information:

$$b_i(t) = b_i(t-1) + \Delta b_i(t) \tag{4.6}$$

where $b_i(t)$ is the updated bid price and $b_i(t-1)$ is the previous bid price submitted by customer i; the value of $\Delta b_i(t)$ is the influence factor that decided the value of bid price based on task utilization and user's consumption and self-generation condition.

$$\Delta b_i(t) = \alpha(u(t) - u_{th}R) \bullet b_i(t-1) \tag{4.7}$$

where α is the coefficient used for controlling the rate of altering the bid price; $u_{th}R$ refers to the task utilization for the consumer. $u(t)$ is defined as:

$$u(t) = \sum_{i=t_0}^{T} x(i) / \sum_{i=t_0}^{T} N(i) \tag{4.8}$$

where $\sum_{i=t_0}^{T} x(i)$ is the amount of P2P resources consumed by user i during the period $[t_0, T]$; $\sum_{i=t_0}^{T} N(i)$ is the amount of P2P resources offered by the community during the period $[t_0, T]$.

The constraint for the $b_i(t)$ is $[C_{stg}, C_{bfg}]$,where C_{stg} is the price selling to the grid and C_{bfg} is the price buying from the grid.

In the community, every customer places a bid initially, and updates their bidding prices periodically.

The social welfare of the community during the period t is calculated as:

$$\sum_{t_0}^{t} S = \sum_{i=t_0}^{t} b_i(t) \bullet d_i(t) \tag{4.9}$$

where $b_i(t)$ represents the customer i P2P price during time period t, $d_i(t)$ represents the customer i P2P demand during time period t

To maximize the social welfare for the P2P trade in the community, the auction algorithm is applied in the allocation part. The Auction algorithm plays the role of optimising the assignment distribution. In P2P trading, such assignment refers to energy allocation [84].

Auction algorithms have been used in the real world to determine the best prices of a set of products offered to multiple buyers. It is an iterative procedure, so the name "auction algorithm" is related to a sales auction, where multiple bids are compared to determine the best offer, with the final sales going to the highest bidders [84].

In this P2P case, after deciding the bid price of each customer, the procedure enters into a program of auction match. The auction match algorithm is applied in this process. The purpose of this auction match is to optimally allocate energy and maximize the social welfare of the whole community through P2P trading [84].

All P2P transactions under IP are identical, consumer i and producer j achieved their aim by providing high price and providing surplus generation offer [84].

Algorithm: Identified Pricing Strategy and energy allocation

```
Arrange end user profiles in the community at time period t
    for consumer i from 1 to M
        for producer j from 1 to N
            if i Pdemand(t) > 0
                consumer i submit bid price
            if j Pgeneration(t) >0
                producer j submit surplus generation offer
                Calculate potenial transaction =bid price*demand           required
                Auction match algorithm to distribute energy allocation
                end if
            end if
        Display P2P transaction Tij during period t
    end for
end for
```

Both of the pricing strategies are applied on simulation case study in next chapter. Two pricing strategies would be based on real solar customers to achieve the comparison on effect of peer to peer energy trading system [84].

4.5 Chapter Summary

This chapter concentrates the key point on the market, therefore discusses the detailed trading mechanism and pricing strategy. In order to make the peer-to-peer trading happen, the development of Internet of energy industry and ICT technology is essential. The operational mechanism is the fundamental guarantee for realising the optimal allocation of resources in the energy Internet market. The mechanism includes price, supply and demand, competition, settlement and incentives. Among them, the price mechanism is at the core. The construction of the P2P energy trading system steady-state analysis model needs mainly solve the problems of following three key perspectives 1) power flow 2) information flow 3) currency flow. It mainly relies on the distributed energy scheduling model based on game theory and iterative search method is applied. The iterative process is a dynamic process that ends the iterative search process until the market bidding game reaches the Nash equilibrium state or the maximum number of iterations. As a trading auction mechanism, through the quotation of buyers and sellers to match the deal, it is explained how distributed energy P2P transactions completed. When this paper adopts this mechanism, we need to consider the issue of maximising benefits.

Two innovative pricing strategies (unified piecing and identified pricing) were proposed to achieve the maximum financial benefits and social welfare for end-users.

Chapter 5 P2P Energy Trading Option Determination Based on Prosumer Profile

5.1 Residential Microgrid Simulation

A simulation case based on 15 customers' real data was designed and extracted from the 2013-2014 solar home data electricity data v2, which was resourced from Ausgrid. The dataset included power consumption and generation profiles of 300 customers from 1/7/2013~30/6/2014. The profile included the users' daily gross consumption (GC), and gross generation (GG) for every half hour from 0:30~24:00. All data was collected by the smart grid from Ausgrid. The half-hour electricity data was for 300 homes with rooftop solar systems, measured by a gross meter that recorded the total amount of solar power generated every 30 minutes [84].

The data was sourced from 300 randomly selected solar customers in Ausgrid's electricity network area who were billed on a domestic tariff and had a gross-metered solar system installed for the whole of the period. The quality of the data was checked and customers on the high and low ends of household consumption and solar generation performance during the first year, were excluded. Table 5.1 shows the data format for solar household data from Ausgrid. And the meaning for each column from the data is given in table 5.1. These customers could be prosumers or customers only.

Table 5.1 Data format for solar household data from Ausgrid

Column	Field	Description
1	Customer	Customer ID from 1 to 300
2	Postcode	Postcode location of customer
3	Generator capacity	Solar panel capacity recorded on the application, which is the solar panels peak power under full solar radiation and tested under standard conditions
4	Consumption category	GC=General consumption CL=controlled load consumption (eg. washing machine)

		GG=Gross generation
5	Date	Date in DDMMMYYYY format
6	0:30	Kilowatts hours (KWh) of electrical energy consumed or generated in the half hour ending at (e.g between 0:00 and 0:30). The value positive regardless of whether it is consumption or generation
7 to 53	1:00 – 0:00	As above, covering every half hour of the day up until the last hour of the day at 0:00 (eg. Between 23:30 to 0:00)
54	Row Quality	(Blank)=every half hour value in the row is the actual electricity recorded by the meter in the half hour NA=Non-Actual where some or all of the half hour values in the row are estimates or substitutes of the electricity consumed or generated

A. Simulation Result

The dataset included the data of users' gross consumption, gross generation, and house owners' solar generation capacity. Since the priority for generating energy was self-used, the actual demand of each home was determined based on the deduction of gross consumption and gross generation. Fig. 5.1 illustrates the 15 households' actual demand in one day. The negative values represent the period that household has surplus renewable energy which can be sold into the P2P market.

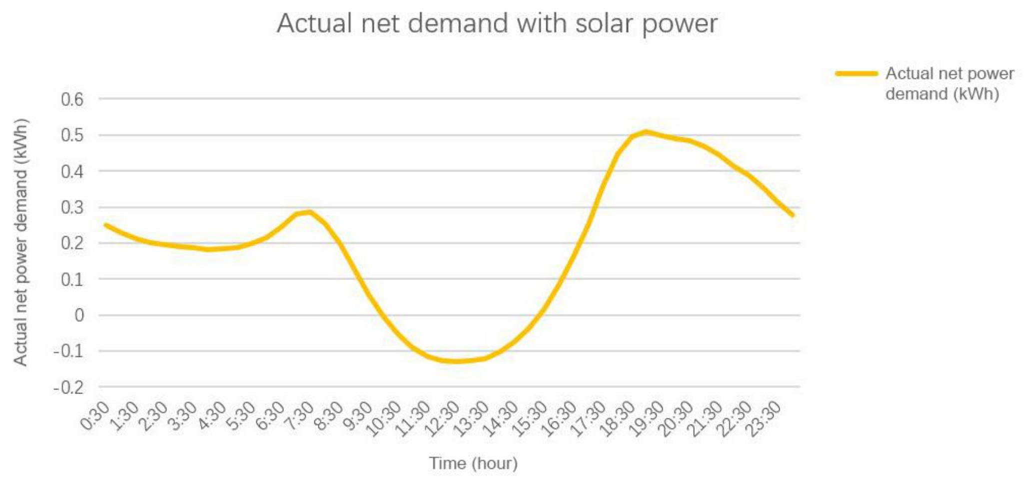

Figure 5.1 15 household actual net demand

The following calculations and simulations are based on the data from the Australian retailer company AGL. In it, a customer who bought electricity from the grid would pay $0.25/kWh, and the feed-in tariff was $0.06/kWh.

From the method unified pricing strategy, the P2P price for every 30 minutes was calculated by the algorithm. Fig. 5 shows the variation of P2P price in one day. For the period before 8:30 and after 17:30, a P2P price for transaction doesn't exist because there is no generation from any household. The P2P price is fixed during 10:00-15:00 the same feed-in tariff as this period as the DER generation is much higher than the local demand.

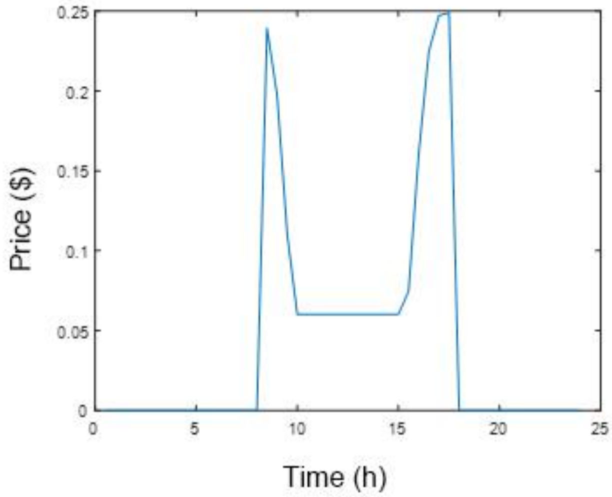

Figure 5.2 Unified pricing strategy P2P price

For the identified pricing strategy, the initial bid of the customer is $0.25 which is the price customer buy electricity from the grid. The bid price is updated by equation (10), parameter α and $u_{th}R$ is defined as 0.1 and 0.9 respectively. Between the period 11:30-12:00, it completes 6 transaction [Buyer5, Seller7, $ 0.03097], [Buyer6, Seller13, $ 0.01243], [Buyer8, Seller15, $ 0.03230], [Buyer9, Seller1, $ 0.04744], [Buyer10, Seller12, $ 0.04022], [Buyer14, Seller3, $ 0.01415]. While for the time period 17:00-17:30, there completes only one transaction between end users as there is only one producer provider surplus electricity at that time [Buyer10, Seller1, $ 0.005058] [84].

The below table shows Identified Pricing Strategy for 11:30-12:00 Transaction

Table 5.2 IPS for11:30-12:00 Transaction

Buyer	Seller	Transaction
No.5	No.7	$0.03097
No.6	No.13	$0.01243
No.8	No.15	$0.03230
No.9	No.1	$0.04744
No.10	No.12	$0.04022
No.14	No.3	$0.01415

For the comparison, the electricity bill of the conventional method, unified P2P pricing market and identified pricing market are calculated for 15 households. Table 5.3 shows as below:

Table 5.3 Electricity bill on three methods

Customer No.	Generator Capacity(kw)	Conventional Electricity Bill($/day)	Unified P2P market pricing($/day)	Identified market pricing($/day)
1	3.78	1.8301	1.7290	1.6191
2	1.62	2.5064	2.4443	2.4260
3	1	0.7229	0.6943	0.6513
4	1	1.6233	1.4623	1.6692
5	0	2.7365	2.1470	2.6111
6	2	5.0329	4.3315	4.7367
7	2.16	1.0873	1.0443	0.8783
8	1.02	5.0443	4.1691	4.6589
9	0	1.4815	1.2668	1.8595
10	0	1.9587	1.5870	2.2064
11	2.04	3.1513	3.1167	3.1483
12	4	2.0592	2.0038	1.8373
13	1.5	2.5526	2.5323	2.5411
14	1.1	3.3124	2.9616	3.1955
15	2.1	2.7283	2.6314	2.6892

In order to illustrate the comparison visually clear, the comparison is shown is graph forma as below:

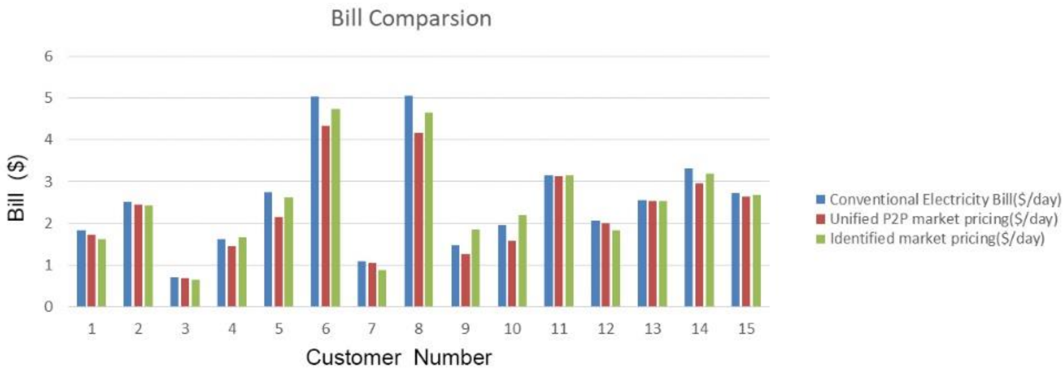

Figure 5.3 Bill Comparison on three methods

Fig. 5.3 shows the bill comparison of the three methods. It can be seen that with P2P trading, the bill is reduced by 5% to 15%. For the unified pricing, the end users in the community get similar welfare in reflection on the bill. The identified pricing strategy provides more profit for households who have larger capacity (etc No.1 3.78KW), while the customers who do not have DERs pay more on their electricity bill [84].

5.2 Preference Option Comparison Based on Prosumer Profile

From the case study, we can see that the consumers who have low generation capacity, even zero DER, get more benefit when the unified pricing strategy is applied. The prosumers who have larger DER systems get more advantage on the identified pricing strategy which saves them more money on bills. Prosumer profile difference results in a different determination of the pricing plan in regards to the final saving on the electricity bill.

Based on the comparison result, the profile of the consumers was found to be a key factor tin deciding which trading mechanism or pricing strategy they preferred go with. In order to further explore the customers' electricity usage pattern deeply, it is recommended to update the format with some new factors, and add information on solar households over and above the basic information. When managing professional consumers, it is important to understand their energy behaviour, activities and processes. Professional consumer archives are a set of characteristic requirements that may affect how users consume their energy. The data may include various aspects, such as demographic and family information, the type of real estate the user lives in, the status of residence, the style of work and hobbies, the use of budgetary constraints, and the equipment used, including their mode of use [5,55].

Table 5.4 Recommendation of new format

Column	Field	Description
1	Customer	Customer Name and ID
2	Postcode	Postcode location of customer
3	Generator capacity	Solar panel capacity recorded on the application
4	Consumption category	GC=General consumption CL=controlled load consumption (eg. washing machine) GG=Gross generation
5	Day job	If the members of family all have a day job, which means the day time consumption in home would be relatively low
6	Energy storage type	The energy storage capacity(etc.battery)
6	Family member	The family amount decides the consumption load
7	Property type	Own or rent

The new field components recommended include information such as day job, family member. Day job is a factor that would affect efficiency a lot. For houses in which people all have a day job, the daytime electricity consumption would be relatively low. In that case, for P2P energy trading, they will mainly play the role of prosumer or will sell electricity to neighbours during day time. The number of family members will affect the flexibility and consumption of electricity. The load consumption pattern will largely decide the mode of use for different families. The property type will also influence the electricity usage pattern.

5.3 Organised Prosumer Group Identification

Organised prosumer groups serve the interests of a group of prosumers (e.g., community, organisation). It is essential to provide high quality energy services to all by optimising the integration of limited numbers of organised prosumer groups into the system prosumers act mostly as partners that provide various services to the grid. At times, they can become a competitor for generation— integrating and optimising large amounts of data provided by prosuming groups—leading to complexity and high transaction costs of managing prosumption relations within the group

When managing professional consumers, it is essential to understand their energy behaviour profile, activities and processes. Professional consumer archives are a set of characteristics that may influence users' energy demand. The data can include various aspects, such as demographic and household information, the type of real estate the user lives in, occupancy status, work and hobby patterns, budget-use constraints and the equipment used, including their mode of use [55].

A study analysed the energy production, consumption and sharing behavior of solar photovoltaic users in Australia [2]. This analysis produced consumer energy patterns in summer and winter. The results showed that the configuration files changed one day and one month a year. Therefore, the author suggested that the variability of the energy curve should be taken into account when investigating consumers. In addition, it is essential to review the behavioural profile of professionals during energy system planning. Analysing all the factors leading to consumers' behaviour and interaction in a smart grid can help to shape the system load situation and predict energy demand [56]. To illustrate this principle, the proposed method simulates the driver's behavior to assess how the charging of electric vehicles affects the public power grid in Dutch residential areas. The survey results show that the increase in electric vehicles needs to correspondingly increase the communication between electric vehicles and utilities.

One of them is to follow the best timetable for using household appliances. For example, the analysis of professional consumer behaviour leads to prototypes of informatics solutions that help to make decisions and choose the best use of uncontrollable devices. Similarly, another energy scheduling model for residential consumers aims to optimise their consumption, generation and storage time [58]. Other similar intelligent dispatching of electrical appliances are also found.

As an active participant in energy co-creation, we also discussed the co-creation activities of consumers. These four activities include conceiving, developing, testing and providing feedback.

Co-creation is a key component of ensuring sustainable energy supply for community power grids. Therefore, we recommend the following: understanding the general situation of professional consumers' energy behaviour, organisation and motivation is an important part of effective consumer management and energy system planning. Goal-oriented PCG establishes closer links among its members, motivates them, enhances their bargaining power and maintains the energy sharing process.

Therefore, based on the general situation of consumer behaviour, the energy system planning determines the appropriate energy consumption optimisation technology.

One of them is to follow the best timetable for using household appliances. For example, the analysis of professional consumer behaviour leads to prototyping of informatics solutions, which helps to make decisions and choose the best use of uncontrollable devices [57]. Similarly, another energy scheduling model for residential consumers aims to optimise their consumption, generation and storage time [58]. Other similar intelligent dispatching of electrical appliances can also be found in document [59].

In a residential microgrid, prosumer groups as mentioned can be divided into different groups: a commercial generation group, a high day-time generation group, a high day-time consumption group, a regular low generation group, and a regular low consumption group. For the constitution of residential microgrid, the different types of groups need to feed-in to make the best social welfare for the microgrid through the trade.

The prosumer group identification is very critical to determine the willingness of prosumers to participate in the P2P trading. Therefore, to make an organised classification prosumer group should be a main focus when applying large size residential end-users to peer-to-peer energy trading.

5.4 Chapter Summary

In this chapter, A simulation case based on 15 customers' real data was designed and extracted from the 2013-2014 solar home data electricity data v2, which was resourced from Ausgrid. With the two innovative pricing strategies, the simulation result indicates that the outcome, as expected, the end-user got more financial benefits on their electricity bill with the P2P method. From the simulation result, it is found the prosumers who have larger DER systems get more advantage on the identified pricing strategy which saves them more money on bills. While two pricing strategies both benefit the customers, the prosumer profile difference results in a different determination of the pricing plan in regards to the final saving on the electricity bill. In the future, it is recommended that more factors can be added into customer profile such as day job, family member, energy storage capacity etc. Those customers who have similar electricity usage pattern can be classified as organised prosumer group, in that way high quality energy service including optimal peer-to-peer energy trading plan can be served.

Chapter 6 Conclusion

6.1 Thesis Conclusion

In the thesis, the importance of a user-centric energy system was introduced and the challenges being faced were explained. In the literature review, the history and contribution of research on peer-to-peer energy trading systems was summarised. In the chapter on the architecture and design of peer-to-peer energy trading system, three different types of P2P architecture were explained. A SWOT analysis was also applied on the P2P energy trading system and detailed modelling on prosumers was demonstrated. Internet of energy industry was introduced and business model in Internet of energy was explained. Stating how the trading mechanism should work and proposing two innovative pricing strategies, the Unified Pricing Strategy (UPS) and Identified Pricing Strategy (IPS), and proving they have ideal outcomes on results, were the major contribution of this thesis. The aim was to maximise the owners of small-scale distributed energy resources' profit and provide service while taking into account the uncertainty around solar photo-voltaic generation. The outcome, as expected, was that with the P2P method, the end-user got more financial benefits on their electricity bill. The last chapter focused on a P2P energy trading option determination based on prosumer profile. In it, a recommendation on profile format was given to provide more suitable plans for future prosumers. This thesis shows the importance and benefit of a user-centric peer-to-peer energy trading system and, in the residential microgrid, gives the solution.

6.2 Future Work

In future work, an energy storage system is expected to be added into the residential microgrid. Some of the prosumers will be assumed to have energy storage capacity for their renewable system. In that case, peer-to-peer trading will have different flexible options and the trading between prosumers will become more promising and competitive. The peer-to-peer business model can be more comprehensive with the integration of energy storage system. It is expected that, in the future, a P2P energy trading system will be incorporated into large-size users and prove the effectiveness of a user-centric system.

The regulation of peer-to-peer energy trading has not been established properly; it could be improved with law regulation, monopoly refusion, and involvement of retailers. In the future, it will be necessary for more action to be taken when regulation is set up, which will satisfy the end-users and improve the effectiveness of business operation. Better regulation of peer-to-peer energy trading will also improve the willingness of the participants in the community.

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