Chapter 12
Participation of Active Buildings in Peer-to-Peer and Local Transactive Energy Markets

V. Vahidinasab, M. Nasimifar, B. Mohammadi-Ivatloo

12.1 Introduction

A *Collaborative Economy* which is sometimes called *Sharing Economy*, is an economic model that highly affecting the way of trading products and services between corporations, startups, and people. This results in a more efficient marketplace which brings new products, services, and business growth [1]. According to this concept, all members of a community might be able to have access to certain goods or services and can share them through a proper infrastructure [2]. *Airbnb* and *Uber* are two examples of many platforms that have been formed upon this paradigm. The collaborative economy is the opposite of traditional concepts in which a limited number of players are in charge of providing services and goods.

The energy systems, also affected by the collaborative economy paradigm. Especially with the evolving development of the distributed energy resources (DERs), especially Renewable Energy Sources (RESs), and their deployment on the demand-side of the energy sector, the issue of potential energy sharing and small-scale transactions between the peers are highlighted [3]. While the prosumers (i.e. agents who are able to produce, consume, or store the energy) were able to trade their energy and ancillary services with the main grid, the paradigm shift achieved by the collaborative economy concept paved the way for energy trading according to their preferences not only with the main grid but also with the peers in the neighbourhood area. Also, consumers should be able to choose the provider and the type of energy to buy.

All these points along with advances in Information and Communication Technologies (ICT) have led to the creation of new concepts of Transactive Energy (TE) [4] and Peer-to-Peer (P2P) energy market [5]. In such markets, prosumers and consumers can make use of a distributed, secure, and transparent platform to trade energy and service with all of the players in the network. A variety

Vahid Vahidinasab
Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, UK
e-mail: vahid.vahidinasab@ntu.ac.uk

Mohammad Nasimifar
Faculty of Electrical Engineering, Shahid Beheshti University,Tehran, Iran
e-mail: m.nasimifar@mail.sbu.ac.ir

Behnam Mohammadi-Ivatloo
Department of Electrical Engineering, University of Tabriz, Tabriz, Iran and School of Engineering, Aalborg University, Aalborg, Denmark
e-mail: mohammadi@ieee.org

of players can be considered, namely, small-scale users, community/microgrid managers, system operators, and large-scale producers. Hence, players at all levels of the network have the possibility of participating in the provision of energy and ancillary services while they seek to reach their own goals. These goals can be individuals, such as reducing the total cost of energy, or social goals such as using green energy, or even philanthropic purposes, such as helping people who have energy poverty.

In such an environment, active buildings are able to perform a pivotal role in future P2P energy transactions. By employing the different generation technologies and smart appliances, a community of active buildings has the potential to not only procure internal demand at the minimum cost but also provide flexibility and other services for grid operators [6, 7]. Hence, in this chapter, the role of active buildings and their potential to provide internal and external services through P2P energy transactions are investigated. Figure 12.1 shows the graphical overview of the presented topics in this chapter.

12.2 Transactive Energy and P2P Markets

In this section, an overview of the definition, concept and challenges of the TE and P2P markets will be introduced and their potential applications at active building level are discussed.

12.2.1 Transactive Energy: Overview, Concept, and Challenges

Among the various definitions proposed for TE, the following definition which is provided by the GridWise Architecture Council (GWAC) [8] is the most popular definition used in the literature: *"a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter"*. According to this definition, TE exploits the whole power system potentials, including demand-side response (DSRs) and DERs to achieve a more sustainable, affordable and secure network. While TE and DSR share the same objective of seeking to balance demand and supply across the network, they are acting differently in approach. As its name reveals, DSR focuses on the demand part of the network. Hence, by providing economic incentives, they lead demand-side potentials to match with the available energy generation [9, 10]. Although this approach has been around for many years, it seems that DSR programs are not able to respond to the current requirements of the movement toward a smarter network [11]. Thus, by utilizing the generation potential of the grid along with the demand-side resources, TE defines its decisive role in the current energy sector evolutions.

It should be mentioned that other variations of electrical energy, such as ancillary services, might be also considered as a transactive product. Hence, each agent at different levels of the grid is able to perform a transaction with other agents. Hence, transactions may occur on the lower levels of the grid between two prosumers, or between a prosumer and the Distribution System Operator (DSO), or even on the higher levels between distribution utilities and wholesale energy market [12]. In this regard, participants in TE markets might be categorized as follows (Fig. 12.2) [8]:

- **Utilities:** Including large-scale producers and consumers along with system operators, such as DSO and Transmission System Operator (TSO);
- **DERs:** Including producers and prosumers with the ability to procure energy;
- **End-Users:** Who seeks to provide energy demand according to their preferences;
- **Policymaker:** A regulatory entity that procures a secure and transparent marketplace.

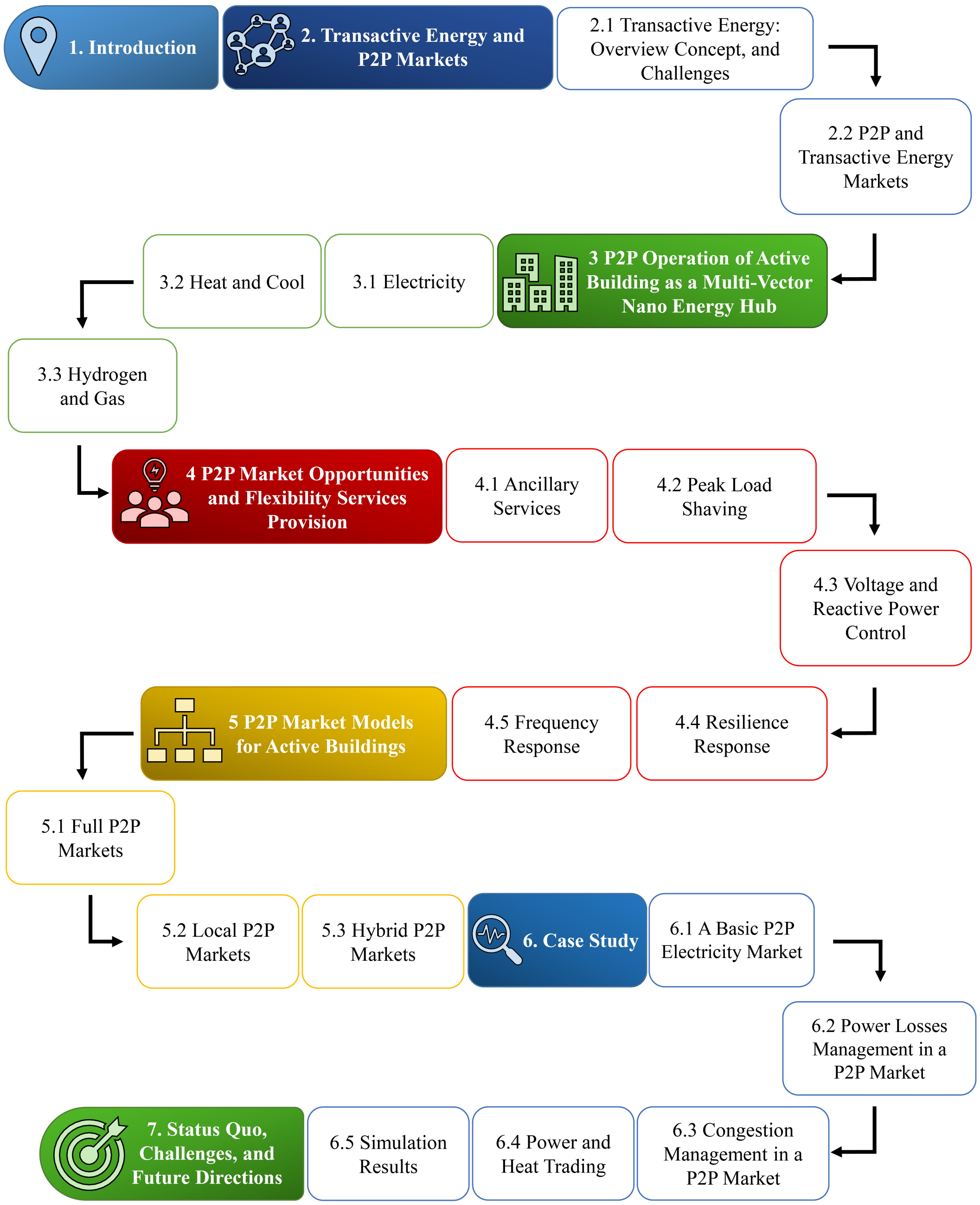

Fig. 12.1: A graphical overview of the presented topics

According to GWAC and as illustrated in Fig. 12.3, the entire power system can be segmented into four layers of *residential*, *microgrid*, *local*, and *regional* as explained in the following.

In the residential layer, consumers and prosumers might participate in DSR programs to decrease their energy costs [13] or even make a profit through direct energy trading with other users. Small-scale energy transactions can unlock the opportunity for energy to be seen as a heterogeneous commodity.

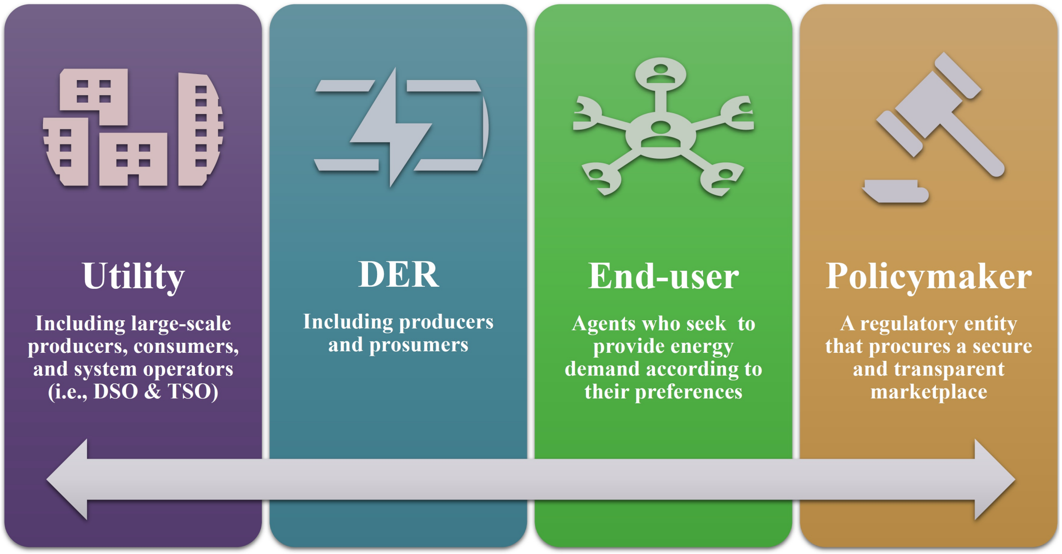

Fig. 12.2: Main Participants of a TE marketplace.

Through this feature, user preferences are considered and customers can choose desired technologies and trade parties for energy provision.

In the microgrid layer, advanced control and management of resources, such as DERs and smart appliances, lead to a more flexible and resilient network [14]. By exploiting different DER technologies together with intelligent devices, active buildings can play a pivotal role in this layer. In the local layer, enhanced data exchange would results in new services for end-users to participate as active agents in the energy market. In this layer, DSO operates as an intermediary agent between the retail and wholesale market participants while matching the demand and supply at the distribution level.

Finally, in the regional layer, by increasing interoperability among local and regional markets, the efficiency and reliability of the system would be improved. In this layer, TSO plays a key role in enhancing interoperability between these two layers.

TE brings significant benefits to electric energy systems. Due to the smart control of resources, TE would suggest new solutions to address the intermittency of RESs, which results in a more reliable network. Additionally, thanks to price signals and the available price information, end-users have the opportunity to not only minimize energy costs but also consider their preferences in energy provision. Furthermore, by providing the right framework for integrating more DERs into the grid, TE contributes to developing more sustainable grids. Besides, economic signals for different generation technologies ensure efficient production and delivery of energy.

Although TE would benefit the grid in several ways, several challenges must be addressed. Due to the necessity of more involvement of end-users, increasing their knowledge about this new framework would affect their engagement with the TE architecture. In other words, they must be convinced why it is important to put aside their passive role and act as an active agent in the system. Furthermore, since all participants can make transactions at any time and the number of users would increase over time, managing all communications and transactions result in scalability issues, which must be tackled.

Fig. 12.3: TE-based classification of the power systems from the GWAC point of view.

Moreover, since successful TE deployment highly depends on ICT infrastructures, investment, and maintenance costs of these devices would be another issue to consider [15].

12.2.2 P2P and Transactive Energy Markets

While TE concept comprises a variety of applications at each level of the electric energy system, it can be categorized into the following three main areas [8].

- **Transactive network management:** Managing the electricity supply chain through the centralized, decentralized, or distributed operation of microgrids and aggregators;
- **Transactive control:** Exploiting DSR approaches, such as Time-of-Use (ToU) and direct load control, along with price signals for operators to keep the balance of supply and demand;
- **P2P markets:** Enabling direct energy trading among small-scale participants.

Among the aforementioned areas, this chapter focuses on the P2P energy markets and discusses its potentials at active building level.

Among the different DER technologies, RESs are among the promising energy sources at the distribution level that enable the end-users such as buildings and houses to produce energy and share the redundant energy with their neighbors [16]. As a result, they are no longer passive consumers and are able to take a more proactive role as a prosumer. While RESs address environmental concerns and are beneficial from different aspects, they bring some challenges to the operation of the electric power networks [17].

Among all TE solutions, the concept of P2P market is the one with the promising future for facilitating the contribution of the RESs into the energy networks.

P2P markets can be beneficial for prosumers as well. In conventional electricity markets, prosumers with energy surplus have only three options of curtailing production, storing energy, or selling the surplus to the grid. However, by employing P2P markets, prosumers would have another option of trading the surplus with neighbors and other network participants. As a result, instead of being a challenge for the network, DERs become a new opportunity for both of the grid operators and end-users. Accordingly, following modes can be considered for P2P markets operation in a transactive structure [12]:

- Autonomous operation based on user preferences;
- Based on available bids and offers of other participants;
- Based on incentives and price signals from network operators;
- Based on instructions from the network operators.

In the first operation mode, the only factor that needs to be considered in a trade is the user or community preferences. For instance, for the sake of environmental concerns, a particular consumer may only prefer to buy green energy generated from Photovoltaic (PV) panels. Furthermore, a philanthropic organization/community might decide to perform P2P transactions to provide low-cost energy for those who are struggling with energy poverty.

The second operation mode suggests a more economic-based structure in which demand and supply and bid-ask price strategies are the only deciding factor for participants [18]. Consequently, a P2P energy market would be similar to stock exchanges where each person can submit buy-sell orders for a certain amount of shares at the desired price. Accordingly, an order book is constructed in which relevant transactions would be matched with each other.

In the third operation mode, DSO is able to affect the P2P market and lead transactions by providing price signals. For example, by increasing the energy price at peak-hours or providing economic incentives, DSO can encourage P2P trading at those periods to lower down peak-load of the network. Likewise, in the occurrence of congestion on grid lines, by assigning a penalty value to transactions on those lines, DSO can perform congestion management in the P2P market [19]. Furthermore, aggregators can participate in DSR programs by allowing P2P trading among their clients [8].

Finally, in the last operation mode, DSO has full control and management over the P2P market. In this mode, all transactions must be validated and accepted by DSO before taking place. Furthermore, by occurring grid problems, such as contingency or voltage regulation, local P2P markets may be employed as service providers for the main grid.

It can be noticed that among these operation modes, the first two gives agents the maximum privilege for performing a transaction, even if it may not be the suitable choice for the grid according to no supervision from DSO. On the other hand, the last two modes would be more secure and reliable for the grid while agents are more constrained. Consequently, in a TE framework, agents must be able to changes between these four modes according to the market and grid circumstances [12].

In the rest of this chapter, various potentials inside active buildings and methods of using them for different P2P operation modes are discussed.

12.3 P2P Operation of Active Building as a Multi-Vector Nano Energy Hub

The building is the intersection of different energy sectors such as electricity, gas, heat and cool, and water (see Fig. 12.4). In this section, we focus on the P2P operation of such an energy hub.

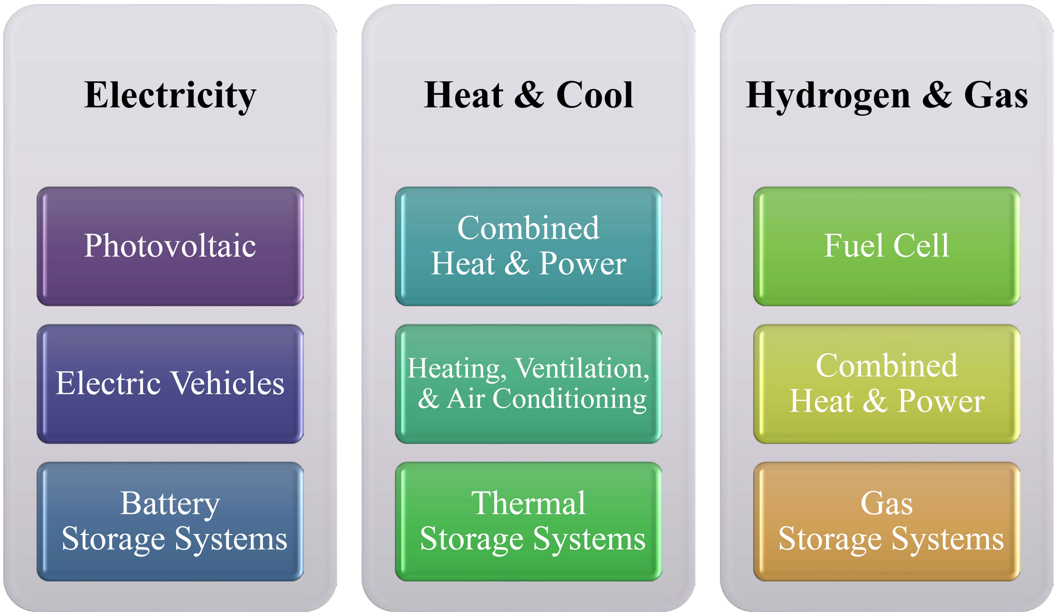

Fig. 12.4: Different technologies inside a community of active buildings

12.3.1 Electricity

In this subsection, different technologies for producing and storing electricity in buildings area is introduced which enable buildings to participate in P2P electricity trading.

12.3.1.1 Photovoltaic and Battery Storage Systems

Since solar PV provides clean and low-cost energy, it is one of the most popular technologies for energy production. Because of the intermittent nature of renewable energies, most of the case buildings exploit Battery Storage Systems (BSS) to save energy for other times of the day. Through the traditional structures, these buildings are only allowed to trade energy with the main grid. For instance, each active building makes use of DERs to supply its demand. If the internal generation does not cover the demand, active building must buy energy at fid-in tariffs from the grid. On the other hand, by covering the demand and having a surplus of energy, each active building is only allowed to sell energy at export tariffs to the grid [20].

On the other hand, by integrating a P2P market, each active building has the opportunity to store its excess energy to use it later that day or sell it to the other buildings at a price higher than export tariffs but also lower than fid-in tariffs. Similarly, other buildings can provide their demand at a lower price compared with fid-in tariffs. As a result, a revenue flow would be shaped in the community in which benefits all participants.

In summary, PV storage systems in active buildings can result in the following opportunities for the grid operation:

- P2P energy trading during peak-hours would result in eliminating the stress from the grid and reducing the need for spinning reserves that mostly work with fossil fuels.

- Active buildings with only solar PV can sell the surplus to the building, which has BSS. Accordingly, the building with BSS either can use the energy to cover its load or participate in the P2P market.
- A higher-level actor, such as a community manager or even DSO, can use BSS to buy energy from buildings with solar PV and sell it later to the local consumers. The resulted profit may be used in line with community interests or enhancing its infrastructures.

12.3.1.2 Electric Vehicles

Due to concerns related to greenhouse gas production, by providing different incentives, governments encourage Electric Vehicles (EVs) deployment. Despite environmental advantages, EVs would cause several challenges for electricity grids, e.g., frequency regulation, voltage stability, operational costs [21]. Moreover, because of the random behavior of drivers, EVs would create an unpredictable load for the grid, which increases the need for spinning reserves and new grid investments.

In conventional methods under Vehicle-to-Grid (V2G) concept, an optimized schedule for charging/discharging of each EV is determined to enhance load profile and grid stability. Through this concept, each EV would be controlled by an aggregator, which uses the potential of EV batteries to alleviate peak-demand.

Although the V2G concept is a suitable method to manage large-scale EV integration, P2P energy sharing would provide new opportunities for EVs to not only provide grid services but also make a profit out of local energy trading without an intermediary agent.

According to [21] in a P2P energy scheme, EVs can be divided into two groups. The first group comprises EVs that have excess energy after performing their scheduled trips. On the other hand, other EVs need to be charged at different intervals to be able to reach their destinations. In a community of active buildings and having a shared parking spot for residents of each building, all EVs would be able to trade energy with one another. Moreover, each parking spot can be connected to other spots in the community to form a larger scale local market. Hence, each EV is able to trade a particular amount of energy at an agreed price. It should be mentioned that the energy price in the P2P market should be lower than grid tariffs at that specific time to incentivize local trading.

12.3.2 Heat and Cool

Heating and cooling are among the most essential needs of each building. In this subsection, it is described how different units can be employed to enable buildings to trade energy not only as electricity but also as heat power.

12.3.2.1 Heating, Ventilation, and Air Conditioning System

According to a report, buildings are responsible for about 40% of the end-use energy, which half of that is consumed by Heating, Ventilation, and Air Conditioning System (HVAC) systems [22]. Hence, by controlling the indoor temperature through the HVAC system in each building, a flexible community of buildings would be shaped, which can participate in different DSR programs. Besides, allowing P2P energy sharing among buildings with HVAC systems would provide several opportunities as follows:

- By participating in DSR programs or intentionally deviating from comfortable temperature, energy usage would be decreased at particular times. Hence, buildings with DERs, such as solar PV, have more energy surplus to offer in the P2P market, and consequently, they can make more profit.
- By reducing the consumption of the HVAC system according to the desired temperature range, each building can sell its demand right at particular times to other buildings in a p2p manner.
- According to [22], integrating a P2P energy market into a community of buildings would result in more efficient use of HVAC systems, and indoor temperature would get closer to a comfortable temperature.

12.3.2.2 Combined Heat and Power Systems

Along with electricity, thermal energy is also an important demand for buildings that need to be supplied. By using the extracted heat from electricity generation, Combined Heat and Power Systems (CHP) systems can provide heat and electricity simultaneously. The resulted heat in conventional generators gets wasted which causes a reduction in energy efficiency, while by using a CHP system it can be converted to hot water or steam to supply thermal demand.

By using CHP systems through a P2P market, each building is able to not only sell electricity but also exchange thermal energy to other buildings. Through interconnecting buildings using pipelines, the hot water can flow to other buildings. Hence, along with electricity, the surplus of thermal energy can also be traded locally, which results in both power and heat optimization.

12.3.3 Hydrogen and Gas

In this subsection, the role of gas and hydrogen units in P2P trading of the buildings is discussed.

12.3.3.1 Fuel Cell Combined Heat and Power System

Despite the high system costs, Fuel Cell Combined Heat and Power (FC-CHP) systems provide several benefits for the power grid, e.g., producing power and heat efficiently, reducing GHG, lowering energy costs. Hence, FC-CHP has been one of the attractive DERs for supplying local loads, which reduces the dependency of buildings on the main grid. Along with power production, the exhausted heat from FC would be used to heat the input water of the building. By storing the hot water in a storage tank, it can be used for supplying hot water needs of the building, e.g., conditioner, bath, toilet. As a result, in many buildings and dwellings, the FC-CHP system is the main source of energy production.

Integrating a P2P energy market can also leverage the benefits of the FC-CHP system. In a community of buildings with FC-CHP, each fuel cell working under its rated power output, can participate in local energy trading and sell its surplus to other building that reached their rated power but still not fulfilling their demand. Hence, the need for BSS and consequently the investment costs would be reduced. Furthermore, the opportunity of local trading would result in increasing FC output, which results in more efficient power and heat production.

According to the results of [23], without employing a P2P market, most of the buildings are forced to provide energy from the main grid, while fuel cells of other buildings might work in low power output. On the other hand, by integrating a local energy market, the import of energy would be decreased and most of the demand is provided with the FC-CHP system of the building and the P2P market.

12.3.3.2 Gas Storage Systems

Power-to-Gas (P2G) technology has attracted a lot of attention in recent years. P2G units can convert energy into hydrogen gas with an approximate efficiency of 80%. On the other hand, hydrogen fuel cell is able to convert gas to electricity with an efficiency of around 40%-60% [24]. By comprising a P2G unit along with a gas storage unit and hydrogen fuel cell, Gas Storage Systems (GSS) can store electricity in gaseous form and convert it back to electricity at particular times.

Exploiting GSS would result in the proper integration of RES and addressing the intermittent nature of renewable energies. For instance, when export tariffs get much lower than import tariffs, the energy surplus from PV panels can be converted to hydrogen and be transformed back to electricity in times with lower PV generation. Hence, the export and import of the main grid would be reduced considerably.

Moreover, by employing a P2P market, each building with GSS can participate in the local market as a prosumer. At certain times with available PV generation, it can act as a consumer and buy the excess energy. While at other times with zero or lower PV generation it can be a producer by selling energy back to other buildings.

According to results from [24], without employing GSS and a P2P market, PV prosumers would sell their surplus to the grid and in other times a high amount of energy would be imported from the utility. However, by using GSS through a local market, a portion of the excess generation of PV panels would be sold to building with GSS and at other times, GSS would decrease energy import from the grid by supplying the community through the P2P market.

12.4 P2P Market Opportunities and Flexibility Services Provision

In the previous section, different technologies in active buildings and their possible interactions through P2P markets have been proposed. P2P transactions in a community can also bring new opportunities for grid services provision. According to the potentials in the community and the diversity of technologies, several services can be realized to be provided for the main utility, as shown in Fig. 12.5. Hence, in the following subsections, the contribution of P2P markets in providing different services is discussed.

12.4.1 Ancillary Services

Ancillary services can be considered as a variety of actions that help the grid operator to maintain the secure operation of the power system while balancing demand and supply. the number of ancillary services and the purpose of them might be different in each part of the world. Several common services include energy imbalance service, operating reserves, frequency response, etc.

Ancillary services provision can be realized on both the demand and supply sides of the power system. On the supply side, most of the time, these services would be provided by large-scale power plants which result in a considerable increase in operational costs. On the other hand, ancillary services can also be provided through DSR programs on the demand side of the system.

The diversity of DERs and appliances in a community of buildings would bring a new option of providing ancillary services through P2P energy transactions. This concept is called "*federated power plants*", which can unlock new opportunities for the P2P energy market while addressing several challenges faced by top-down hierarchical structures [25].

Fig. 12.5: Different flexibility services through P2P transactions inside a community of active buildings.

In a P2P market, prosumer buildings can sell their surplus to other consumers and prosumers. However, for reaching demand and supply balance at each time-step, some buildings might need to trade energy with the main grid. Accordingly, all participants can also be allowed to trade ancillary services with the utility. For instance, to provide peak shaving/valley filling services, each consumer/prosumer can adjust its consumption/production to support the operational needs of the grid. Consequently, it not only contributes to a more secure operation and management of the utility but also results in more profits for the small-scale participants.

The operation of such a structure can be performed through three mechanisms, namely, P2P, P2G, and ancillary services. At first, each active building would use DERs and flexible loads to procure the required energy at the minimum cost. Then, after supplying its internal demand, the excess energy would be traded locally with other buildings through a P2P mechanism.

However, due to different preferences, prices, or conditions for energy transactions, likely, some asks and bids do not get matched with each other, forcing buildings to trade energy with the main grid. In this situation, active buildings would participate in a P2G mechanism to sell their excess energy or buy more energy to supply internal loads. Therefore, the power utility would supply loads at retail prices and buy energy at export tariffs which are relatively lower than retail prices. It makes the community of buildings a price taker which can be considered as a typical customer from the perspective of the grid [26].

Then, according to the other two mechanisms, the utility would evaluate its operational challenges (e.g. congestion, frequency deviation, voltage deviation) to provide price signals and incentives for ancillary services provision. Accordingly, the grid operator would determine the actions that contribute to reaching a secure operation, namely peak shaving, and request these actions from P2P market participants through ancillary services. This mechanism would be performed in three steps [26]:

- **Submission of asks for ancillary services:** According to the current status of the system and future assessments, the grid operator would specify the type, the amount, and the price of required ancillary services and announce them to P2P market participants.
- **Submission of bids from P2P market participants:** After determining services and their prices, all buildings in the P2P market aiming to maximize their economic benefits would respond to broadcasted services and submit their bids for ancillary services provision.
- **The final decision on ancillary services provision:** After receiving all bids from the P2P market, the grid operator would decide to accept/reject orders and purchase services according to the grid conditions and offers submitted by buildings.

Hence, three different markets for P2P transactions, peer-to-grid trading and ancillary services can be realized. These markets might be operated sequentially or simultaneously. In the case of sequential operation, some levels of sub-optimality may appear in the system. On the other hand, a simultaneous operation would lead to a more complex structure. Moreover, in some countries, such as Great Britain, ancillary services may be procured by different entities, such as DSO or electricity provider, which makes the simultaneous operation of energy and ancillary services more difficult. In such situations, designing and operating separate mechanisms seems to be a more feasible and flexible option [26].

It should also be noted that according to the type of ancillary services, some buildings might be forced to deny their transactions in the P2P market. In such circumstances, there should be a procedure to assign an extra payment to compensate for the revenue losses of the service provider due to the violated transactions.

12.4.2 Peak Load Shaving

Although the challenge of peak load periods has been around for many years, integrating DERs, such as EVs, would make this challenge more crucial to address. In conventional approaches, grid reinforcements would be exploited to solve the peak load problem. However, it is not a cost-effective approach and due to the high dependency on fossil fuels, it increases environmental concerns.

On the other hand, unlocking the potential flexibility of demand-side resources can be a relatively low-cost solution for peak load shaving. The demand-side flexibility is conventionally provided by large-scale customers. However, using local P2P markets can be a suitable enabler to provide market access for small-scale customers willing to offer flexible services. Hence, not only small-scale users would minimize their energy costs but also DSO would use this capacity to maintain the secure operation of the grid. As a result, in recent years, exploiting transactive approaches and local market designs to provide system flexibility has attracted a lot of attention from policymakers.

The local market can be operated in two modes of with or without an intermediary agent. By the lack of a third party, the P2P market would incentivize buildings to trade locally at peak hours due to the high energy prices at the wholesale market. Therefore, in peak periods, buildings would sell their surplus at a lower rate compared to the main grid and at the same time at a higher rate compared to export tariffs. Furthermore, by enabling prosumers to perform direct P2P transactions with the main grid, they can sell energy at higher prices in peak periods. As a result, prosumers would make more profits while the main grid would acquire more generation at peak periods.

On the other hand, with the existence of intermediaries, several aggregators can control and manage the DERs of the customers and representing them in P2P transactions with DSO to reach peak load shaving. Moreover, an entity, called TE operator, can be considered to provide a trading platform between aggregators and DSO. Accordingly, three main roles can be categorized as follows [27]:

- **Aggregators:** At first, aggregators would evaluate the energy needs of their customers by scheduling and optimizing DERs and appliances of each building. Then the energy profile would be broadcasted to DSO for further analysis. Next, if DSO announces flexibility requirements, aggregators would assess the flexibility potentials of their customers and accordingly will submit bids to DSO through the TE platform for flexibility provision.
- **DSO:** This entity is responsible to maintain the secure and reliable operation of the grid at each given time or condition. At first, DSO would evaluate the announced energy profiles from aggregators to assure no network violations. By foreseeing any network issues, DSO would request flexibility services for peak periods through orders in the TE platform with specific price and quantity of energy to be decreased.
- **TE operator:** An agent that can be a physical entity or even a virtual platform through ICT, such as blockchain. The main responsibility of the TE operator is to provide a trading platform for aggregators and DSO to submit ask/bid orders. TE operator would match orders and clear the market. Then, the final results and information would be broadcasted to both parties.

12.4.3 Voltage and Reactive Power Control

Voltage deviation is one of the most challenging issues in power systems which invites the use of reactive power compensation strategies. Nowadays, by the proliferation of unexpected loads, such as EVs, and due to the intermittent generation of RES, Volt/VAr control strategies are getting more important. On the other hand, since most DERs are connected to the grid through inverters, they can be suitable resources to compensate for reactive power.

Volt/VAr feedback control strategies, such as Volt/VAr droop control, are promising choices to address reactive power compensation [28]. As a result, the reactive power injection of each inverter can be controlled according to the voltage at the point of common coupling.

Two types of centralized and decentralized can be considered for feedback control. In both types, the only parameter to measure is the voltage at the point of common coupling and the difference is through the way these measurements are processed. Exploiting P2P markets to provide reactive power, is a decentralized way to perform feedback control for compensating reactive power.

In a community of active buildings, due to the diversity of loads and generation, there are lots of inverters that can be employed as a feedback Volt/VAr controller for contributing to reactive power compensation when it is needed. The architecture for such a mechanism might be similar to the one explained in Subsection 12.4.2. Inverters of active buildings can be managed by an intermediary agent, called aggregator or community manager. This agent is responsible to provide reactive power services when there is a call from DSO. Hence, a transactive platform can be realized that DSO can submit asks orders and aggregators, according to the inverters of their customers, can bid for participating in reactive power compensation. Hence, voltage control would be performed in a decentralized way, while providing benefits for both the community of building and DSO.

12.4.4 Resilience Responce

Natural disasters and storms, such as hurricanes, can occur anywhere in the world and humans do not have the control to stop them from happening. Since these events are responsible for many blackouts around the world, power systems should evolve to a more resilient network. For instance, hurricanes Irma and Maria caused massive damage to the power grid of Puerto Rico which resulted in a blackout for around 80% of end-users for one month [29]. Resilience in a power system is defined by the ability of the network to withstand High-impact and Low Frequency (HILF) events and recover rapidly to a stable operation. Although HILF events rarely occur, they can result in immense damage to a power system which makes them an important challenge to solve.

The enhancement of resilience response might be categorized into two types of planning-based and operation-based. In terms of planning-based resilience, although activities like the optimal placing of grid equipment would enhance resilience response it leads to much higher investment costs.

On the other hand, operation-based resilience, such as reconfiguration and rescheduling, might be a more cost-effective option. However, to reach a proper amount of resiliency, a variety of back-up generators and reserves should be considered which would increase investment costs as well [29]. Coupling microgrids together is another operation-based approach to address resilience response which has proven to be a low-cost solution. Thus, in occurring HILF events and switching to islanding mode, each microgrid can share its surplus with other microgrids.

The concept of P2P markets would be best applied to a structure of networked microgrids. In our case, each community of buildings can be considered as a microgrid that can trade energy not only internally but also with other communities. Hence, by occurring any natural disasters and losing connectivity from the main grid, the networked microgrids can support each other to stop blackouts or at least minimize the load curtailment. The diversity of DERs in the community of buildings can facilitate this process. Accordingly, to modes of P2P operation can be realized during HILF events:

- A full P2P market can be realized in which all participants of all communities can trade energy directly with one another. Hence, during an unexpected event and disconnecting from the main grid, each prosumer would optimize its demand and generation and then share its surplus through the P2P market with other prosumers and consumers in all communities. This operation mode results in considering energy as a heterogeneous product and each participant can trade according to its preferences. However, scalability issues are the main characteristic of this design which should be addressed.
- A community-based market can be realized in which each community has a manager or aggregator. These agents are responsible to assess the internal needs and potentials of their communities to not only provide the energy of buildings but also represent them in P2P transactions with the aggregators of other communities. Thus, by occurring HILF events and disconnecting from the utility, all communities can be connected through a common coupling point while they are able to trade energy with each other. As a result, each community aims to maximize its export to reach minimize load curtailment in the whole system which results in the enhancement of resilience response [29].

12.4.5 Frequency Response

Maintaining system frequency at the desired set-point is a crucial task for grid operators. In some countries, such as the UK, frequency should be maintained around 60 Hz, while in some other countries, like the US, it is 50 Hz. Hence, all generators in a national grid should spin at the same speed or otherwise it would cause serious damage to the system. Therefore, grid operators consider different approaches for frequency regulation to prevent frequency deviations and maintain the secure operation of the grid.

Frequency deviation is a result of mismatched demand and supply. If energy generation gets higher compared to the loads, it causes the frequency to increase. On the other hand, in the situation of not being enough generation to feed the loads, the frequency would start to drop. Due to the proliferation of unexpected loads, such as EVs, and also the intermittent generation of RES, nowadays, frequency regulation is getting more critical for operators.

In the case of higher frequency compared to the set-point, the operator can perform frequency regulation by decreasing the output of some generators. On the other hand, if frequency gets lower than the standard set-point, frequency regulation would be more challenging for the grid operator; Especially, when there is no more room to increase the output of generators. In such circumstances, besides ancillary services and regulation markets, considering DSR programs would be a proper option to use demand-side potentials for frequency regulation.

By exploiting different generation technologies and a variety of smart loads, a community of active buildings is capable of providing frequency-responsive services for the grid. Interestingly, in the existence of a P2P market, buildings are not limited to load shifting/shedding to provide DSR but they can procure their loads from the local market in the community to remove the burden from the grid. Furthermore, the whole community of buildings can also participate in frequency services provision. For instance, if the frequency drops below the set-point, a community or microgrid can switch to a P2P operation mode in which all the loads would be supplied through P2P transactions inside/among the buildings. As a result, a considerable amount of loads would be mitigated from the grid and it contributes to frequency regulation. It should be noted that considering such concepts for frequency response highly depends on the internal capabilities of each community along with price signals and incentives from DSO.

12.5 P2P Market Models for Active Buildings

In a community of active buildings, a P2P energy market is a network of buildings capable of exchanging energy with each other. according to the type of connectivity between buildings and the degree of decentralization, three structures can be considered for a P2P market. In the following sub-sections, a brief introduction of these architectures is presented.

12.5.1 Full P2P Markets

A full P2P market is characterized by direct energy trading between peers. Through this mechanism, buildings are able to negotiate to buy/sell a specific amount of energy at an agreed price. This design is the most decentralized structure compared to other P2P architectures since it eliminates the need for an intermediary agent. Fig. 12.6 shows a full P2P market and the connectivity between the agents. It should be mentioned that these connections illustrate communication links between peers, while electricity connectivity can be different [30]. Due to the focus of this chapter, each peer can be considered as an active building with DERs and smart appliances that are capable of consuming, producing, and storing energy.

In a full P2P energy market, the exchangeable product is the excess energy. Thus, a building that has an available energy surplus from its DERs, can sell it to other buildings. Accordingly, a transaction would be performed among buildings to exchange a certain amount of energy at an agreed price.

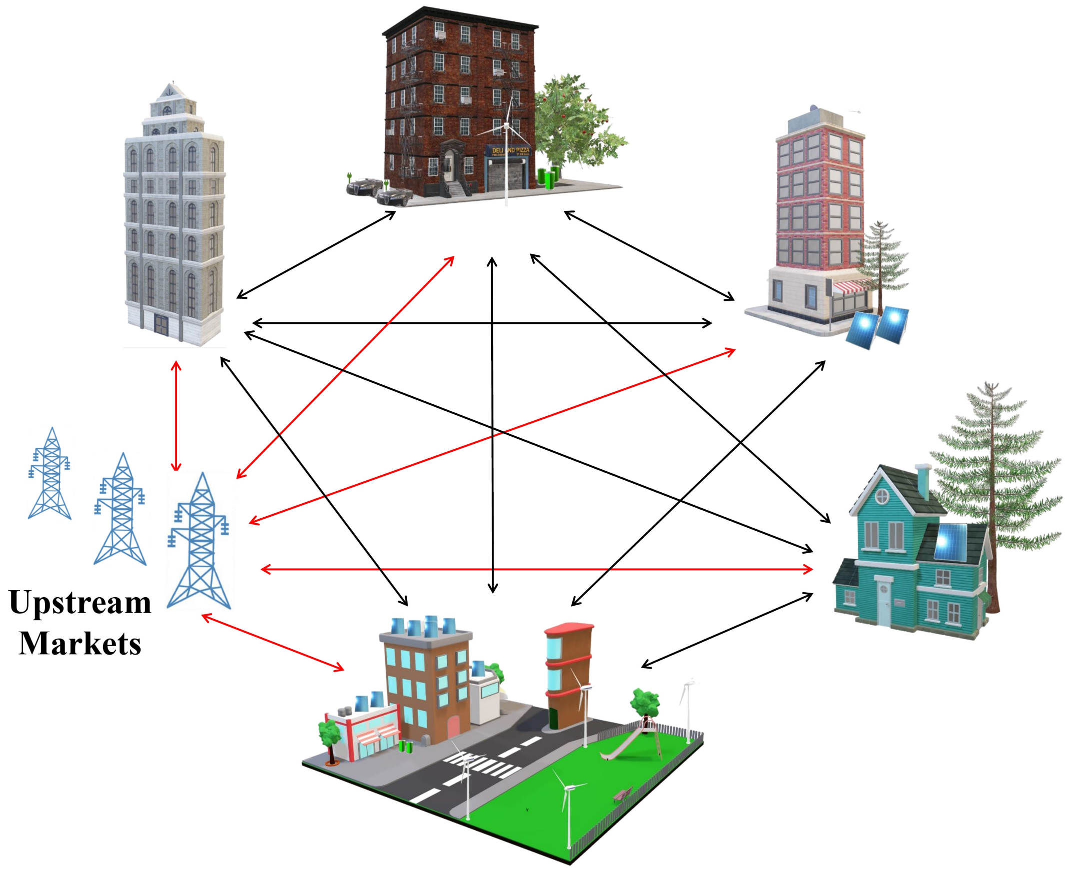

Fig. 12.6: A full P2P market (Arrows represent cash flow and communication links. black arrows: among buildings, red arrows: between each building and other existing markets).

Therefore, all buildings would compete on asking/bidding processes to reach their desired objective, which is buying energy at a low price or selling it at a high rate.

Full P2P markets have diverse advantages for a community of active buildings. First of all, it considers energy as a heterogeneous product. Accordingly, each building might decide to buy energy according to its preferences for the type of resources (e.g. renewable) and trading parties. Furthermore, due to its distributed design, a P2P market has a modular structure which makes it work even by collapsing any peers of the network. Moreover, new buildings can be added to the network at any time, without the need to change operation methods [31]. This modular structure, not only results in a more secure operation of the network but also enables buildings to share updated data and information more conveniently. Furthermore, since energy would produce and consume locally, line usage and transmission losses would decrease considerably.

Due to the possibility for each peer to trade with any other peers in the network in semi-real time, scalability is the main challenge of this design. High investment and maintenance costs for ICT infrastructures are other challenges that should be addressed. It is also necessary to consider that according to the lack of central control, grid operators, such as DSO, have the most limited supervision on the P2P market comparing to two other designs.

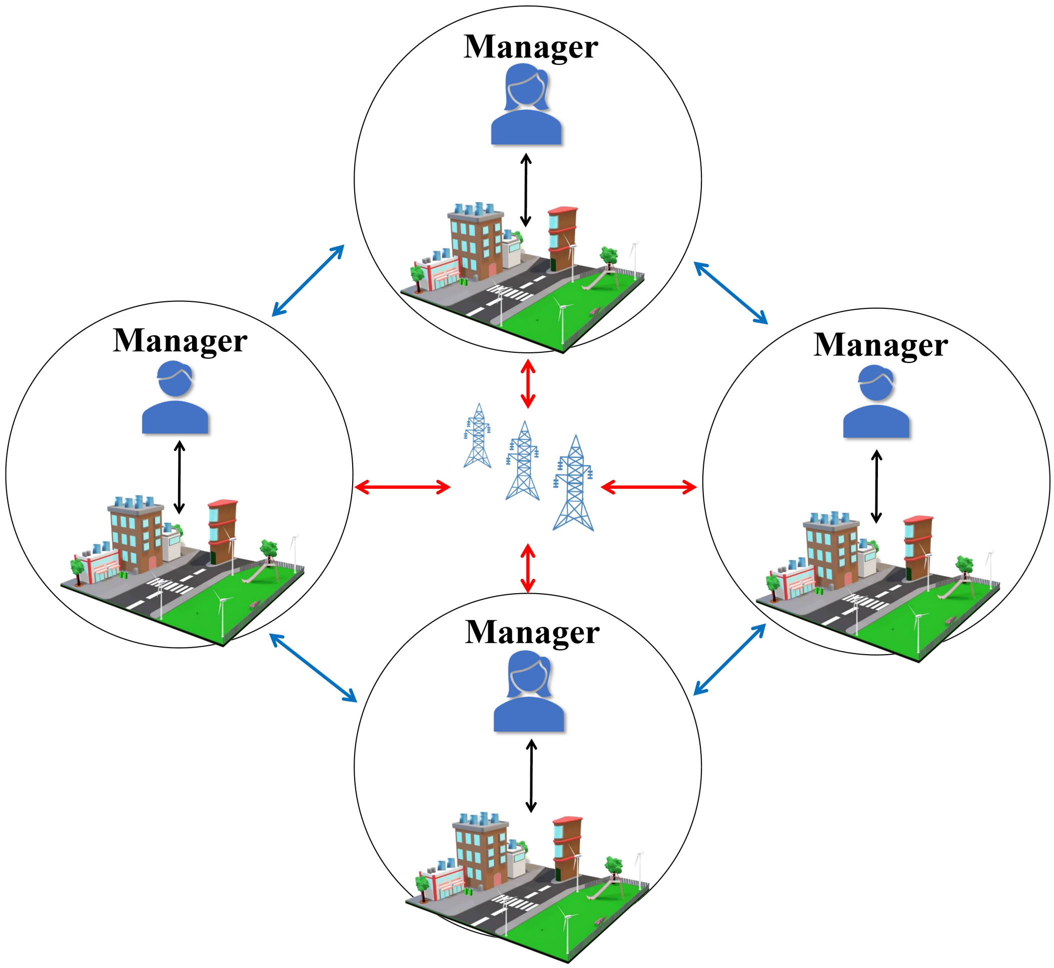

Fig. 12.7: A local P2P market (Arrows represent cash flow and communication links. black arrows: among buildings and the manger, blue arrows: between local communities of buildings, red arrows: between each community and other existing markets).

12.5.2 Local P2P Markets

In this design, instead of individual peers, groups of peers are able to trade energy with each other. Fig. 12.7 illustrates this structure. In a local P2P market, each group/community has a manager which not only manages the entire community by evaluating their needs and potentials but also represents internal peers in trading with other groups/communities in the local area. Although this agent might be referred to with different phrases, such as community/district/microgrid manager, the responsibility of this intermediary agent stays the same.

According to its mechanism, local P2P markets can readily be applied to a community of buildings in which each community has a manager. As a result, several communities can be shaped in the local area which is capable of sharing energy and services not only with each other but also with the main grid. Moreover, peers of each community may have common interests and preferences through energy provision that would be considered in their transactions. These common interests might be environmental goals, such as using green-only production to contribute to the reduction of carbon emission, or social goals, such as supporting those who are in energy poverty by sharing energy at the lowest possible rates.

A local P2P market has several advantages over a full P2P design. First of all, by assigning a manager to each community/group, it has a semi-decentralized structure which can enhance scalability considerably. Furthermore, it increases the collaboration of community members and mobilizes them to reach certain goals. Through their collaboration, different services can also be provided for the main grid, e.g., peak shaving, voltage regulation, congestion management.

Despite the advantages, this design has also some challenges that should be addressed. Comparing to the full P2P architecture, the community manager makes the last decision for energy trading. Hence, this is difficult to consider the interest and preferences of all individual peers in the community simultaneously. Moreover, collecting the information of each peer and managing their needs and expectations would be challenging for the community manager. However, exploiting distributed ledgers, such as blockchain, seems to be a promising solution for such challenges.

12.5.3 Hybrid P2P Markets

A hybrid P2P market can be realized as a combination of two other designs. Hence, in the lower level of the market, peers would trade directly to one another while at the upper-level communities would interact with each other through their community manager [2]. Fig. 12.8 shows the architecture of this design.

A hybrid design would be beneficial since it combines the advantages of two other structures. By using communities as the upper level it would result in scalability enhancement while this structure can be more predictable for grid operators. Simultaneously, each peer can trade with other peers and even communities according to their preferences. However, implementing proper coordination between the two levels of this design is a challenging task that should be addressed.

12.6 Case Study

In previous sections, different structures for P2P markets and their advantages for not only a community of buildings but also the main grid has been discussed. Now, in this section, a P2P market for buildings area is modeled to show the basics of such markets and giving ideas for further research on the subject.

12.6.1 A Basic P2P Electricity Market

Consider a P2P market with a set of peers Γ, which includes two groups of producers Γ_p and consumers Γ_c, capable of trading electricity directly with each other. To model this market, the power injection of each peer P_i is assumed as cumulative trades with neighboring peers:

$$P_i = \sum_{j \in \mu_i} P_{ij} \ , \ \forall \, (i, j) \in (\Gamma, \mu_i) \tag{12.1}$$

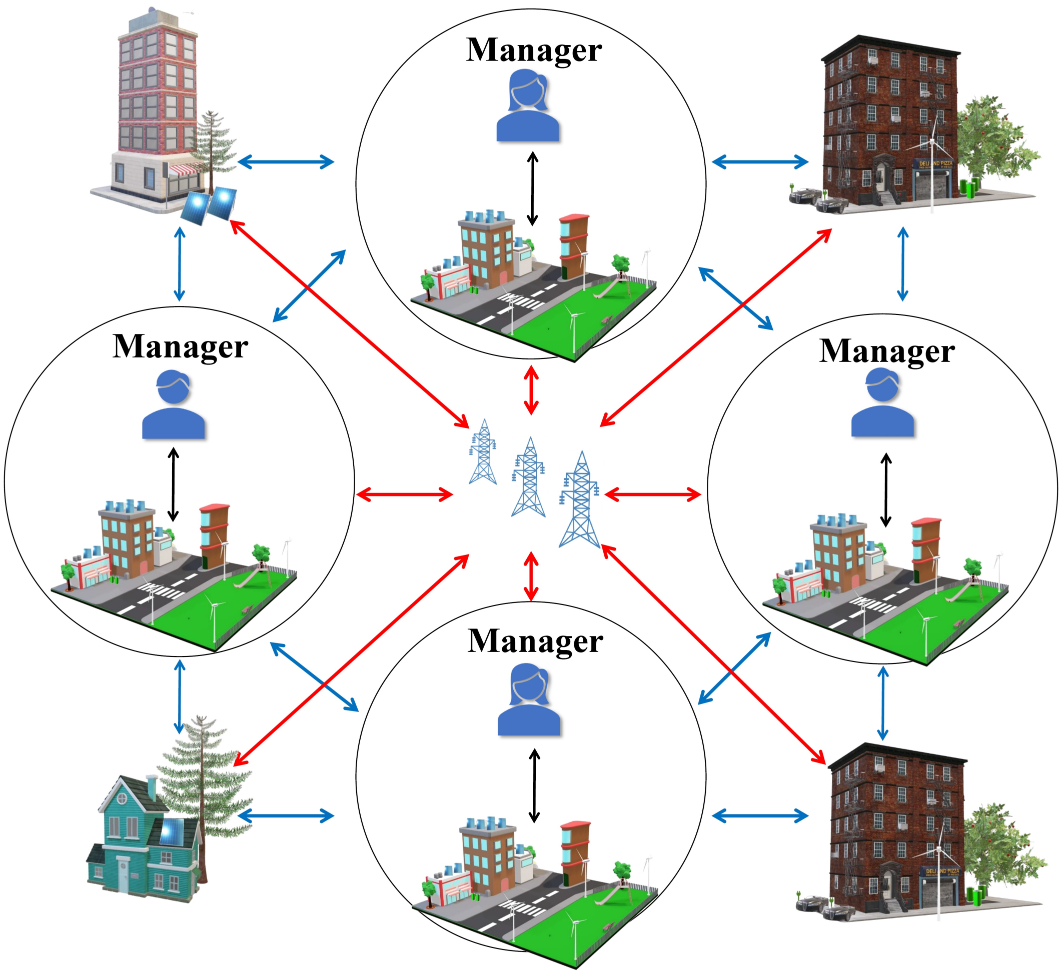

Fig. 12.8: A Hybrid P2P market (Arrows represent cash flow and communication links. black arrows: between buildings and the manger, blue arrows: between all of the buildings and communities, red arrows: transactions of buildings and communities with the main grid).

where $\{P_{ij} | i \in \Gamma, j \in \mu_i\}$ is the set of decision variables that represent the amount of energy traded between peers i and j. Furthermore, μ_i is the set of participants that peer i can trade with. Hence, P_i can also be considered as the amount of all power transactions of peer i. Furthermore, the injected power of each peer is limited by the following constraint:

$$P_i^{min} \leq \sum_{j \in \mu_i} P_{ij} \leq P_i^{max}, \ \forall i \in \Gamma \tag{12.2}$$

where P_i^{min} and P_i^{min} are upper and lower bounds for the injected power of peer i. Furthermore, according to the role of each peer at any given time, the sign of P_{ij} would be determined as follows:

$$P_{ij} \begin{cases} Positive, & i \in \Gamma_p \\ Negative, & i \in \Gamma_c \end{cases} . \tag{12.3}$$

Thus, according to the role of each peer, $P_i^{min} P_i^{max} \geq 0$. Furthermore, the objective function of the problem would be formulated according to the production cost/willingness to pay function of each peer as follows:

$$c_i\left(P_i\right) = \sum_{i \in \Gamma} \frac{1}{2} a_i \left(\sum_{j \in \mu_i} P_{ij} \right)^2 + b_i \left(\sum_{j \in \mu_i} P_{ij} \right) + c_i \ , \ a_i, b_i, c_i > 0. \tag{12.4}$$

Due to the limited insight about the actual utility and cost functions of small-scale agents, these functions are modeled in a quadratic form. However, any other types of functions can be used as long as it is convex [30]. Finally, the balance of each transaction would be ensured through:

$$P_{ij} + P_{ji} = 0 \ , \ \forall \left(i, j\right) \in \left(\Gamma, \mu_i\right). \tag{12.5}$$

Thus, the optimization problem for minimizing operation costs of a P2P market would be formulated as follows:

$$\min \ \ F = \sum_{i \in \Gamma} \frac{1}{2} a_i \left(\sum_{j \in \mu_i} P_{ij} \right)^2 + b_i \left(\sum_{j \in \mu_i} P_{ij} \right) + c_i \ , \ a_i, b_i, c_i > 0 \tag{12.6}$$

subject to:

$$P_i^{min} \ \leq \ \sum_{j \in \mu_i} P_{ij} \ \leq \ P_i^{max} \ , \ \forall i \in \Gamma \tag{12.7}$$

$$P_{ij} \geq 0 \ , \ \forall \left(i, j\right) \in \left(\Gamma_p, \mu_i\right) \tag{12.8}$$

$$P_{ji} \leq 0 \ , \ \forall \left(i, j\right) \in \left(\Gamma_c, \mu_i\right) \tag{12.9}$$

$$P_{ij} + P_{ji} = 0 \ , \ \forall \left(i, j\right) \in \left(\Gamma, \mu_i\right). \tag{12.10}$$

This is a cost allocation problem for the forward market mechanism and does not consider network constraints and grid services, such as reserves and ancillary services. Moreover, for the sake of simplicity, a single time-step formulation is simulated to focus on interactions between different buildings and further developing to include grid considerations. However, it can readily be employed for a multi time-step implementation for any operation horizon.

12.6.2 Power Losses Management in a P2P Market

In Equations 12.6−12.10, the only factor for performing a power transaction is production costs and the amount of willingness to pay. Hence, each peer aims to minimize its energy costs regardless of the effect on the grid operation and network constraints. Hence, in this subsection, a method based on penalty functions is proposed which results in considering network constraints and using the potentials of a P2P market to obtain different grid services.

In this approach, buildings not only consider their preferences but also contribute to power loss reduction by providing energy from transactions that cause minimum energy losses. As one of the most important reasons for energy losses is the resistance of lines, a penalty function based on the total resistance existing in each transaction would be added to the objective function as the cost of power losses [19]. Hence, total resistance between peers i and j can be calculated as:

$$R_{ij} = \sum_{l \in \Lambda_{ij}} r_l \ \ , \ \{\Lambda_{ij} | \, (i, j) \in (\Gamma, \mu_i)\} \subset L = \{1, \ \ldots, l\} \tag{12.11}$$

where L is the set of all lines of the network and Λ_{ij} is the set of lines between peers i and j. Hence, R_{ij}would be the total resistance between each pair of peers. It should be mentioned that the amount of R_{ij} would be derived according to the network topology. Moreover, a radial network is considered since P2P markets usually are implemented at the distribution level of the network. Hence, all lines are series and R_{ij} can be easily calculated. In the next step, a positive variable called the resistance-based penalty α_i, would be defined which represents the amount of penalty that peer i should pay according to the amount of existing resistance in its transactions with other participants. Accordingly, resistance-based penalty function would be defined as:

$$C_i^R \left(P_i\right) = \sum_{j \in \mu_i} \left(R_{ij}\alpha_i\right) \times S_i^R \times P_{ij} \tag{12.12}$$

where S_i^R is the sign parameter which would be determined according to the role of each peer:

$$S_i^R \begin{cases} Positive, & i \in \Gamma_p \\ Negative, & i \in \Gamma_c \end{cases} . \tag{12.13}$$

It should be mentioned that the amount of α_i would be decided by the grid operator according to the operational conditions and network situation at any given time. Finally, by adding Equation 12.13 to Equation 12.6, the objective function would turn into:

$$F^R = \sum_{i \in \Gamma} \left[\frac{1}{2} a_i \left(\sum_{j \in \mu_i} P_{ij} \right)^2 + b_i \left(\sum_{j \in \mu_i} P_{ij} \right) + c_i + \sum_{j \in \mu_i} \left(R_{ij}\alpha_i\right) \times S_i^R \times P_{ij} \right] . \tag{12.14}$$

According to this model, along with minimizing operational and energy costs, peers would also consider energy losses in their transactions. Furthermore, since these penalties show the usage of lines in each transaction, it can also be used as a cost recovery tool for grid operators to assign fees particularly to each peer instead of socializing it to the whole participants. Additionally, due to the reduction in line usage, this method would also result in some levels of congestion management. However, by occurring congestion on a particular line or a group of lines, there should be a more exact method to eliminate congestion; Which is the subject of the next subsection.

12.6.3 Congestion Management in a P2P Market

Congestion management is an essential part of the power systems operation. Due to the decentralized nature of P2P markets, it is hard to predict the behavior of each peer and their transactions. Hence, grid operators need a tool for particular situations to ensure the secure operation of the grid at any given time. By using the approach proposed in [19], congestion management in a P2P market can be performed according to price signals and incentives broadcasted from the grid operator. At first, the set of congested lines σ should be specified according to the power flow of the network. Then, a binary variable θ can be defined as:

$$\theta_{ij} = \begin{cases} 0 & \sigma \not\subset \Lambda_{ij} \\ 1 & \sigma \subseteq \Lambda_{ij} \end{cases} , \ (i, j) \in (\Gamma, \mu_i) \tag{12.15}$$

which determines the existence of congested lines between peers i and j. Then, the same as the previous subsection, a congestion-based penalty function is considered as follows:

$$C_i^C = \sum_{j \in \mu_i} \left(\theta_{ij}\beta_i\right) \times S_i^C \times P_{ij} \tag{12.16}$$

where S_i^C is the sign parameter which would be determined according to the role of each peer:

$$S_i^C \begin{cases} Positive, & i \in \Gamma_p \\ Negative, & i \in \Gamma_c \end{cases} . \tag{12.17}$$

Now, according to different operational conditions, the grid operator can signal an amount of penalty β_i for transactions on congested lines. Therefore, the power flow on congested lines would be reduced. Finally, the objective function for the problem turns into:

$$F^C = \sum_{i \in \Gamma} \left[\frac{1}{2} a_i \left(\sum_{j \in \mu_i} P_{ij} \right)^2 + b_i \left(\sum_{j \in \mu_i} P_{ij} \right) + c_i + \sum_{j \in \mu_i} \left(\theta_{ij}\beta_i\right) \times S_i^C \times P_{ij} \right]. \tag{12.18}$$

It should be mentioned that both penalty functions F^C and F^R can exist at the same time to achieve simultaneous management of congestion and power losses [19]. Moreover, since developed models are convex, they can be solved with a variety of centralized and decentralized optimization approaches.

12.6.4 Power and Heat Trading

A community of active buildings may employ different technologies for producing energy. In previous subsections, a basic model for electricity trading in the community has been developed. As mentioned in subsection 12.3.2.2, P2P transactions are not limited to electricity. Hence, other forms of energy, such as heat, can be traded in the community of buildings. Hence, in this subsection, the proposed model in equations 12.6-12.10 would be developed to also consider CHP technology and heat transactions between peers.

Consider a community with a set of peers Γ, which includes three groups of heat and electricity producers Γ_p, heat and electricity consumers Γ_c, and CHP units Γ_{chp}, which are able to trade energy directly with one another. The heat injection of each peer H_i would be:

$$H_i = \sum_{j \in \mu_i} H_{ij}, \ \forall (i, j) \in (\Gamma, \mu_i) \tag{12.19}$$

where, $\left\{H_{ij} | i \in \Gamma \ , j \in \mu_i \right\}$ is the set of decision variables that represent the amount of energy traded between peers i and j. Moreover, the injected heat of each peer would be limited by:

$$H_i^{min} \ \leq \ \sum_{j \in \mu_i} H_{ij} \ \leq \ H_i^{max} \ , \ \forall i \in \left\{\Gamma_p, \Gamma_c\right\} \tag{12.20}$$

where, H_i^{min} and H_i^{min} are upper and lower bounds for the injected heat of peer i. Furthermore, the sign of H_{ij} would be determined according to the role of the peer at the given time:

$$H_{ij} \begin{cases} Positive, & i \in \Gamma_p \\ Negative, & i \in \Gamma_c \end{cases} . \tag{12.21}$$

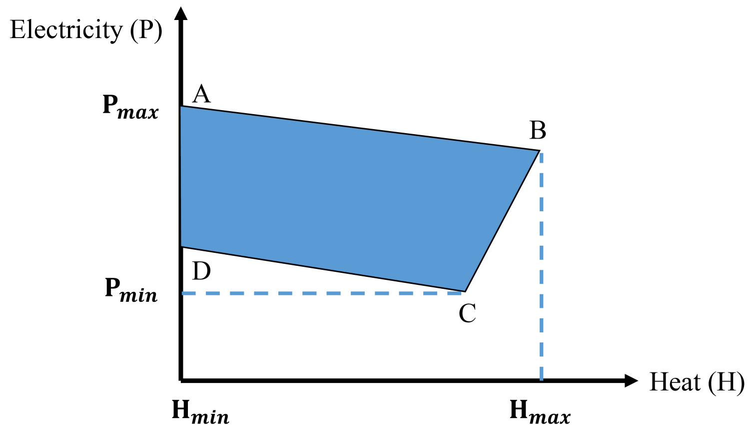

Fig. 12.9: An example of the feasible region for the operation of CHP units.

Next, the objective function in equation 12.4 would turn into:

$$\min F = C^p(i) + C^h(i) = \tag{12.22}$$

$$\sum_{i\in\Gamma}\left[a_i^p\left(\sum_{j\in\mu_i}P_{ij}\right)^2 + b_i^p\left(\sum_{j\in\mu_i}P_{ij}\right) + c_i^p\right] + \sum_{i\in\Gamma}\left[a_i^h\left(\sum_{j\in\mu_i}H_{ij}\right)^2 + b_i^h\left(\sum_{j\in\mu_i}H_{ij}\right) + c_i^h\right]$$

where $C^p(i)$ and $C^h(i)$ are cost/willingness to pay functions of peer i for electricity and heat, respectively. Furthermore, the balance of each heat transaction would be ensured through:

$$H_{ij} + H_{ji} = 0\ ,\ \forall (i,j) \in (\Gamma, \mu_i) \tag{12.23}$$

Next, CHP units, with the ability to produce electricity and heat simultaneously, can be added to the model. The production of these units is limited to a feasible operation region, as shown in Figure 12.9. Hence, P_i and H_i for CHP units are limited to this region and can be modeled as:

$$\sum_{j\in\mu_i}P_{ij} - D_p \geq \left(\sum_{j\in\mu_i}H_{ij} - D_h\right) \times \left(D_p - C_p\right)/\left(D_h - C_h\right)\ ,\ \forall i \in\ \Gamma_{chp} \tag{12.24}$$

$$\sum_{j\in\mu_i}P_{ij} - A_p \leq \left(\sum_{j\in\mu_i}H_{ij} - A_h\right) \times \left(A_p - B_p\right)/\left(A_h - B_h\right)\ ,\ \forall i \in\ \Gamma_{chp} \tag{12.25}$$

$$\sum_{j\in\mu_i}P_{ij} - B_p \geq \left(\sum_{j\in\mu_i}H_{ij} - B_h\right) \times \left(B_p - C_p\right)/\left(B_h - C_h\right)\ ,\ \forall i \in\ \Gamma_{chp}. \tag{12.26}$$

Therefore, the optimization problem for minimizing operation costs of a P2P market, with consideration of heat trading and CHP units, is formulated as follows:

$$\min F = C^p(i) + C^h(i) \tag{12.27}$$

subject to:

$$P_i^{min} \leq \sum_{j \in \mu_i} P_{ij} \leq P_i^{max} , \forall i \in \{\Gamma_p, \Gamma_c\} \tag{12.28}$$

$$H_i^{min} \leq \sum_{j \in \mu_i} H_{ij} \leq H_i^{max} , \forall i \in \{\Gamma_p, \Gamma_c\} \tag{12.29}$$

$$\sum_{j \in \mu_i} P_{ij} - D_p \geq \left(\sum_{j \in \mu_i} H_{ij} - D_h \right) \times \left(D_p - C_p\right) / (D_h - C_h) , \forall i \in \Gamma_{chp} \tag{12.30}$$

$$\sum_{j \in \mu_i} P_{ij} - A_p \leq \left(\sum_{j \in \mu_i} H_{ij} - A_h \right) \times \left(A_p - B_p\right) / (A_h - B_h) , \forall i \in \Gamma_{chp} \tag{12.31}$$

$$\sum_{j \in \mu_i} P_{ij} - B_p \geq \left(\sum_{j \in \mu_i} H_{ij} - B_h \right) \times \left(B_p - C_p\right) / (B_h - C_h) , \forall i \in \Gamma_{chp} \tag{12.32}$$

$$P_{ij} \geq 0 , \forall (i,j) \in \left(\Gamma_p, \mu_i\right) \tag{12.33}$$

$$P_{ji} \leq 0 , \forall (i,j) \in (\Gamma_c, \mu_i) \tag{12.34}$$

$$H_{ji} \geq 0 , \forall (i,j) \in \left(\Gamma_p, \mu_i\right) \tag{12.35}$$

$$H_{ji} \leq 0 , \forall (i,j) \in (\Gamma_c, \mu_i) \tag{12.36}$$

$$P_{ij} + P_{ji} = 0 , \forall (i,j) \in (\Gamma, \mu_i) \tag{12.37}$$

$$H_{ij} + H_{ji} = 0 , \forall (i,j) \in (\Gamma, \mu_i) . \tag{12.38}$$

This is a cost allocation problem that can be used for the forward market mechanism. However, despite the basic P2P model, it considers technical constraints of the generation technology, which is the CHP unit in this example. Following the same method, one may further develop this model by adding technical constraints of other generation technologies and different appliances that are available in active buildings.

12.6.5 Simulation Results

To simulate the proposed models, an 11-bus radial distribution network is considered as the case study (see, Fig. 12.10). The simulation is performed at a particular time-step in which the role of each building is specified as there are 11 consumers $\{C_1, C_2, \ldots, C_{11}\}$ and 9 producers $\{G_{12}, G_{13}, \ldots, G_{20}\}$, including the main grid. This would help to focus on the interactions among participants and their responses to signals from grid operators. However, as mentioned in Subsection 12.6.1, it can easily be developed to perform a multi time-step simulation which invites the consideration of technical constraints, such as ramp up/down of producers and the flexibility of consumers. It should be mentioned that each peer can be an entire building or even a small office or household inside the building. For further information about the case study and input data, the reader is referred to [19].

12.6.5.1 Transactions in the Basic Model

By using Equations 12.6–12.10, peers interact with each other to minimize their energy costs. Hence, each producer that sells energy at a lower price would be the first choice of consumers. Table 1 shows

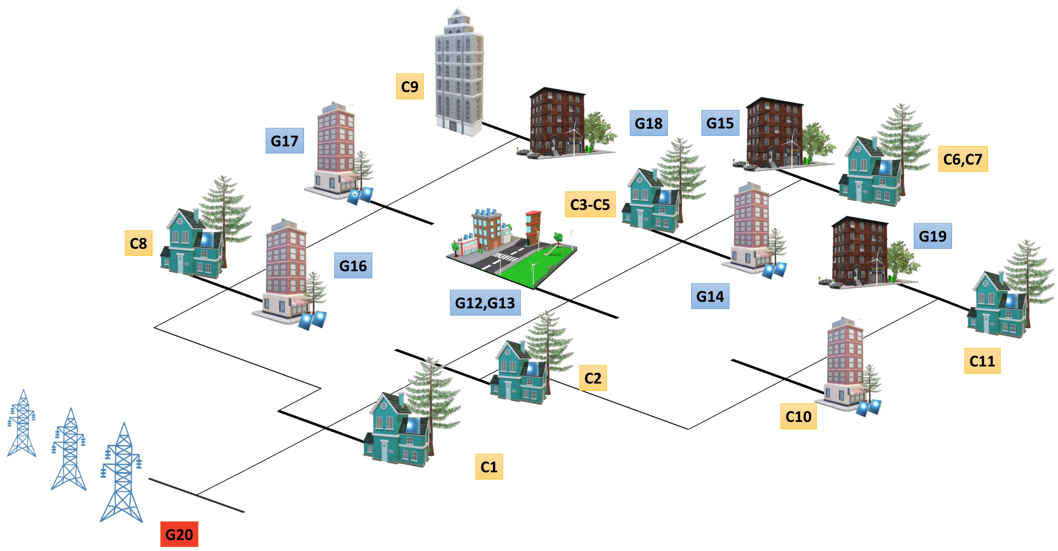

Fig. 12.10: The 11-bus radial distribution network test case.

Table 12.1: Transactions among buildings and the main grid in the basic model

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**
G12	0	0	220	0	0	235	0	0	195	140	0
G13	0	0	220	0	0	235	0	0	285	53	18
G14	0	0	0	246	262	0	122	30	0	191	0
G15	0	166	0	46	49	0	29	29	0	357	74
G16	0	0	0	0	0	0	0	0	0	0	0
G17	0	0	0	0	0	0	0	0	0	0	0
G18	0	0	0	0	0	0	0	0	0	0	0
G19	0	0	0	0	0	0	0	0	0	0	0
G20	420	344	0	77	80	0	60	481	0	140	748

P2P transactions among different participants. It is clear from Table 12.1 that most of the buildings are willing to trade with the main grid since it offers energy at a relatively lower price than the other producers. However, this might be not desirable for the grid since these transactions may violate several network constraints or cause power losses and congestion.

12.6.5.2 Power Losses Management

Now, by using Equation 12.14 as the objective function and through different amounts of resistance-based penalty α_i, it is possible to achieve power loss reduction in the P2P market. For a better understanding of the impact of this model, a pool-based structure is also considered as a base for comparison. By considering $G20$ as the only producer of the network, the basic P2P model would turn into an economic dispatch problem for a pool-based market. Hence, Table 2 shows the amount of power losses for each structure and different amount of α_i. It can be seen that the maximum reduction in power losses occur in $\alpha_i = 35\left(10^{-3}\$/\mathrm{kW}\Omega\right)$ which is particular to this case study. However, according to the diversity of generation technologies, the number of peers and also the topology of the network, lower or higher power loss reduction can be achieved in other cases.

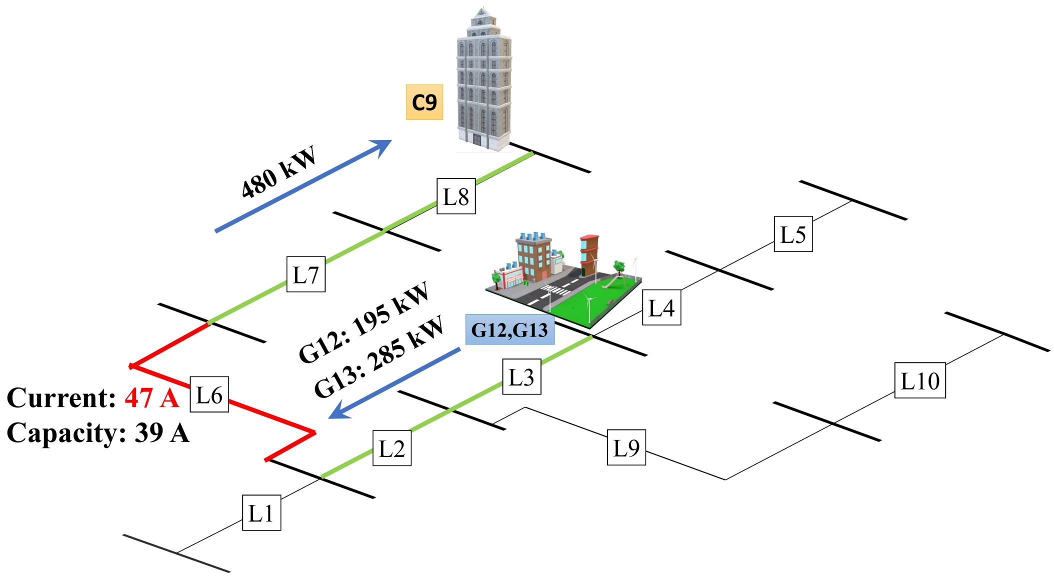

Fig. 12.11: The power flow between $C9$, $G12$ and $G13$ before performing congestion management.

Table 12.2: The amount of power losses in different structures.

α_i ($/kWΩ)	Power Losses (kW)
α_i = 0*	110.76
α_i = 0**	26.95
α_i = 5	8.56
α_i = 10	8.56
α_i = 20	7.97
α_i = 30	7.38
α_i = 35	7.07
*: Pool-Based	**: Basic P2P

12.6.5.3 Congestion Management

One of the advantages of P2P markets is its decentralized approach to solving problems. By using the model in Equation 12.18, with encountering congestion or natural disasters in the power system, the grid operator has a tool to control transactions on congested or damaged lines. Hence, according to the type of incident and the scale of the community, some level of flexibility can be achieved for the main grid. According to the line capacities, in both previous structures, lines 6 and 9 were congested. However, by using the proposed method and $\beta = 5$ (10^{-3}\$/kW), power transactions on these lines would be reduced which result in eliminating the congestion. To investigate the reason for these results Fig. 12.11 and Fig. 12.12 show the transactions of the building $C9$ before and after congestion management. It can be seen that in the basic P2P market, $C9$ prefers to procure its energy from $G12$ and $G13$ which involve one of the congested lines ($L6$). The reason is, in the basic structure, $C9$ only seeks to buy energy at the minimum cost and does not consider the grid situation in its transactions. On the other hand, by using the proposed method for congestion management, $C9$ buys all the energy from $G17$ which only involves one line ($L8$). The same analysis can be performed for $C11$ which results in congestion management on $L9$. Hence, by assigning penalties to congested lines and their

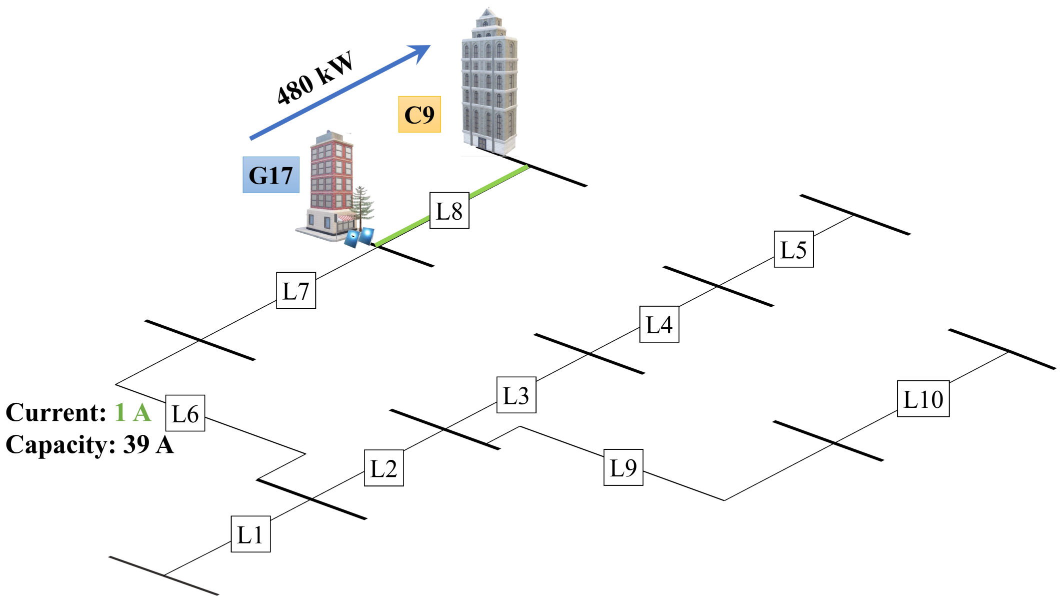

Fig. 12.12: The power flow between $C9$ and $G17$ after performing congestion management.

transactions, the grid operator can achieve congestion management through the operation of the P2P market.

12.6.6 Heat and Electricity Trading

As mentioned before, electricity is not the only tradable product in a community of active buildings. By employing different technologies, such as CHP, buildings are able to trade heat energy with each other. Hence, in this subsection we consider equations 12.27-12.38 to model a P2P market with the existence of CHP units. To simulate this market, the 11-bus network, shown in Figure 12.10, is considered as the test case. Despite the earlier subsections, along with electricity, $C1$-$C11$ have also heat demand, which should be procured through the P2P market. On the other hand, $G12$-$G15$ are able to produce electricity and heat simultaneously through CHP units. Furthermore, $G16$-$G20$ are considered as electricity-only producers in the network. Input data and further information about the case study are available in [32].

Finally, Table 12.3 and Table 12.4 show the heat and electricity transactions between all peers of the network, respectively. This model can be considered as an example for integrating different technologies in the P2P market. It can also be combined with the models proposed in subsections 12.6.2 and 12.6.3 to also achieve power losses reduction and congestion management.

12.7 Status Quo, Challenges, and Future Directions

Decarbonization of the energy systems is a priority all around the world and affected most of the parts of the energy systems. In parallel, the advances in renewable energy generation technologies and

Table 12.3: Electricity transactions among peers with the existance of CHP units

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
CHP12	0	0	0	0	0	0	0	0	338	0	0
CHP13	0	124	288	0	0	0	58	0	0	150	0
CHP14	0	386	152	0	0	0	152	0	0	0	0
CHP15	0	0	0	0	0	0	0	0	142	117	261
G16	0	0	0	59	284	408	0	0	0	0	0
G17	345	0	0	258	53	62	0	0	0	0	101
G18	0	0	0	0	0	0	0	540	0	0	260
G19	0	0	0	0	0	0	0	0	0	460	218
G20	175	0	0	53	53	0	0	0	0	152	0

Table 12.4: Heat transactions among peers with the existance of CHP units

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
CHP12	28	0	0	87	31	0	0	0	31	31	31
CHP13	54	0	170	23	31	39	110	240	31	31	0
CHP14	128	200	0	40	41	82	0	0	41	56	0
CHP15	0	0	0	0	56	69	0	0	46	181	279

BSS and promising reduction in their production costs, along with the smart grid solutions accelerate this evolution. These developments are on both the bulk energy systems (which is mostly managed by the system operators) and the demand-side (which is mainly a result of public awareness about the environmental issues). This evolution on the demand-side has led to an increased rate of uptake of PVs, BSS, and EVs at the level of building and houses which as a result has changed the role of these entities from a passive consumer to an active agent of the energy systems who is able to provide energy services to the network. The recent studies on the peer-to-peer transactions along with the TE provide a proper platform that enables trading of a small amount of energy without any needs to have a third party who guarantees these kinds of transactions. The following directions need to be more investigated to pave the way for the new generation of energy systems and cope with the current challenges:

- Design of an active energy management system (AEMS) that enables a wide range of transactions inside the buildings among the IoT-enabled appliances and residents and also among the buildings and houses in a district area, is a promising direction in this field that need to be more investigated.

- Considering the dynamic and changing state of the demand side energy sources and energy demands, artificial intelligence and machine learning techniques would be an important direction for making a distributed data-driven decision instead of the conventional optimization-based approaches.
- By defining a tradable energy packet (ePKT) instead of current interpretation for energy, the transactions would not be limited to the electricity and are able to be done on any types of energy.
- Another direction is to develop a special cryptocurrency for energy transactions (e.g., we can call them EGY-coin or EGC) or defining a trading mechanism based on the current cryptocurrencies.

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