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Review of demand-side energy sharing and collective self-consumption schemes in future power systems

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ABSTRACT

The widespread use of distributed energy sources provides exciting potential for demand-side energy sharing and collective self-consumption schemes. Demand-side energy sharing and collective self-consumption systems are committed to coordinating the operation of distributed generation, energy storage, and load demand. Recently, with the development of Internet technology, sharing economy is rapidly penetrating various fields. The application of sharing economy in the energy sector enables more and more end-users to participate in energy transactions. However, the deployment of energy sharing technologies poses many challenges. This paper comprehensively reviews recent developments in demand-side energy sharing and collective self-consumption schemes. The definition and classification of sharing economy are presented, with a focus on the applications in the energy sector: virtual power plants, peer-to-peer energy trading, shared energy storage, and microgrid energy sharing cloud. Challenges and future research directions are thoroughly discussed.

KEYWORDS

Energy sharing, future power systems, demand-side energy management, distributed energy resources, sharing economy.

As the largest developing country in the world, China's energy demand is rising to meet the requirement of social and economic development. China's energy structure is highly dependent on fossil fuels such as coal and oil, which makes China the largest fossil-fuel consumer and carbon emitter in the world[1]. However, the depletion of fossil fuels and the emission of greenhouse gases pose significant challenges to society and the environment. Adjusting energy structure is one of the critical tasks facing China's energy development and an important measure to solve China's energy security problems. On September 22, 2020, at the 75th United Nations General Assembly, the Chinese president thoroughly reported China's future energy development path. More specifically, China is committed to working hard for carbon peaking by 2030 and achieving carbon neutrality by 2060.

China's coal fuel is mainly consumed in the power industry, which accounts for about half of China's coal consumption. For these reasons, the decarbonization progress of the electric industry will directly affect the process of achieving carbon peaking and carbon neutrality goals. Therefore, the structural transformation of the energy sector is necessary and urgent. It is well known that the electric industry has mature transmission networks and can easily convert directly to other energy sources. Energy electrification and energy decarbonization are regarded as two critical measures of China's energy structure transition.

Energy electrification facilitates the centralized control of pollutant emissions and improves energy use efficiency. China has made excellent progress in electricity substitution in transportation electrification and electric heating in recent years. The share of electrical energy consumption in end-use energy consumption in China was 28.2% in 2020, compared to the world average of 20.0%[2]. In future, energy supply and consumption electrification still need to improve to achieve carbon peaking and carbon neutrality goals.

To achieve the purpose of energy decarbonization, countries in the world pay great attention to developing renewable energy sources (RESs). According to Renewables 2021[3], the International Energy Agency (IEA) issued that RESs will become the dominant energy source to achieve net zero. Net zero means the anthropogenic removal of anthropogenic emissions of greenhouse gases into the atmosphere over a specified period of time. Promoting the development of RESs can effectively solve the increasingly severe greenhouse gas emission problem. RESs are an inevitable trend to replace traditional energy sources in the future.

Under the vision of carbon reduction targets, building a future power system has become a significant initiative[4]. In 2021, the wind and solar share climbed above 11.2% of China's electricity generation[5]. Figure 1 shows the scheme of source-grid-load-storage coordination foreseen for the future power system. As a potential energy alternative, new energy sources represented by hydro, wind, and solar energy are receiving increased attention due to their rich resource stock and pollution-free characteristics. These new energy sources will become the primary power source. Traditional power generation resources with flexible regulation ability are gradually reduced. The daily operation and control of future power systems will face some new challenges.

The power system has always faced the challenge of the impossible trinity of security, economy, and environment[6]. A power system needs an instantaneous balance. Conventional power systems follow the principle of "source follow load" real-time balancing, by using the dispatchable power units such as thermal, hydro, and nuclear power plants and their capability to adapt to real-time load changes. This model is no longer suitable for future power systems. With the increase of new energy penetration on the power generation side and the load diversification caused by power substitution, the energy structure experience increased source-load imbalances. The newly proposed "source-grid-load-storage coordinated operation" is regarded as a practical measure[7].

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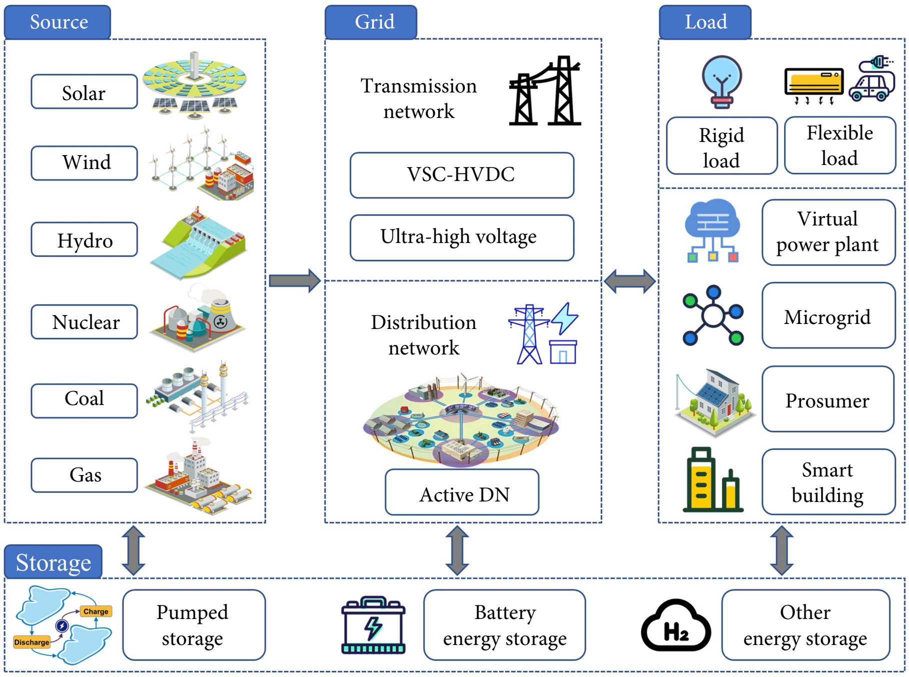

Fig. 1 Schematic diagram of source-grid-load-storage coordinated operation of future power systems.

Integrated load control and energy storage technology will be two critical technologies in future power systems. Users' participation in power system control is expected to increase through demand response signals such as electricity price. Energy storage usually plays a two-way control role and can provide various services, such as peak shaving, frequency control, standby, and demand response for the power grid.

The future power system requires the joint development of centralized and distributed energy sources (DERs). DERs is the core of future energy infrastructure deployment. Distributed photovoltaic (PV) has the advantages of abundant exploitable resource, low development and construction difficulties, and easy integration with load centers. As a result, distributed PV in China has seen explosive growth in recent years. The new grid-connected capacity of distributed photovoltaic power generation in China in 2021 is 29,279,000 kW[8]. Demand-side energy systems are district energy systems that can effectively integrate distributed generation systems and energy storage systems. The demand-side energy system must meet multiple operational requirements of end-users, such as residential, commercial, and industrial users. The demand-side energy system provides flexible resources to cope with growing source-load uncertainties in the future power system.

Based on the characteristics of energy interactions, end-users are classified as: (a) traditional consumer end-users and (b) active end-users. Active end-users (also called prosumers) exploit the availability of DERs and controllable loads[9]. Some active end-users can form a small-scale energy system. They perform bi-directional energy trading with the distribution network. The application scenarios of active end-users include campus/community microgrids (MGs), intelligent buildings, home storage systems, electric vehicle (EV) charging stations, etc. The efficient collaboration between active end-user and the distribution network can improve the reliability and flexibility of the power supply. Active end-users have significant potential to take part in grid operation and control.

Under the construction of a future power system, the development of demand-side energy systems is characterized by high efficiency, cleanliness, openness, interaction, and sharing. With the continuous breakthrough and innovation of business models, end-users are increasingly willing to contribute to the coordinated operation of demand-side DERs. These changes have also led to constant innovation in the operation mode of demand-side energy systems. Currently, the research on demand-side DERs focuses on demand response technology, load flexibility control technology, MG technology, prosumer technology, virtual power plant technology, and energy storage technology.

However, the willingness to deploy DERs still is low for most end-users. DERs are asset-intensive devices, and the excessively long payback period and specialized management technology requirements will directly affect users' interest in DERs. The cost of residual power management for active end-users is high. The existing market mechanism usually sells the surplus power directly to the distribution network, which cannot achieve the nearby consumption. The considerable variation in the capacity of the massively distributed power sources tends to cause uneven distribution of distribution network nodes. Feeder congestions and power quality problems in the distribution grid are prone to occur. A sharing economy in the energy sector is expected to address these challenges.

Currently, more and more scholars are analyzing the application of sharing economy into the energy and electricity field. Internet technology is used to address the above-mentioned problems. However, the development of sharing economy in the energy sector is still in the nascent stage, and the definition of sharing economy is not uniform and needs further clarification of concepts and categories in the context of the current development process. A detailed review of demand-side energy sharing technologies is helpful for future studies. This paper comprehensively reviews the demand-side energy sharing economy under the future power system. The definition and category of sharing economy, energy sharing technologies, and some future directions are provided.

The rest of the paper is organized as follows. Section 1 summarizes the definition and classification of sharing economy. Sections 2, 3, 4, and 5 review four energy-sharing schemes in power systems. Section 6 points out challenges and research directions for future work in the topic. Section 7 concludes the paper.

1 Sharing economy

With the development of Internet technology and the popularity of network connected devices, people's lifestyles have changed, with the rise of various new business operation models. As early as 2011, Jeremy Rifkin, a famous American scholar, proposed the vision of the energy Internet in the book "The Third Industrial Revolution", which attracted widespread attention from scholars at home and abroad[10]. The energy Internet exploits demand-side access to distributed power generation and distributed energy storage systems and realize wide-area energy sharing. The sharing economy is widely used in many contexts, such as transportation, space, finance, resources, knowledge, logistics, and goods.

1.1 Definition and category of sharing economy

Collaborative sharing is a new economic model. There is no uniform definition of sharing economy. According to some scholars, sharing economy is also called access economy. The sharing economy can be understood as a business activity that relies on online platforms to share idle resources[11]. Separating ownership and usage rights enables the creation of value by both suppliers and consumers. Typical examples of sharing economy are Airbnb (sharing accommodation) and Uber (sharing cars)[12]. Sharing platform mainly relies on Internet technology to solve the problem of information asymmetry between the supply and demand sides. It dramatically reduces the access threshold for the participation of the users.

Some users change from consumers to prosumers to meet their demand using local resources. The prosumer may have idle resources in some periods, when the production capability does not match the internal demand that changes over time. The sharing economy connects the supply and demand sides to improve the utilization of under-utilized infrastructures.

The emphasis on trading surplus resources is an essential feature of the traditional sharing economy. With the continuous development of Internet technology, the current sharing economy is developing toward a broader trend. The concept of a generalized sharing economy emphasizes that any underutilized resources can be shared through online platforms. At present, shared resources can be either stock resources provided by users or centralized resources invested by businesses.

The sharing economy cover excess production capability in addition to products. Based on the attributes of supply and demand agents, the generalized sharing economy can be classified into four sharing modes: consumer to consumer (C2C), business to consumer (B2C), business to business (B2B), and consumer to business (C2B).

The C2C represents the direct trading of the right to use surplus resources between users. The B2C implies that users get the right to use resources from companies through short-term leases. The C2B is based on the surplus resources that users provide to enterprises for centralized management to obtain benefits. The B2B focuses on the sharing of excess capability between enterprises.

1.2 Demand-side energy sharing

The sharing economy has promising potential for application in the energy sector. The concept of an Energy Sharing Economy is quite new[13]. A review of the literature follows with and comparison of the four typical sharing schemes in the demand-side energy system: virtual power plant (VPP), peer-to-peer (P2P) energy trading, shared energy storage, and MG energy sharing cloud. The main features and system architecture are shown in Table 1 and Figure 2, respectively.

Flexible loads, such as electric vehicle charging stations and data centers, play an important role in coordinated operation of future power systems. Providing flexibility to power systems and participating in demand response are two important applications of flexible loads. It is worth noting that there are some differences in the participation of flexible loads in demand-side energy sharing frameworks. Flexible loads can be considered as a good flexibility resource in a VPP. VPP operators aggregate flexible loads with power regulation capabilities (including electric vehicle charging stations, data centers, regulable loads, interruptible loads, etc.) as a whole to provide a flexible response to the grid. However, in other energy sharing frameworks of peer-to-peer energy trading, shared energy storage, and MG energy sharing cloud, flexible loads serve as an internal demand response. In order to reduce users' operating costs, users might have to regulate the operating state of flexible loads so that they are less dependent on external shared resources.

The four energy sharing technologies show the key role that Internet technologies play in matching supply and demand. The

Table 1 Main features of demand-side energy sharing technologies

Energy sharing technology	Sharing mode	Sharing resource	Main features
Virtual power plant[14–16]	C2B	Distributed generation, energy storage system, and loads	(1) The platform does not occupy resources and gathers user capability to provide auxiliary services for the grid. (2) A virtual power plant operator needs to evaluate the aggregated resources for preference. (3) The model exerts the scale effect.
Peer-to-Peer energy trading[9, 17–20]	C2C	Surplus electricity	(1) The platform does not occupy resources and provides transaction channels for users. (2) Specific schemes are needed to assure the quality of user transactions. (3) The model may consider the network effect. The larger the scale, the better the experience.
Shared energy storage[21–24]	B2C	Energy storage system	(1) The sharing platform is usually built by enterprises. (2) Users share the services provided by enterprises, and the quality of services is standardized. (3) The model exerts the scale effect.
MG energy sharing cloud[25, 26]	C2B2C+B2C	Distributed generation, energy storage system, and electricity in MG	(1) The shared resources include users' stock resources and enterprises' incremental resources. (2) Sharing platforms need to guarantee the standardized quality of the services. (3) The model exploits the scale effect, and users can respond directly to the distributed generation output.

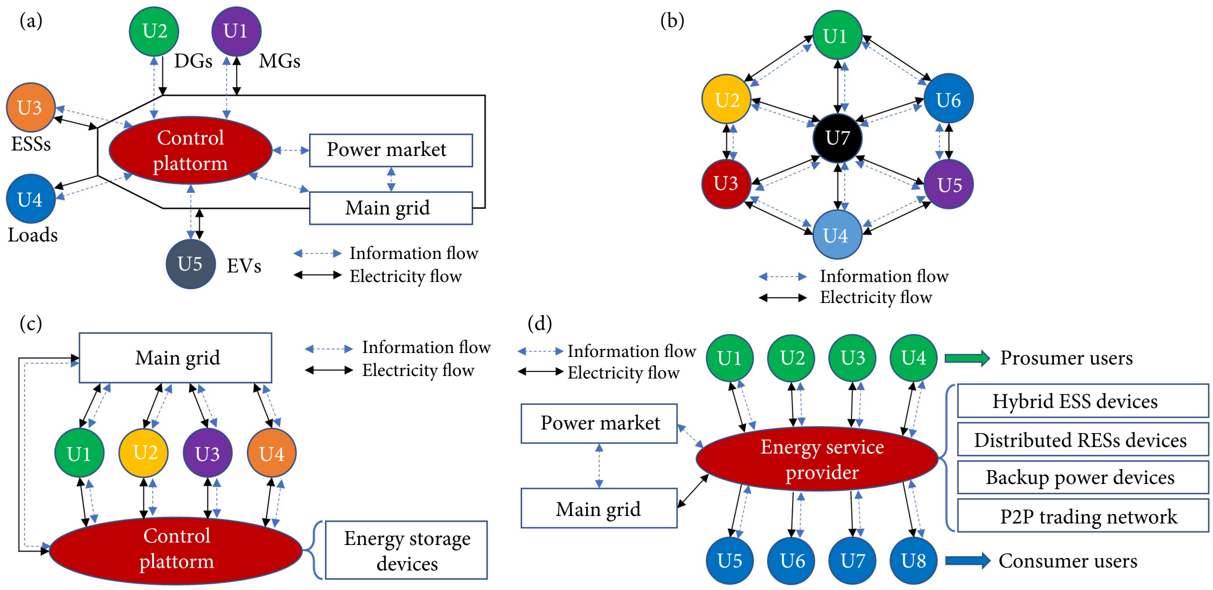

Fig. 2 System architecture of demand-side energy sharing technologies. (a) Virtual power plant, **(b)** peer-to-peer energy trading, **(c)** shared energy storage, and **(d)** MG energy sharing cloud.

pairing of supplier and demander is not static, but changes frequently. Energy sharing economy increases the demand-side participation. In the C2C model, users transact energy directly with users. The sharing platform operator is usually not involved in the commodity transaction, but only provides a trading platform. In the C2B and B2C models, business acts as a participant in the sharing economy. The aggregated decentralized resources are fully utilized in the C2B model. The B2C model exploits the decentralized use of pooled resources. These two models are not contradictory, but correspond to application scenarios of different regional scales. Since the B2B model carries out the sharing of excess production capacity between enterprises, it is not within the scope of demand-side energy sharing technologies. The following sections further analyze these energy sharing technologies.

2 Virtual power plants

The emergence of MGs and VPPs can effectively avoid the negative impact of DERs on the power system. MGs have geographical area constraints and cannot achieve large-scale DERs integration. Unlike MGs, VPPs do not have specific limitations on the geographic location and composition of DERs. VPPs are always connected to the utility grid.

The concept of the VPP originates from the definition of virtual utility given by Shimon Awerbuch in his book in 1997[27]. VPPs became one of the key elements in constructing the smart grid. Figure 3 illustrates the VPP as an energy management technology. Through advanced information and communication technology and control and metering technologies, VPPs aggregate and coordinate the operation of several small-scale distributed resources such as power sources, energy storage, controllable loads, electric vehicle charging stations, and reactive control devices[15].

The three critical issues of VPP are: aggregation of DERs, coordinated and optimized operation, and benefit allocation.

2.1 Value property of VPPs

VPPs fit the characteristics of the C2B model of the energy sharing economy. VPPs can aggregate the users' idle DERs and transfer the right to use them to the VPP operator. A VPP is an energy management technology. It aggregates all the demand-side resources that can be regulated and gain revenue by participating in the electricity market. With the development of future power systems, DERs will grow in size. VPPs will be critical in addressing the technical and economic risks associated with intermittent energy sources[28].

A VPP is usually used as a power plant to satisfy the power system operation or to take part in the market of auxiliary services[29, 30]. The auxiliary services of the power system include frequency regulation services[31, 32], energy reserve services[33, 34], and voltage management services[35]. VPP can effectively manage large-scale DERs, such as flexible loads. VPP helps to promote the consumption of clean energy and reduce the operating costs of DERs, which in turn promotes the green transformation of the power system, as VPPs are significantly more environmentally friendly and economical than building thermal power plants to cope with instantaneous peak loads.

The development of VPPs in China is relatively late, as the country has focused on transmission grid construction and less on the distribution network and demand-side regulation. China's VPPs are mainly demonstration sites but are developing relatively quickly. On August 26, 2022, China's first VPP management center was set up in Shenzhen, dedicated to easing power voltage control.

2.2 Aggregation of DERs

Wind farms, photovoltaics, electric vehicles, energy storage, micro gas turbines, and flexible loads are the main aggregated elements of a VPP. For example, many electric vehicles and wind farms are integrated into a VPP[36]. Ref. [37] proposed a carbon-to-power-based VPP composed of the gas-power plant carbon capture, power-to-gas, and the conventional VPP. Ref. [34] explored a VPP equipped with distributed thermal generators, renewable generators, and energy storage systems. Ref. [38] designed a VPP structure consisting of a conventional power plant, an energy storage facility, a wind power unit, and a flexible demand. Ref. [39] developed a multi-energy VPP to achieve the coordinated operation between electricity, thermal, cooling, and natural gas.

Further, considering the differences in control potential and historical credit of resources provided by each user, the aggregated

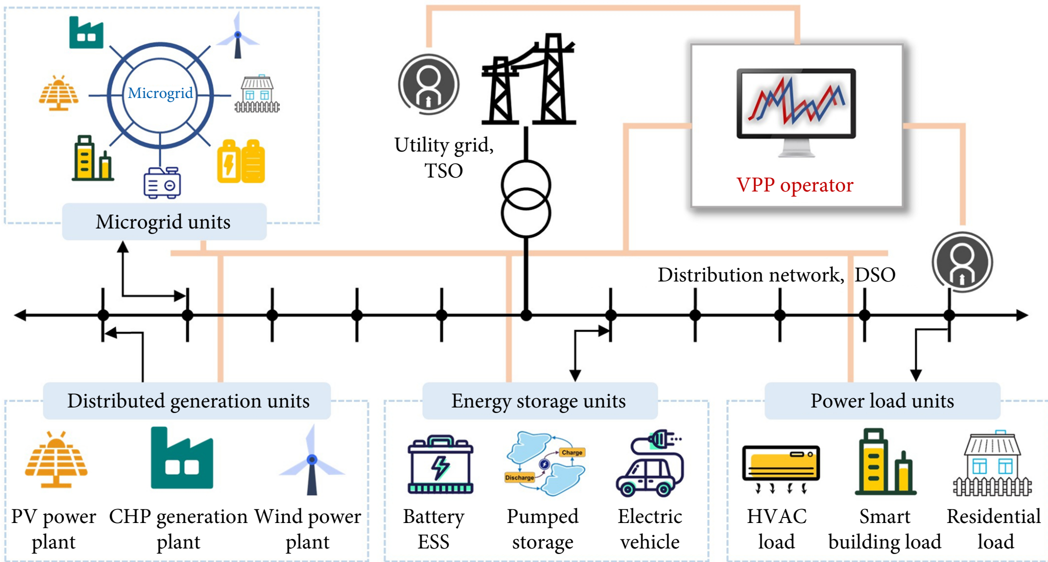

Fig. 3 Schematic diagram of VPP aggregated DERs.

resources performances need to be evaluated. A user selection index system for VPP is proposed to determine the priority order of users[40]. VPP operators use a data-driven resource planning methodology to enable the selection of demand response customers and the sizing of energy storage[41].

2.3 Coordinated and optimized operation

The flexibility of VPP's aggregation regulation is mainly shown by the ramp-up and ramp-down abilities. The operation of the VPP is a complex economic scheduling problem due to the varying constituent elements. The VPP scheduling problem can be centralized or distributed[42]. Centralized is the most widely used, but its communication efficiency and user privacy are sometimes difficult to guarantee. Ref. [43] proposed a three-layer hierarchical VPP control architecture to accommodate the scheduled demand of day-ahead scheduler, intra-day model predictive control (MPC) controller, and local controllers. In the distributed model, each user can be regarded as an intelligence agency that can make independent decisions after obtaining the necessary information. Simulation results indicate that the distributed dispatch performs similarly to the centralized dispatch[44]. Ref. [45] presented a fully distributed alternating direction method of multipliers (ADMM)-based algorithm for the operation problem of the VPP. Ref. [46] used an attack-robust distributed economic dispatch strategy for the VPP to avoid communication failures and cyber-attacks. Some scholars make a distinction between distributed and decentralized: there is no direct information exchange between the agents in the decentralized architecture, and distributed energy units and intermediate layer entities only communicate with upper layer entities[47].

In addition, the uncertainty associated with the VPP has become another research topic. Ref. [28] built a two-stage stochastic robust optimization model based on data-driven, in which the total system cost of the VPP is optimal, although in the worst case. In Ref. [48], the robust capability curve is proposed to characterize the power output range of VPP. Ref. [33] developed a risk-aware stochastic adaptive robust optimization model for VPP trading under the day-ahead energy-reserve market. The Benders-decomposition-based iterative algorithm is used to solve the optimization model.

2.4 Benefit allocation

A VPP consisting of multiple stakeholders must ensure that each participant can reduce production costs. Cost decrease is the only way to maintain the stability of the coalition structure. Therefore, the VPP needs to establish a fair benefit allocation mechanism to motivate users with DERs to collaborate actively and play a regulatory role.

Since there is a cooperative game relationship among DERs, kernel allocation[49] or Shapley value[50] can form a fair allocation strategy. Ref. [31] proposed a revenue allocation method based on the Nash–Harsanyi bargaining solution to reflect the actual contributions of the cooperating parties. Ref. [51] adopted the Shapley value and bargaining-based approaches to distribute the cooperative revenue.

3 Peer-to-peer energy trading

An increasing number of end-users are keen to set-up small-scale, geographically dispersed DERs, such as small-capacity rooftop PV and residential energy storage systems. These end-users are producers and consumers, which we refer to as prosumers. Prosumers will actively manage their electricity consumption, production, and energy storage[52]. The emergence of prosumers has given the possibility of energy interaction and powerfully mobilized end-users to participate in renewable energy consumption while meeting their load demand.

3.1 Peer-to-peer energy systems

Energy prosumers in a community usually include residential prosumers, electric vehicles, and intelligent buildings. According to emerging regulatory frameworks in several countries, prosumers have the possibility to trade energy with other energy agents to improve renewable energy utilization and minimize the cost of purchasing electricity from the distribution network[53, 54]. Energy prosumers sharing their surplus power build a community according to a certain market scale[55].

The P2P energy system consists of a physical and a virtual layer[17]. As shown in Figure 4, the physical layer corresponds to the electricity flow, and the virtual layer corresponds to the information and value flows.

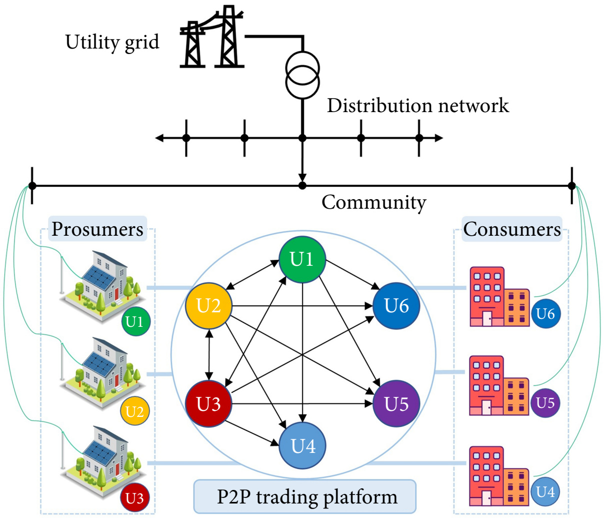

Fig. 4 Schematic diagram of the P2P energy sharing within a community.

The physical layer is the physical electricity network that enables the delivery of electricity. The power network used for P2P energy trading can be a distribution network built and maintained by an independent operator. P2P energy trading can also be achieved within stand-alone MGs or grid-connected MGs. When a transaction agreement is reached, the physical network transfers electricity from the seller to the buyer. At the same time, the physical layer is the necessary architecture for connecting the different prosumers. Each prosumer must have metering devices to transfer relevant data information of P2P transactions efficiently. The virtual layer is a virtual information platform that guarantees prosumers' secure connectivity and equal access to the physical network. It also ensures the successful matching of energy and finance. As the core of P2P energy trading, the information system of the virtual platform provides equal access to the market for potential participants. Meanwhile, the virtual information platform provides market operations management, pricing mechanism decisions, and energy management for P2P energy trading.

3.2 Peer-to-peer energy markets

P2P energy markets are decentralized market structures that use the idea of a cooperative economy to advocate peer-to-peer exchanges between users[56]. With the accelerated deployment of DERs construction, the electricity market tends to develop toward a decentralized mechanism. The P2P trading mechanism is well-positioned to encourage small and medium-sized DERs and customers with demand-side responses to participate in market transactions. The P2P trading mechanism relies on decentralization to improve the resilience of the local power system. P2P trading markets can be combined with blockchain technologies to protect the private information of regional participants[57].

P2P electricity markets can be divided into three categories: (1) full P2P electricity markets, where participants can negotiate directly[20, 58]; (2) community group-based P2P electricity markets, where community operators manage electricity transactions and information exchange[59, 60]; and (3) hybrid P2P electricity markets, which combine the first two market structures.

Numerous studies have shown that P2P energy markets can have a positive effect. For example, it can facilitate energy balancing, reduce energy storage capacity, and reduce network losses[17]. In addition to DERs, electric vehicles can also participate in the P2P energy market. Ref. [61] proposed a new algorithm for two-way intelligent charging of electric vehicles, which considers user preferences and P2P energy trading and provides auxiliary services to the power grid. In addition, P2P trading can advance the community energy transition to low carbon. Ref. [62] explored an implementation scheme for a net-zero community by sharing renewable energy and hydrogen energy storage. The pricing strategy of P2P energy trading among individuals has also been proposed to promote the effective reduction of community electricity costs and carbon emissions.

3.3 Peer-to-peer trading strategies

The P2P market structure is essentially a decentralized market, usually based on some distributed algorithms or game theory to implement P2P energy trading. Solving methods applied to various energy-sharing and trading strategies include bilateral auctions, game theory, mathematical optimization, blockchain, etc.

(1) Bilateral auctions. Bilateral auction theory is applied to P2P markets, where the auction mechanism effectively satisfies individual rationality and incentive compatibility. Ref. [63] proposed a distributed network containing local energy and flexibility transactions, where prosumers participate in the P2P energy market based on their self-preferences. The clearing is decentralized, and distributed system operators are set up for iterative auctions to avoid violation of network constraints and improve network flexibility. Ref. [64] established a P2P energy exchange framework for active distribution networks based on an average pricing mechanism (APM) multi-round auction approach. It considers voltage regulation, blocking, and centralized proxy payments for power losses.

(2) Game theory. Two game methods, non-cooperative games and cooperative games, can be carried out for transaction decisions in the P2P market. Currently, non-cooperative games occupy a larger share of the decentralized characteristics of the P2P market and privacy protection needs. The non-cooperative game includes a master-slave game and a generalized Nash equilibrium problem.

Participants have a master-slave relationship and a decision-making sequence in the master-slave game. After the upper layer gives the strategy first, the lower layer makes the optimal strategy according to the upper layer's strategy. The lower layer feeds the strategy to the upper layer to make adjustments. This cycle is executed until the benefits are maximized in the upper and lower layers. Ref. [65] proposed an interdisciplinary P2P energy-sharing framework. In the paper, a risk-utility model is developed by interpolation fitting, and a dynamic price-profit model is designed for the energy-sharing provider.

The participants' strategies are mutually influential and interdependent in the generalized Nash game equilibrium problem. The main algorithms used in the solution contain variational inequality methods, optimal response algorithms based on the Nikaido–Isoda function, and penalty function methods. The Nash equilibrium problem-oriented to distributed energy sharing tends to be standard. Ref. [66] considered residential shared energy storage deployment in a P2P energy trading model and describes the competition among shared energy storage users as a generalized Nash equilibrium problem. The Karush–Kuhn–Tucker (KKT) condition and linearization are used for P2P energy trading, which verifies that all market participants can benefit.

Cooperative games imply joint decision-making among independent decision-makers to reach an overall optimum. Multi-MG cooperation can achieve high-quality energy sharing and ensure the stability of the electricity market. In Ref. [67], a stochastic cartel game based P2P energy trading strategy is proposed to reduce the total energy cost of a multi-MG under uncertainty. Ref. [68] explored Cooperative negawatt P2P energy trading in low voltage distribution networks with benefit allocation using Shapley and Nucleolus.

(3) Mathematical optimization. Mathematical optimization contains linear programming, mixed integer programming, and nonlinear programming. In addition, common distributed constrained optimization algorithms for prosumer P2P energy sharing include the original pairwise approach, the consistency approach, and the ADMM algorithm. In Ref. [69], the Nash and bargaining nonconvex model is transformed into a mixed integer linear programming problem, including KKT conditions and logarithmic transformations, and the effectiveness of a graph theory-based modeling approach for solving energy trading models with optimal power flow constraints is demonstrated. In Ref. [70], a pricing mechanism for P2P energy trading that considers voltage and line-blocking management is proposed. A new mutual reputation index is introduced to evaluate the bilateral trading willingness of prosumers, and the ADMM algorithm is used to ensure that the social welfare of the mechanism is maximized. In Ref. [71], an ADMM-based scheduling of a local energy community is proposed, in which a day-ahead multistage stochastic optimization approach is combined with an intra-day rolling-horizon optimization procedure, to cope with the uncertainties of the renewable power generation and consumption during the day.

(4) Blockchain. Blockchain is a distributed, decentralized network database system and has been applied to P2P energy trading. Ref. [72] proposed a P2P energy trading architecture based on Istanbul Byzantine fault tolerance (IBFT) 2.0 consensus algorithm and blockchain. Privacy protection is implemented through off-chain and on-chain licensing. The P2P framework based on flexible permission ascription has good performances in terms of latency, throughput, block time, garbage collection time, CPU, and memory utilization. Ref. [73] combined blockchain technology and auction mechanism to facilitate P2P energy trading by prosumers within MGs.

3.4 Peer-to-peer energy trading projects

Currently, the number of projects in P2P energy trading has significantly increased worldwide[74]. Some typical projects are listed here. Additional details are provided in the indicated websites.

- Brooklyn MG Project (https://www.brooklyn.energy/) was co-founded by LO3 Energy and Consensys in the spring of 2016.
- Yeloha (https://www.yeloha.com/), a Boston-based company founded in 2012, operates a renewable energy power trading platform.
- Piclo (https://www.piclo.energy/), a P2P energy trading platform, was established by Open Utility and Good Energy in the UK with the support of the Government in 2014. With the addition of Piclo Match and Piclo Flex services, its business scope is expanding.
- SonnenCommunity (https://sonnengroup.com/sonnencommunity/), a P2P energy trading platform, has been operating in Germany since 2015 using battery storage technology.
- Vandebron Project (https://vandebron.nl/) is a website-based direct trading platform founded in 2014 in the Netherlands, which allows consumers to purchase electricity directly from renewable energy generators.

4 Shared energy storage

The intermittent, random, and fluctuating nature of large-scale renewable energy generation poses an increasingly serious challenge to the generation side of the future power system. Moreover, on the energy demand side, e-mobility has also led to a significant increase in load and more drastic load fluctuations[75]. Whether on the power generation side or the load side, the transformation of the energy structure can complicate the safe and stable operation of the power system. As a valuable flexible resource, energy storage can play the role in peak and frequency control[76]. Energy storage can also smooth out the fluctuation of renewable energy output and improve the reliability of demand-side power supply. Therefore, the deployment of energy storage is an effective means to maintain the stable operation of the power system.

4.1 Challenges of energy storage

Despite decades of energy storage development, the current development still faces difficulties.

(1) High investment cost of energy storage[77]. Current energy storage technology is not yet perfect due to high investment costs and long payback periods, particularly for residential customers with rooftop PV units.

(2) Difficulty in customizing energy storage capacity[24]. On the one hand, each user's load curve is different, and manufacturers can supply a limited list of products, making it difficult for users to purchase an optimal storage capacity module. On the other hand, users' electricity demand is constantly changing, and it is difficult to predict whether their future demand for energy storage capacity will increase or decrease.

(3) Low utilization of energy storage devices[78]. For users, the arbitrage of energy storage is mainly obtained through the peak-to-valley tariff difference. However, the changing load curve makes it possible for users to directly use low-priced grid power rather than opting for energy storage charging, which leads to short-term idleness of storage capacity.

(4) Worrying safety issues of distributed energy storage[79]. Demand-side energy storage is dominated by chemical energy storage. Some users consider the safety of energy storage to be a concern. As many residential users lack professional energy storage management skills, energy storage failures in the prosumer mode occur from time to time, even threatening personal safety.

4.2 Sharing mode of energy storage

Shared energy storage has become an attractive direction to solve the abovementioned dilemma. Shared energy storage makes the benefits available to participants by sharing the cost of energy storage, allocating energy storage capacity rationally, and making full use of the complementarity. Currently, the mainstream of shared energy storage includes shared centralized public energy storage and shared distributed owned energy storage. The two categories are divided based on the deployment of the shared energy storage devices.

Research on shared distributed owned energy storage can be traced back to a handful of literatures[21, 80–82]. Re. [21] proposed the concept of sharing domestic energy storage between customers and network operators to deal with the pressures in energy prices and network conditions. In a residential community, the residential units shared partly energy storage capacity with facility controllers of the community[80]. The solution not only reduces the deployment of energy storage, but also benefit economically. Ref. [81] explored the coalitional game model among users who already have distributed owned energy storage. The users can minimize the electricity cost by sharing storage with each other. Ref. [82] pointed out that the users can trade their individual energy storage by creating a block of capacity. Ref. [82] also summarized the advantages and disadvantages of the four structures of shared energy storage. Although shared distributed owned energy storage can increase the efficiency of energy storage utilization, there are still significant shortcomings. The shortcomings are mainly the high operating costs and control complexity caused by the small-scale distributed energy storage. Therefore, the distributed owned energy storage is usually used to participate in VPPs or as an owned equipment for supporting P2P energy trading.

Nowadays, the shared energy storage usually refers to providing energy storage services for multiple users by a public energy storage device[82]. Figure 5 presents a schematic diagram of shared centralized public energy storage. Energy storage devices are built centrally by a third party or a user group so that the cost of energy storage can reflect the scale effect. Shared centralized public energy storage model is more suitable for a wide range of applications among users.

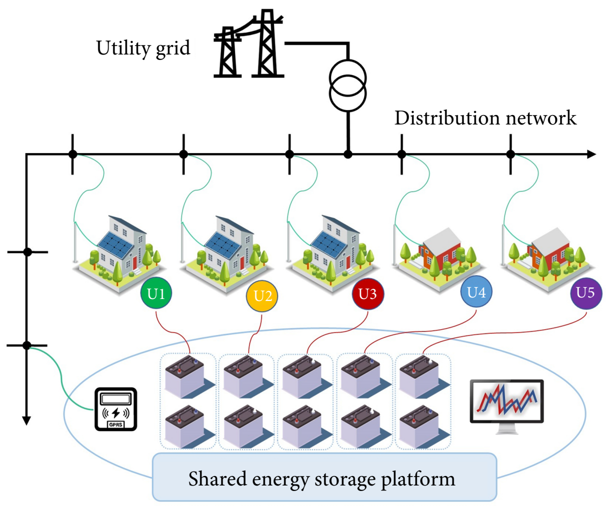

Fig. 5 Schematic diagram of centralized shared energy storage.

In the case of prosumers, both their load demand and rooftop PV output have seasonal variations[23]. Shared energy storage operators allow users' access to the optimal storage capacity for their needs. Research on shared energy storage has focused on three main elements: operational mode, pricing mechanisms, and capacity allocation.

The research on the operation mode of shared energy storage focuses on the development direction of shared energy storage from an overall macroscopic perspective. With policy support and market demand, several provinces in China, such as Qinghai and Zhejiang, have started to explore their shared energy storage models. At present, however, shared energy storage projects still face technical and economic challenges, which hinder the further development of shared energy storage.

The study of operation mode covers both the operating system and operation process. The operating system includes a shared energy storage power plant, an operator, and a user group of three subjects. The operator acts as a third-party platform to coordinate the services and transactions between the energy storage plant and the users. The operation process includes two parts: operation control and service pricing. Specifically, the operation process aims to study the charging and discharging behavior during real-time operation and the benefit distribution among the three subjects.

4.3 Pricing mechanism for shared energy storage

As independent decision-makers, users and operators pursue cost reduction or benefit maximization in a shared energy storage system. Because they have conflicting interests, a fair and reasonable price for energy storage is necessary. Game theory is used in the problem of benefit allocation or pricing coordination mechanism of multi-interest subjects. The current research can be divided into two categories based on the type of game: non-cooperative and cooperative.

The non-cooperative game approaches include auction theory and the Stackelberg game. Ref. [83] proposed a distributed combinatorial auction approach considering multiple resource allocations for shared energy storage. The capacity, energy, charging power, and discharging power of the energy storage system will be auctioned in combination. Ref. [84] presented an adaptive bidding-based double-side auction mechanism solved by a two-stage decision-making process. The first stage optimizes the total cost of electricity through supply-demand modeling and tariff forecasting, and the second stage introduces penalty rules to address supply-demand uncertainty in the real-time market clearing process. Ref. [85] proposed an incentive-compatible energy trading framework. Stackelberg enables the provider of shared energy storage to maximize revenue, and the retailer minimizes the social cost of participating users.

A cooperative game-based pricing mechanism can motivate shared energy storage participants to cooperate. A fair and efficient allocation mechanism to measure each participant's contribution should be designed. Ref. [86] proposed an incentive profit-allocation mechanism based on the asymmetric Nash bargaining model, which has made a reasonable distribution of benefits to users and operators.

4.4 Capacity allocation of shared energy storage

The capacity allocation problem of shared energy storage can be divided into two parts, according to the physical properties of energy storage: the storage capacity planning of operators in the actual sense and the capacity allocation problem of users in the virtual concept.

The operator's capacity planning problem is similar to the traditional siting and sizing problem. Operators of shared energy storage usually determine the optimal storage address and capacity for the planning model with the optimization objective of minimizing the operating cost of the energy storage plant. In Ref. [87], the basic framework of multi-park shared hydrogen energy storage is established by using the spatial and temporal complementary characteristics of wind and solar power generation and energy consumption of multi-park users. Meanwhile, the paper proposed a shared capacity allocation model of hydrogen energy storage based on a cooperative game to reasonably determine the capacity of each device. To promote new energy consumption, a shared capacity allocation method based on a two-layer planning model for the energy storage plant is developed in Ref. [88]. The outer model is dedicated to solving the plant allocation problem in the two-layer planning model. The inner model focuses on the optimal operation of the micro-energy network. Reference [89] defined a two-stage evaluation model that maximizes self-consumption rates and power quality. The first stage aims at improving the power quality and uses a genetic algorithm to determine the optimal location of the energy storage. The second stage focuses on optimizing the energy storage system (ESS) size by considering the techno-economics metrics as the second state.

The virtual energy storage capacity planning for users is determined based on their generation and load profiles over a certain period. The cloud energy storage proposed by a research team at

Tsinghua University aims to provide distributed energy storage services for users[22, 90]. Cloud energy storage centralizes energy storage resources in the cloud and leases them to users in virtual energy storage. Users who join cloud energy storage can use the shared energy storage resources anytime, anywhere, on-demand, and pay for the service according to the usage. Similarly, the virtual energy storage configuration can be divided into two phases[91]. In the first stage, the aggregator determines the unit price of the virtual energy storage capacity; in the second stage, the user selects the storage capacity and the storage schedule. Storage virtualization can significantly reduce the total physical capacity for all users compared to each user having their own physical energy storage.

5 Microgrid energy sharing cloud

5.1 Microgrids and prosumers

MGs and energy prosumers are considered small-scale power systems capable of grid-connected and independent operation. They are widely used for aggregation and grid integration of demand-side DERs. Local autonomy and energy interaction are achieved through energy management systems (EMSs). Although P2P energy trading technology can effectively promote the efficient use of excess energy, there are still several challenges in the nearby consumption and efficient utilization of distributed renewable energy.

As a complement to the utility grid, MGs supply power to a specific group of users in a particular area, where the users are usually single energy consumers. Currently, most studies on MG EMS focus on distributed energy capacity planning[92, 93], demand response optimization[94, 95], uncertainty scheduling methods[96, 97], and optimization solution methods[98, 99].

MGs and energy prosumers are two key schemes for distributed renewable energy consumption. MGs have several advantages, such as centralized construction, unified dispatch, and nearby consumption. However, in the traditional mode of operation, end-users can only participate in electricity consumption in a one-way manner according to the MG operator's retail price. Electricity price is an indirect reflection of power output. Consumers cannot directly respond to the power output of renewable energy, and their enthusiasm for participation in consumption is usually limited. Therefore, the participation of energy consumers is not high. It is not easy to mobilize demand-side users to consume nearby production of renewable energy[25]. Prosumers are an effective approach to fully consuming new energy by directly responding to the new energy generation situation. They manage their own power generation, consumption, and energy storage to improve their energy economy. However, there are some obstacles to their widespread deployment. For example, the installation environment is restricted, the equipment assets are intensive, the capacity is not adjustable, and the operation and maintenance are highly specialized[25]. Most energy-intensive end-users (e.g., residential customers in apartment buildings or urban communities) are not eligible for installation due to the constraints of distributed energy deployment. This type of user can only act as an energy consumer or participate in demand response schemes.

The energy imbalance of prosumers can be mitigated by interacting with distribution networks or other prosumers[17]. However, the simple distribution network interaction model cannot transfer surplus power to other neighboring users, which also causes unnecessary transmission loss. Due to the potential to reduce cost, prosumers trade surplus energy among themselves[100]. P2P energy trading is a measure to solve the energy imbalance between prosumers. The special nature of electricity commodities, network constraints, and power quality issues may hinder the match between production and consumption.

To effectively solve the demand-side distributed energy consumption problem, it is necessary to avoid some root problems caused by too centralized and too decentralized modes. Full consideration of the random fluctuation characteristics of renewable energy generation, the operational features of hybrid energy storage systems, and the impact of demand-side energy use on schedule is needed.

5.2 Novel sharing mechanism in microgrids

As described, currently, the research on sharing in the energy sector mainly focuses on two parts: surplus energy sharing and energy storage sharing. In addition, Ref. [101] focus on a small-scale framework for sharing rooftop PV and battery energy storage within an apartment building. Apartment consumers share electricity at time-varying rates. Moreover, residential building cluster can share rooftop PV output and energy storage in Ref. [102], in which the electricity consumers make their electricity schedule with the given electricity prices.

A scientific and reasonable energy-sharing mechanism should consider the relationship between supply and demand and improve the economy of cooperative dispatching and the local consumption of renewable energy. It is necessary to research the energy-sharing operation of MGs with energy prosumers to promote distributed energy consumption in the vicinity. The sharing mechanism requires further construction of a new model based on existing research on EMSs for MGs and the application of the Internet cloud technology.

Inspired by the cloud storage model for data (such as the Baidu Netdisk), the ISESOOC team at South China University of Technology has worked to develop an MG energy sharing cloud (ESC)[25, 26]. The ESC helps demand-side users realize distributed energy leasing and surplus power sharing in energy services. The ESC uses consumer to business to consumer (C2B2C) and B2C sharing models, providing standardized service quality. Previous studies have shown that the MG ESC model integrates the advantages of MGs and prosumers and can fully embody four core advantages: scale effect, capacity determination on demand, cluster dispatch, and local consumption. The proposed MG ESC aims to promote the local consumption of distributed renewable energy and improve the efficiency and economy of energy utilization by mobilizing the demand-side users to respond directly to the power output.

The main goal of building MG ESC is to mobilize demand-side users to participate in renewable energy consumption actively. A reasonable energy sharing mechanism is necessary. In Ref. [25], the ESC-based MG architecture shown in Figure 6 is proposed. The ESC consists of three main components: an energy service provider (ESP), cloud users, and the utility grid. Cloud users include both consumer and prosumer users. They can access the energy services according to their needs. In addition, the ESP combines hybrid energy storage systems, distributed renewable energy generation systems, backup power systems, P2P energy trading networks, and control centers for centralized management. The ESP provides affordable and convenient energy interactions through energy services to cloud users. Three energy services are provided to cloud users: energy storage, renewable energy generation, and surplus energy sharing services. In addition, the ESP can fully use the aggregated resources to provide auxiliary services such as frequency regulation, peak regulation, and backup to the

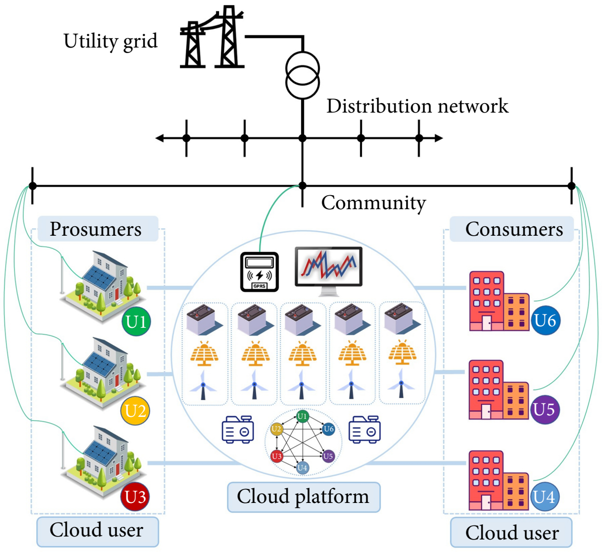

Fig. 6 Schematic diagram of ESC-based MG within a community MG.

utility grid.

In the ESC, the pricing strategy of energy services has a guiding role in the transaction. The pricing strategy for energy services is based on the levelized cost of energy (LCOE), which is an internationally accepted index for evaluating the cost of electricity[103, 104]. The LCOE considers not only the components of construction cost, operation and maintenance cost, and operating power but also the impact of lifetime, depreciation and taxes, and asset value.

In the case of wind turbines and PV arrays, their LCOE is defined as all costs over the life cycle divided by the total electricity generated. It is worth noting that renewable energy generation is highly dependent on both geographic location and generation season, and therefore the cost of generation varies significantly. For the LCOE of an energy storage system, the cost cannot be calculated based solely on the amount of electricity charged and discharged. It has been shown that the throughput approach used is simple and effective for defining the lifetime of energy storage[105]. This approach can characterize the differences in depreciation corresponding to different states of charge (SOCs). A reasonable energy service price should incentivize cloud users to participate in renewable energy consumption actively and guide the utility grid, ESPs, and cloud users to achieve win-win cooperation.

5.3 Double-layer EMS for cloud users

In an ESC, the cloud user builds a virtual prosumer by purchasing energy services from the ESP. The ESP allows the cloud user to adjust the capacity of its leased energy service periodically (e.g., one month or one week). This model effectively solves the problem of capacity mismatch at different times of the year. The cloud user's EMS requires optimal capacity planning for future renewable energy generation and energy storage over a certain period, as well as optimal energy scheduling and real-time control.

To this end, the cloud user can construct a double-layer EMS based on the ESC[26]. In the upper-level EMS, the management center of the cloud user needs to collect representative data of load power and renewable energy generation power in a future cycle. Then, the management center uses energy service price, load power, and power generation power as input data, photovoltaic capacity, wind turbine capacity, and energy storage capacity as decision variables, and energy cost minimization as the optimization objective for optimal capacity planning. In the lower-layer EMS, the daily power dispatch model is constructed and solved to minimize the energy cost of the cloud user. In addition, the user can use energy comfort as an optimization objective to schedule controllable loads.

5.4 Optimal operating strategy for ESPs

The ESP needs to fully consider users' service requirements and scheduling redundancy when planning the sizing of renewable energy and energy storage systems. In addition, ESP can potentially exploit the complementary economics of cloud users since the power profiles of different types of users are significantly different. Different power demand corresponds to different energy storage power, and the peak state of charge (SOC) of energy storage necessarily corresponds to a different time. In the capacity planning of energy storage systems, the ESP can take full advantage of the complementary characteristics of users to reduce the total capacity.

The ESP can perform cluster scheduling optimization, which helps improve the ESP's economic efficiency. When performing cluster scheduling, the ESP needs to consider the generalized loads of users, the power interaction with the utility grid, renewable energy generation, and the operational constraints of the hybrid energy storage system.

Further, similar to VPPs, ESPs can also take advantage of aggregated resources. Through power output regulation and flexible load power regulation, ESPs provide auxiliary services to the grid, including peak regulation services, frequency regulation services, and standby services.

6 Outlook of demand-side energy sharing

To meet the requirements of green power development, distributed energy will further penetrate into the demand-side energy system, and demand-side users will actively participate in the consumption of new energy. Among many emerging technologies, a promising hierarchical layout of VPPs, MG energy sharing clouds, and prosumers is coordinately developed within an active distributed network (ADN). As shown in Figure 7, the future demand-side energy system under future power systems achieves energy balancing and sharing on both local and wide areas through the coordination of multiple systems. The members of prosumer/consumer users, MG energy sharing clouds, and VPPs are expected to play a key role in the low-carbon green production and lifestyle. MG energy sharing clouds are responsible not only for aggregating neighboring prosumer and consumer users, but also for providing energy services to end-users. VPPs are mainly used to achieve a wide area energy balance by coordinating multiple MGs and electricity markets.

The sharing economy in the energy field is an inevitable result of social development. Demand-side energy sharing is a challenging project in current society because the sharing economy in the energy field is still in its infancy. Some challenges in decision-making problems of individual participants in energy sharing programs deserve attention. For example, before users participate in a shared program, they need to weigh whether the benefits of resource sharing will meet their expectations. Moreover, as the energy sharing scale will increase, the risk of energy data leakage will increase as well. And again, when the actual demand of shared resources deviates from the planned demand, users need to evaluate and solve the reliability problem of their own operation. These issues need to be properly addressed because they directly affect the behavior of users who participate in energy sharing. In addition, other challenges and research directions for future work

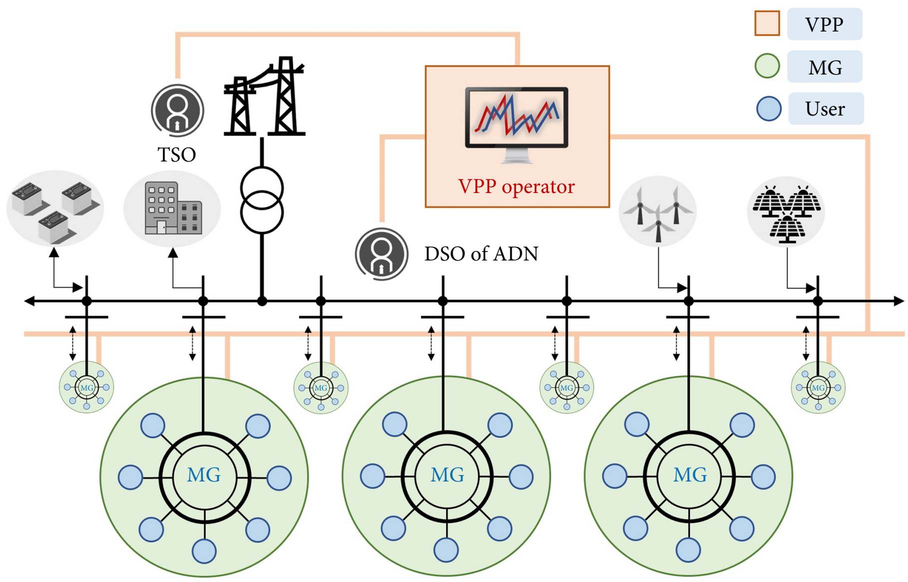

Fig. 7 **Layout of future demand-side energy system under future power systems.**

in demand-side energy sharing also need to be further explored from the following perspectives.

(1) Coordinating transmission networks: a well-established energy-sharing network requires integrating the power network with the information and value networks. Particularly, the power network needs bidirectional mobility to meet increasingly diverse business needs.

(2) Establishing market mechanisms: promoting the business model of the energy-sharing economy depends on establishing an energy market mechanism. Carbon markets can promote green energy consumption and stimulate users' environmental awareness. How to design a long-term healthy electricity–carbon market taking into account the interests of all parties is still in the exploration stage.

(3) Guaranteeing information security: the development of sharing economy cannot be separated from the collection of user data. Platforms need to accumulate a large amount of data. Currently, the sharing platform does not have good protection for user privacy and information security. Information leakage will threaten users' rights and interests and limit the energy-sharing economy's scale of development.

(4) Improving the theoretical system: the energy sector's theoretical system of the sharing economy still needs continuous improvement. Some techniques, such as energy management, social psychology, reinforcement learning, game theory, and cluster control theory, still need further exploration.

(5) Development of laws and regulations: there is a need of specific laws and regulations for the sharing economy. The legal system should clarify the rights and responsibilities of the sharing platform, the supply side, and the demand side, especially in improving the credit mechanism of the participating sharing entities.

7 Conclusions

Distributed renewable energy has seen rapid development in the context of energy structure transformation with the goal of carbon emission reduction. The demand-side energy system plays a key role in future power systems. Energy sharing is an effective way to promote the consumption of distributed energy. The construction of the demand-side energy sharing economy exploits end-users' flexibility. The energy sharing economy allows each end-user to participate in the construction of a new power system, which helps to achieve the goals of carbon peaking and carbon neutrality.

This paper comprehensively reviews the existing research in demand-side energy sharing technologies for future power systems. First, the analysis of the development history of the sharing economy clarifies the concept and defines four categories according to the difference between supply and demand subjects. A detailed overview of the background and motivation, key issues, and recent advances in VPPs, P2P energy trading, energy storage sharing, and MG energy sharing cloud, respectively, is provided. Finally, an outlook on demand-side energy sharing technologies concludes the paper.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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