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Sharing Economy in Energy Markets

Modeling, Analysis and Mechanism Design

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Foreword by Saifur Rahman

With the core idea of "access over ownership", the concept of sharing economy has gained substantial popularity in the housing and transportation sectors in recent years. Sharing economy—the theme of this book—refers to a market model that enables individuals or entities to share their idle resources with others upon payment for the purpose of efficient resource allocation and social welfare maximization, which will bring new challenges and opportunities for deregulated energy markets.

In recent decades, the importance of achieving a high share or even 100% renewable penetration has become a global aspiration. While the ever-increasing proliferation of renewables contributes to a more sustainable energy sector, considerable challenges remain for the secure and economic operation of electric power systems. For a long time, the popularized locational marginal pricing-based market settlement rule has been considered to give strong incentives for profit-seeking participants to make strategic bids for price manipulation, leading to market efficiency loss. On the other hand, an effective market model deserves further development for sharing the availability of ubiquitous idle demand-side energy resources. There remain enormous tasks to take a further step toward a deeper renewable penetration on the premise of the present electricity market framework and mechanism, which prompts us to ponder how to improve the utilization of resources.

This book aims at conducting a systematic examination of the current research and practice of energy sharing and identifying the potential merits of such an emerging business model in the energy sector. In light of sharing economy, energy sharing can contribute to a more accurate match between energy supply and demand, thereby making efficient use of idle resources. Based on a fair and reasonable profit-sharing mechanism, Pareto improvement of an energy system or market can be achieved, which guarantees sufficient incentives for participants' involvement. In this book, the authors analyze the modeling and application in various forms of energy markets, e.g., electricity spot markets, multi-area electricity markets, retail markets and integrated energy markets. In addition, the enabling technologies for the implementation of the energy sharing are discussed, which provides the readers with an explicit sense about the cyber-physical nexus.

Hopefully, this book will provide a fundamental reference for the development of sharing economy-related technologies and business models in the energy sector.

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Foreword by Xiaoxin Zhou

The recent decades have witnessed China's great efforts to a sustainable ecological environment and society. In September, 2020, the carbon neutrality target was declared with China committing to peak carbon dioxide emissions before 2030 and to achieve carbon neutrality before 2060. In March, 2021, China further declared to construct a novel paradigm of renewable-dominated power systems toward a low-carbon and efficient energy transition. In this instance, China has set an ambitious goal for an over 1200 GW wind and photovoltaic portfolio by 2030. In addition to large-scale renewable clusters, distributed energy resource (DER) technology has been advocated as another promising solution to facilitate the accommodation of local clean energy in smart cities and rural communities, e.g., offshore wind power and waste to biomass.

In a foreseeable future, the ever-increasing proliferation of renewables will pose great challenges to the secure and efficient operation of the power grids as well as the electric power industry reform in China. Traditional locational marginal pricing-based market framework has already raised concerns that the merit order effect of zero marginal cost renewables will bring down the electricity market prices. In addition, the design of distribution-level retail markets is arousing a public interest regarding how to manage large-scale intermittent DERs into wholesale markets. A series of energy policies and studies have been proposed to enhance the reliability of renewable-dominated power systems in a market-oriented fashion.

The ambition of the authors of this book has been to produce a fundamental reference that can take advantage of sharing economy to improve Pareto efficiency of energy markets. Based on the core idea of "access over ownership", energy sharing can be interpreted as the sharing economy in the energy sector, namely designing incentive-compatible market mechanisms for Pareto improvement by facilitating the utilization of idle energy resources via advanced information and communication technologies. For example, the capacity of a large-scale centralized storage can be shared among a set of customers for individual use, and a number of distributed storages can be aggregated as a single entity as well. Energy sharing is not only a novel business model, but a transformation of our thinking way. Such a concept enables the maximization of production by making full use of limited resources. I think that the authors have made an admirable success in their objective and task. The chapters in this book present an up-to-date analysis and modeling for energy sharing in a comprehensive framework of energy markets, with a considerable innovation in terms of theories and practices.

I hope that this book will provide well-founded guidance and direction for the research and refinement of sharing economy in the energy sectors.

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Chapter 1
Introduction

1.1 Background and Motivation

The growing awareness of serious environmental challenges and energy shortage issues entails a renewable and sustainable energy transition. In recent decades, the importance of achieving a high share or even 100% renewable penetration has become a global consensus. Regarding the “30·60” Carbon–neutral Target, China declared that great efforts should be made to construct a novel paradigm of renewable-dominated power systems [1]. China has set an ambitious goal for an over 1200 GW wind and photovoltaic (PV) portfolio by 2030, accounting for approximately 34% of the national total installed generation capacity [2]. In addition to large-scale renewable clusters, distributed energy resource (DER) technology has been advocated by many countries around the world as another promising solution to facilitate the integration of near-zero-emission (NZE) generation by matching regional supply and demand [3]. In California, the total installed capacity of DERs has exceeded 12 GW, with 33% of the electric load served by renewable energy since 2020 [4].

While the ever-increasing proliferation of renewables contributes to a more sustainable energy sector, considerable challenges have been posed to the secure and economic operation of electric power systems. Therefore, recent years have witnessed a wide variety of studies and practices striving to enhance the reliability of renewable-dominated power systems in a market-oriented fashion. For example, China has enacted a series of mechanisms to promote the consumption of renewable energy in the Northwest and Southwest in recent years [5]. Another example is the pilot project initiated in US, allowing DER end-users to participate in market bidding for peer-to-peer (P2P) transactive energy [6].

There remain enormous tasks to take a further step toward high-share renewable penetration on the premise of the present electricity market framework and mechanism. On the one hand, in most of the wholesale markets around the world, locational marginal pricing (LMP)-based market clearing and settlement are popularized, depending on the marginal cost of balancing the last-MWh load demand.

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However, such a paradigm has already raised concerns that the merit order effect of zero marginal cost renewables will bring down the electricity market prices. Meanwhile, profit-seeking thermal generators have incentives to make strategic bids for price manipulation, resulting in market efficiency loss. Recent empirical evidence shows that the strategic bidding of the thermal generators in China's load centers may distort global-optimal dispatch, thereby leading to additional curtailment of the wind and PV power from the northwest [7]. On the other hand, the design of distribution-level electricity markets is arousing a public interest regarding how to manage large-scale intermittent DERs into wholesale markets. Despite the success of the world's first blockchain-based solar power trading, it remains challenging to efficiently organize ubiquitous DERs owing to considerable transaction costs. In contrast to the generators in wholesale markets, end-users may be reluctant to serve as participants in retail markets and be involved in frequent bidding processes. What end-users actually need is a well-escrowed service for sharing idle DERs and a bidding-free reward mechanism to receive payment.

To this end, with the core idea of "access over ownership", there is growing concern about the concept of sharing economy in the energy sector in recent years. Sharing economy refers to a market model that enables individuals or entities to share their idle resources with others upon payment for the purpose of efficient resource allocation and social welfare maximization [8]. To date, sharing economy-based business models have achieved substantial success in the housing (i.e., Airbnb) and transportation (i.e., Uber) fields by matching individuals to enjoy underutilized products [9]. Essentially, the physical interconnected networks of energy systems provide a natural platform for sharing economy application. In bulk power systems, for example, PJM has initiated coordinated transaction scheduling (CTS) via interregional tie-lines with NYISO and MISO since 2014 and 2017, respectively, to improve generation utilization and enhance price predictability [10]. In addition, transactive energy-related pilot projects have been launched by Pacific Northwest National Laboratory (PNNL), enabling DER owners to share demand side resources with their neighbors through distribution grids while smoothing the fluctuations of electric load [11].

The concept and business model of sharing economy will bring new challenges and opportunities for deregulated energy markets. Therefore, in this chapter, we call upon an overview of the potential market design for energy sharing, and conduct a systematic review of energy sharing-related research and practice, which will provide a useful reference and insight for the development of the sharing economy in the energy sector.

1.2 Bibliometric Analysis

To provide an overview of the existing research on the sharing economy in energy markets, a bibliometric analysis was conducted on January 1, 2021 using Web of Science (WoS) database. Keywords used for WoS were as follows: TS = ((sharing economy OR collaborative consumption) AND (energy market OR electricity market OR mechanism design)).

The number of publications retrieved by WoS from 2003 to 2021 are shown in Fig. 1.1. In summary, 964 publications were identified. The number of publications before 2008 was relatively small, while it has been rapidly increasing since 2013. This proliferation of sharing economy was driven by the Economic Crisis and Great Recession in 2007–2008. It takes several years to bring sharing economy-related research and practice to publication. The number of relevant publications in popular journals since 2010 are listed in Fig. 1.2.

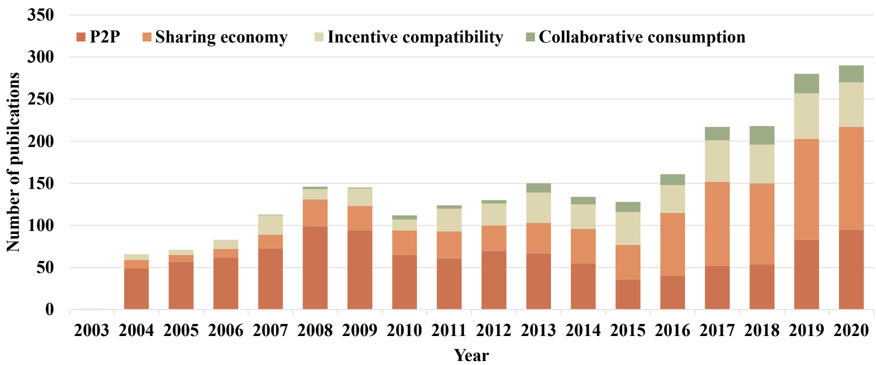

Fig. 1.1 Number of publications retrieved by WoS

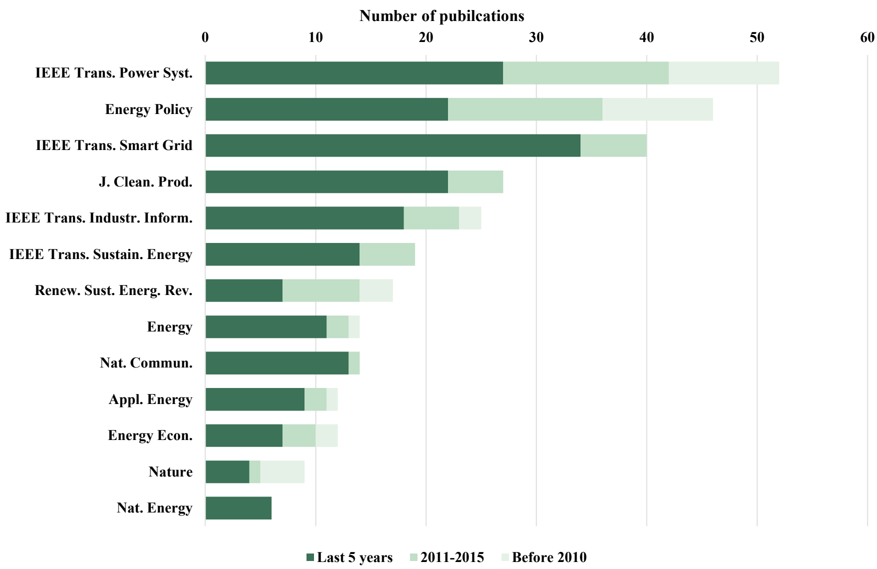

Fig. 1.2 Number of relevant publications in popular journals

In the energy sector, the concept of sharing economy is generally proposed for the purpose of incentive-compatible and individual-rational market participation using mechanism design theory. As explained in the Introduction, the traditional marginal pricing (MP)-based mechanism may not be able to elicit truthful bidding in wholesale markets. In practice, a thermal generator may not fully share its availability by withholding its capacity or making strategic bids. Thus, the sharing economy should contribute to a fair and reasonable pricing mechanism for truthful bidding. On the other hand, the sharing economy should achieve an efficient aggregation of DERs in retail markets and identify the unique value of a participant for rational profit sharing. We briefly review the existing studies related to the sharing economy in energy markets from the perspective of market structure.

For wholesale markets, ref. [12] proposes an incentive mechanism that elicits truthful information on strategic wind power producers supplying stochastic resources for wholesale markets. Ref. [13] applies the Vickrey-Clarke-Groves (VCG) mechanism to electricity spot markets and conducts a comparative study with a marginal pricing mechanism. In [14], the VCG mechanism is adopted in a two-stage electricity market to prevent strategic behaviors of market participants with a high penetration of variable renewables. For retail markets, ref. [15] proposes a nucleolus-based cost allocation method for incentivizing multi-microgrids within a grand coalition. Ref. [16] applies a bargaining game in an agent-based hierarchical framework on the retail side and implements a distributed optimization program for privacy protection. Ref. [17] designs a profit-sharing mechanism based on cooperative game theory, and the cooperative surplus is allocated according to each participant's externality. Ref. [18] proposes a cooperative energy sharing market using generalized Nash bargaining (NB), and develops a linearization solution algorithm.

In recent years, some review articles about sharing economy in terms of P2P transactive energy and demand side management have been published. Ref. [19] reviews energy sharing on the demand side and analyzes its potential for balancing services provision. Ref. [20] conducts a review of the principle of the sharing economy in electricity markets and assesses the development of sharing economy based on economic, social and environmental perspectives. Ref. [21] contributes an overview of the emerging P2P markets that consists of motivation, challenge and mechanism design and proceeds to potential application. Most existing review articles provide an interpretation of energy sharing as collaborative consumption in retail markets and focus on transactive energy among P2P sharing. However, from the perspectives of game and mechanism design theory, there exists no systematic overview or taxonomy for the sharing economy in energy markets, including wholesale, retail, integrated energy, and a high share of renewables.

1.3 Concept of Energy Sharing

1.3.1 History and Development

Sharing economy is a hybrid market that refers to the sharing of the right to use goods and services. The umbrella concept of sharing economy can be explained in contained different labels, such as collaborative economy, P2P economy and other interpretations. The concept of sharing economy is not new and can be dated back to “collaborative consumption”, which was first proposed in 1978 [22]. The original idea was that by sharing idle resources, people would be able to improve the utilization of goods and services, thus achieving Pareto improvements based on existing resources.

Over the past decades, the leapfrog development of the Internet and information and communication technologies (ICTs) has led to a dramatic improvement in computing power and the diversity of display modes, as well as an increasing number of business models related to sharing economy. In 2002, Yochai Benkler from Harvard University proposed the concept of “commons-based peer production”, and then extended the idea to “shareable goods” in 2004 [23]. With the advent of the Great Recession during 2007–2009, there was a growing sense of urgency about global population growth and resource depletion, leading to people’s awareness of the importance and necessity of sharing economy. Conventionally, customers may possess too many belongings that are not frequently used, thus yielding a huge waste of resources. In US, for example, more than $1.2 trillion was spent on nonessential goods each year [24]. There have also been attempts to mitigate the “Tragedy of the Commons”, the idea that when we need to make more efficient use of idle resources when maintain our quality of life [25]. In 2010, the first book of sharing economy was published, which systematically presented the definition, business model and significance of sharing economy.

In recent years, the maturation of various enabling technologies has provided a possible commercialization of sharing economy. Many businesses have been influenced by this phenomenon, including hospitality, transportation as well as insurance industry. The leading companies that are driven by sharing economy are no longer insurgents and newcomers. Uber, Airbnb and a handful of others have gained the capability and scale to compete with, or even surpass, some of the world’s largest players in transportation, hospitality and other industries [26]. Sharing economy has expanded the choice of transaction subjects and the space for welfare improvement so that people can stay at home and employ all kinds of resources for individual use. These business models have endowed sharing economy with new significance.

1.3.2 Characteristics

Based on the core idea of "access over ownership", *Energy Sharing* can be interpreted as the sharing economy in the energy sector, namely designing incentive-compatible market mechanisms for Pareto improvement by facilitating the utilization of idle energy resources via advanced information and communication technologies. According to such an interpretation, the characteristics of energy sharing are summarized as follows:

- **Utilization**: Energy sharing can contribute to a more accurate match between energy supply and demand, thereby making more efficient use of idle resources. Such an accurate energy balance benefits from Internet technologies. For example, Airbnb developed an Internet-based platform for guests with short-term activities, which is able to improve the utilization of idle housing. Similarly, an Internet-based platform is required to support the energy sharing among customers on distribution power networks. In addition to individual use, DER owners can share surplus availability with neighbors, for example, rooftop solar energy transactions.
- **Efficiency**: Energy sharing helps achieve Pareto improvement of an energy system or market, which has to be supported by optimization-based strategies. Generally, an increase in the utilization of idle resources represents a higher efficiency of energy system operation. For example, a virtual power plant (VPP) enables the aggregation of shared DERs to achieve peak load shaving and off-peak wind accommodation. However, a poorly-designed energy sharing strategy may even depress the overall social welfare, e.g., storage sharing. Sharing in-home battery storage with neighbors can accelerate the degradation of the battery bank, and thus extra expenses have to be incorporated into decision-making process.
- **Mechanism**: Energy sharing requires a fair and reasonable settlement rule that defines the payments for the shared resources, which guarantees sufficient incentives for customer involvement. In the energy sector, for example, a well-designed pricing mechanism is the key to eliciting marginal generators' truthful bids. On the other hand, a profit sharing or cost allocation mechanism is needed for efficient and stable aggregation of DERs in retail markets to reward good behavior and penalize bad one.

1.3.3 Taxonomy

We propose a taxonomy for energy sharing-related research in terms of market structure, supply chain and energy attributes, as shown in Fig. 1.3.

From the perspective of market structure, the sharing economy in energy markets can be divided into wholesale and retail markets. Wholesale markets involve the sale of energy among utilities and energy traders before it is eventually sold to consumers, while the retail markets involve the sale of energy to end-use consumers. Generally,

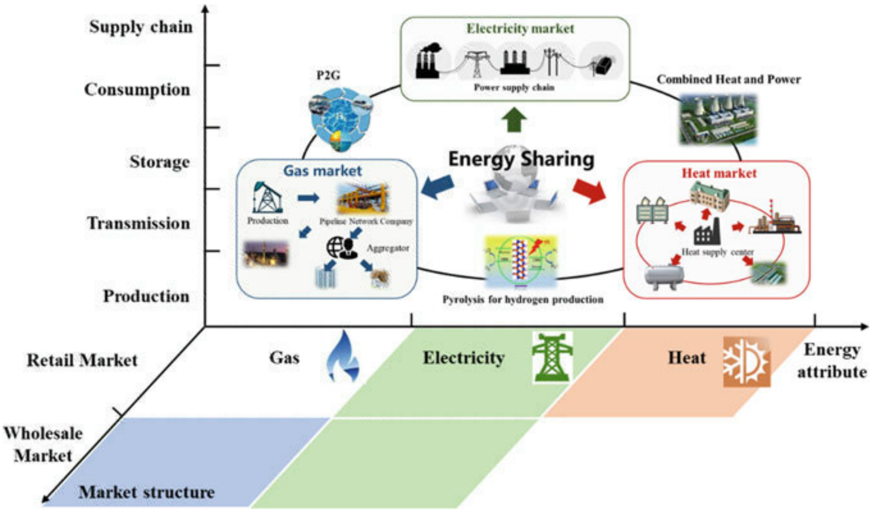

Fig. 1.3 Taxonomy of energy sharing

we focus on the concept of the sharing economy for mechanism designs in wholesale and retail markets.

From the perspective of supply chain, energy sharing is involved in energy production, transmission, storage and consumption. Regarding energy production, energy sharing enables the coordination of various forms of energy. For example, with the gradual maturation of energy conversion technologies such as heat pumps and waste-to-biomass, sharing the cogeneration capability can greatly improve the efficiency of combined power and heating systems. For the transmission sector, energy sharing can realize the coupled transportation of different energy carriers in a single transmission facility, thus reducing the redundancy in materials and corridor coverage. One typical example is superconductor cable, which enables the transmission of electric power and liquid hydrogen. Additionally, the technology and business model of storage sharing have been widely investigated around the world, with a focus on the bidirectional sharing of energy storage. The capacity of a large-scale centralized storage can be shared among a set of customers for individual use, and a number of distributed storages can be aggregated as a single entity as well. In the consumption sector, energy sharing can satisfy the heterogeneous preferences of individual users to the greatest extent. For example, a blockchain-based platform can help end-use customers to bid on rooftop solar power and obtain maximal rewards.

From the perspective of energy attributes, different forms of energy carriers can be shared and traded in interconnected energy markets. For example, power-to-gas (P2G) and fuel cell technologies have been advocated as an appealing solution to provide additional flexibility and facilitate energy sharing in joint gas/hydrogen-electricity markets.

1.4 Sharing Economy in Wholesale Markets

1.4.1 Electricity Spot Markets

The core of an electricity spot market is the pricing mechanism, which is generally based on marginal pricing. The marginal pricing mechanism has been widely used in many electricity markets around the world. In PJM, cost bidding and locational marginal pricing have been applied in real-time markets since 1998 and subsequently in day-ahead and regulation markets since 2000 [27]. Nord Pool is the first transnational electricity market around the world. It receives bids and offers from producers and consumers, and calculates market clearing prices to balance supply and demand curves based on marginal price settlement.

The marginal pricing mechanism meets the requirement of maximizing social welfare in perfectly competitive markets, where market participants cannot manipulate prices and the market prices are determined only by supply and demand. However, there exists potential for market participants to exercise market power under this pricing mechanism, as many actual cases show that market-oriented generators could manipulate market prices by making strategic bids. For example, one of the reasons that electricity prices of California soared between 2011 and 2017 is that the San Onofre Nuclear Generating Station (SONGS) closed. In this case, some power plants made strategic bids to earn more profits.

There is the possibility of market participants exercising market power under the marginal price mechanism. Therefore, efficient market mechanisms should be carefully designed to mitigate the market power of generators. Mechanism design theory, also known as reverse game theory, studies the approaches of economic incentives or cost allocation toward designed objectives, where market participants act rationally through strategic behavior. A lot of research has focused on how to make market participants submit truthful information, and the Vickey-Clarke-Groves (VCG) theory is widely adopted. The payment for a unit based on VCG mechanism is equal to the substitution benefit of the unit for other units, i.e., the change in total cost of the market before and after the unit participates in the market. The VCG mechanism could accurately identify the value created by market participants and motivate market participants to submit truthful information to the market operator. Therefore, under the VCG mechanism, it's the best choice for a generator to make truthful bids, no matter whether other generators make truthful bids or not. The social welfare is shown to be maximized at the dominant strategy equilibrium where every market participant submits truthful information. Ref. [28] applies the VCG mechanism to supply and demand bidding and the VCG mechanism is proved to elicit bidders to bid truthfully, then the feasibility of applying VCG mechanism to power and gas pipeline capacity auctions is evaluated. Ref. [29] applies the VCG mechanism to wholesale electricity markets, but the network constraints and renewable generation are not considered. Ref. [30] improves the standard VCG mechanism and applies it to wholesale electricity markets and the result shows that an efficient Nash equilibrium exists when every market participant submits truthful information. Ref. [31] proposes a VCG-based profit distribution mechanism for wind power aggregators to elicit private information truthfully. VCG mechanism design theory has been widely applied to the design of incentive compatibility mechanisms for general commodities, renewable energy, energy storage and demand response. Theoretically, this mechanism perfectly satisfies incentive compatibility. However, the VCG mechanism has not been implemented in practical applications due to some defects, such as complicated computation and sacrificing budget balance.

1.4.2 Multi-area Electricity Markets

The essence of multi-area electricity markets is to determine the optimal sharing strategy among multiple connected power grids for the concerns of price predictability, renewable accommodation, etc. In recent years, the PJM market has conducted coordinated transaction scheduling (CTS) with electricity markets in other regions of the United States, to improve the optimal allocation of resources and reduce the fluctuation of market prices. Additionally, several European electricity markets have focused on the coordination of multi-area market in recent years in the context of the gradual increase in the penetration rate of renewable energy [32]. Compared with isolated operation, multi-area electricity market realizes the coordination of multi-area power systems, and clean electricity can be shared by each regional power grid, which improves the overall operation economy.

Many scholars regard the lack of algorithmic support as the main barrier to coordinating multi-area electricity markets. Some studies focus on the pricing mechanism or the clearing algorithm. In [33], a joint energy and reserve pricing mechanism is proposed to enable the balance of supply and demand in a multi-area market. In [34], the reliability criteria in a multi-area market are established and evaluated using probabilistic metrics. The proposed criteria are incorporated into the multi-area market clearing formulation. In [35], a market-based cross-border trading mechanism for multi-regional energy markets is designed. Some decentralized coordination strategies have also been proposed to protect information privacy in multi-area energy markets, e.g., optimality condition decomposition [36], alternating direction multiplier method [37], and augmented Lagrangian relaxation [38]. However, in these studies, the marginal pricing mechanism, which may not theoretically meet the requirement of incentive compatibility, is commonly used.

The problem of exercising market power is even more serious in multi-area markets because there is information asymmetry between the multi-area markets. As a matter of fact, generators in the power-receiving area have to provide reserves for the inter-area power to ensure the safe and stable operation of the power system. More inter-area power usually requires more reserves in the power-receiving area. Therefore, when the generators submit higher reserve costs, market operators aiming to minimize system costs will decline the amount of inter-area power to reduce the costs of electricity market. In this case, the generators in the power-receiving area could get more revenue by forcing inter-area power out of the electricity market, but the efficiency of multi-area energy system will decrease and resources cannot be optimally allocated. A real-world case shows that in China, the generators in the power-receiving area prevent renewable energy from the northwest by submitting high reserve costs, leading to the curtailment of wind and solar.

Therefore, it is necessary to design a market mechanism which is incentive-compatible to elicit market participants to make truthful bids in multi-area market. Ref. [7] first applies VCG auctions to joint market clearing in multi-area power systems. The thermal units are elicited to make truthful bids and provide reserves to help accommodate renewable energy. However, how to improve the efficiency of multi-area market coordination and VCG auctions in real-world cases remains a public interest.

1.4.3 Integrated Energy Markets

To date, the market scheduling of electricity, thermal energy and natural gas generally takes other energy systems as static boundary conditions, which leads to inadequate sharing among different energy carriers. However, with the increasing coupling of different energy resources, the interaction between multi-energy markets can no longer be ignored. Therefore, existing studies and pilot projects have proposed constructing an integrated energy market, taking charge of coordinated sharing among different energy market entities. Recent decades have witnessed a rapid development of integrated energy markets in different regions around the world. For example, the U.S. government has initiated integrated energy trading projects with a total investment of 650 million dollars since 2007, which further guarantees national energy supply adequacy and security [39]. Due to a high proportion of gas-fired generation (~34%), Great Britain has been focusing on the construction of joint electricity and natural gas markets, especially technical solutions regarding the challenges brought by the increasing penetration of wind power [40]. Japan has issued a series of policies to establish integrated energy markets for energy sharing. In April 2010, the Japan Smart Community Alliance (JSCA) was founded to balance demand side energy supply and demand [41]. A 100% hydrogen-powered city, Harumi Flag, will be built by 2024 [42].

A wide variety of the existing literature has quantified the cost and benefit of sharing energy resources among integrated energy markets. In [43], a coordinated operation and long-term planning strategy of electricity and natural gas systems is developed based on real-world cases in Spain. In [44], a hybrid gas-electricity model is proposed, in which the potential coupling effects between gas and electric power systems are evaluated. In [45], a day-ahead market clearing framework is designed to investigate the optimal operation strategy of gas-fired power plants in electricity-gas combined markets. In [46], a joint market framework of integrating power grids and heating systems is proposed to evaluate the cobenefits of sharing solar-powered heat pumps.

Additionally, some studies have investigated the strategic behavior of multi-energy market participants. In [47], a computational game theoretic investment model is proposed considering the strategic market behaviors of natural gas participants and its influence on the electricity market and carbon emission market. In [48], the strategic behavior of market participants in a multi-energy market is analyzed, in which a multi-energy participant is allowed to aggregate the local energy system and maximize the expected profits in the whole electricity market. In [49], a heat and electricity coupled system is introduced, and the concept of integrated demand response is proposed in a heat and electricity combined market to investigate the demand flexibility of smart buildings.

In most of the existing literature, the marginal pricing mechanism is adopted for integrated energy market settlement. While this may not be the case in realistic heating or natural gas markets, ref. [50] has explored the marginal pricing design of gas and thermal energy. However, information asymmetry between different energy systems can lead to a much more severe impact on market efficiency than that in a single-energy carrier market. For example, to prevent the strategic bidding of gas-fired power plants, many regions have enacted market regulation and supervision policies, e.g., the Electric Reliability Council of Texas (ERCOT) sets a price cap of $ 2000/MWh when contingencies occur [51]. Therefore, the mechanism design theory of energy sharing may be another promising choice to elicit truthfulness of the participants in integrated energy markets, which deserves in-depth study in the future.

1.5 Sharing Economy in Retail Markets

1.5.1 Agent-Based Energy Sharing

Agent-based energy sharing refers to the case where various DERs are coordinated and organized by an external operator. For agent-based sharing, developing suitable coordinated strategies and mechanisms for different types of DERs is an effective way to incentivize DER owners to share their idle resources. The existing literature can be divided into two categories: (i) intrusive strategies that allow the operator to access individual DERs, e.g., direct load control, and (ii) non-intrusive strategies in which the self-dispatch of DER owners is influenced by the incentive signals sent by the operator, e.g., price-based demand response.

For intrusive strategies, the operator collects the information and sends control signals to DERs. Many realistic cases of intrusive strategies have been developed. For example, the U.S. military has implemented demand-side management projects in many regions and adopted intrusive strategies to dispatch DERs [52]. Demand-side management has been implemented to realize the direct control of DERs in Ningxia, China [53]. Many scholars have conducted research on intrusive strategies. The direct load control algorithm of electric water heaters applied to wind power accommodation is studied in [54]. Based on the state sequence control algorithm, ref. [55] studies the direct load control algorithm of electric heat pumps based on low-pass filtering to suppress the power fluctuation of the connection between a microgrid and distribution grids. However, intrusive strategies bring some problems, such as privacy concern, heavy computational burdens and large data exchange.

Considering the basic nature of a sharing economy structure, non-intrusive strategies, such as edge computing techniques, have been developed. Distributed algorithms such as Lagrangian relaxation and ADMM algorithms are promising candidates. The distributed edge computing framework is designed for energy management that can be applied to renewable energy to improve the control response speed of DERs. Ref. [56] applies decomposition techniques for large-scale distributed prosumers in demand-side equipped with IoT devices.

Agent-based energy sharing is dominated by an external operator or an energy sharing platform. The key issue is to investigate optimal pricing methods and profit sharing between the operator and DER owners. Such mechanisms are uniformly designed and organized by the operator while trying to fulfill Pareto optimality, budget balance, incentive compatibility and other axioms. However, there remains an open question regarding how to design a fair and reasonable profit-sharing mechanism, and some studies have focused on the measurement of "fairness" [57].

1.5.2 Peer-To-Peer Energy Sharing

In contrast to the agent-based model, which is a kind of business-to-customer (B2C) service, P2P energy sharing requires customers to make self-decisions, and is thus defined as a customer-to- customer (C2C) service. P2P energy sharing refers to energy transactions in a P2P trading platform or transactive market among diversified DER owners, including residential and enterprise prosumers. The earliest commercialized energy trading platform is Vandebron, which was launched in the Netherlands in 2014 [58]. Users of the platform first choose different trading contract periods according to personal preference; then, the platform recommends appropriate power suppliers. By this means, the source of power supply can be tracked through P2P trading. The platform has already provided clean electricity for more than 100,000 households, but it is still limited to electricity trading and has not yet covered the costs of ancillary services [59]. Another example is the P2P trading platform in Brooklyn, which enables DER owners to provide clean energy to households on low incomes [60].

P2P energy sharing reduces the threshold of energy transactions and allows small-scale individual DER owners to directly participate while retaining control over their DERs. As a form of energy sharing with a high degree of freedom, P2P energy transactions are not only related to the interests of all parties in energy sharing but also related to wider social interests. As a result, more complicated rules need to be followed than in the existing sharing economy. Unlike the market rules in traditional energy markets, the rules for emerging P2P sharing lack uniform standards and show a diversification trend. The application of game theory and auction theory in P2P energy trading is examined to improve energy efficiency in [61]. Heterogeneous risk aversion of different parties in community-based energy sharing is considered, and a novel definition of fairness is introduced in profit allocation in [62].

As a core component of the market mechanism, the limitations of LMP-based pricing mechanisms in the wholesale market also exist in retail markets. Several studies focus on the mechanism design for facilitating DER aggregation, including ex-post profit sharing based on cooperative game theory and bilateral contracts. The cooperative surplus can be allocated among the DERs based on the Shapley value and nucleolus methods [63]. In [64], a new stability concept is introduced, leading to a trail-stable outcome whenever the preferences of agents are able to satisfy full substitutability. In practice, there may be a large number of market participants in P2P energy sharing, which may cause the problem of computational complexity. Some studies design a Nash bargaining-based profit-sharing mechanism to overcome this problem. In [65], an energy sharing scheme is established among DER owners, and the benefits brought by sharing DERs are allocated based on the contribution rate of each participant.

Some technical challenges remain to be addressed in terms of P2P energy sharing. For example, more efficient consensus-based algorithms need to be investigated to coordinate P2P energy sharing for fast convergence with acceptable negotiations. Additionally, some recent studies have focused on developing cryptocurrency, digital currency and other derivatives for P2P sharing settlement.

1.5.3 Integration of Distributed Energy Resources into Wholesale Markets

With the increasing penetration of DERs, how to efficiently manage large-scale DERs in wholesale markets has become a public interest. In essence, the aggregation of large-scale DERs characterizes the feasible region formed by the operating constraints of different DERs. A distribution system operator can aggregate large-scale DERs to behave as a controllable flexible power plant. Generally, the feasible region of a traditional thermal power plant is described by “static parameters”, e.g., installed capacity, minimum power output and ramping rate. However, the feasible region of a number of DERs is not only restricted by the static parameters of distribution networks but also shaped by the DERs and shiftable/curtailable loads with dynamic spatiotemporal dependency. For example, the “maximum available capacity” of a distribution grid can be changed under the impact of distributed photovoltaic power, power flow, and node voltage along different time slots. The “ramping rate” depends on the operating status and dynamic performance of resources, such as demand response.

In [66], a geometric approach is proposed to explore the flexibility potential of demand response, which facilitates the integration of demand-side resources into system-level operation. In [67], the Fourier-Motzkin elimination method is adopted to represent the dispatchable region of power systems. Ref. [68] proposes a method for approximately calculating the equivalent active-reactive power feasibility region of the energy networks. This method approximates the equivalent feasibility region of distribution networks by heuristically selecting active-reactive four-quadrant operating points. In addition, some papers explore the application of demand-side resources or renewable energy equivalent feasible regions in the optimized operation of transmission grids. Ref. [69] applies equivalence theory to the field of unit commitment and proposes a safety-constrained unit commitment model, which takes the uncertainty of variable renewables into account. The aggregation of DERs makes it possible for distributed individuals to provide upstream grid services for wholesale markets.

The aggregation of various DERs can also serve as non-wire alternatives (NWA) to defer investment of energy networks as well as capacity expansion. In [70], the reliability value is embedded in the planning framework to determine the capacity of rooftop photovoltaic and storage amidst rare weather events when distribution network contingencies occur. Ref. [71] notes that the existing DER pilot projects may help to defer generation and transmission expansion, thereby reducing the system-wide costs by 20–50%. Ref. [72] allows DERs to act as NWAs in a joint planning framework considering DER investment and power system expansion. Ref. [73] evaluates the role of DERs as NWAs against wire investment in traditional distribution network planning.

1.6 Enabling Technology and Business Models

1.6.1 Energy-Related Technology

1.6.1.1 Energy Conversion Technology

In human history, from the replacement of firewood by coal in the sixteenth century to the replacement of coal by oil in the twentieth century, every revolution in energy technology has promoted the course of human civilization. In the future, with the continuous development of renewable energy, energy conversion technology will play a structural role in energy sharing. Efficient conversion of energy can reduce the mining of fossil energy while reducing environmental pollution, yielding great significance for energy security and the development of human civilization.

Recent decades have witnessed a wide variety of emerging energy conversion technologies, including concentrating solar power (CSP), fuel cells and biomass gasification. One of the most important is power-to-gas or -hydrogen (P2G/P2H). Hydrogen energy is a resource-rich, low-carbon and widely-used secondary energy source, and is becoming a critical energy carrier for future clean energy transition. In this instance, P2G enables the transformation from surplus renewable energy to green hydrogen, which is extremely beneficial for the development of renewable-dominated power systems and the decarbonization of the industrial, transportation and energy sectors. In 2017, the installed capacity of P2G in the European demonstration project was approximately 30 MW. It is estimated that by 2050, 10–65% of the energy consumption of the EU's industrial field will come from P2G, and 30–65% of the energy in the heating industry and transportation will come from P2G. There are many technical routes for P2G, which are mainly divided into alkaline electrolysis, proton exchange membranes (PEMs) and solid oxide electrolyzer cells (SOECs). PEM water electrolysis hydrogen production technology has the advantage of flexibility and is able to match the volatility of renewable energy power generation. At present, PEM water electrolysis hydrogen production has entered the 10 MW-level demonstration stage. Additionally, 100 MW PEM electrolyzers are under development, and NEL-Proton, SIEMENS, and ITM Power are in a leading position in the relevant technology and equipment manufacturing. The 718 Research Institute of China Shipbuilding Industry Corporation has also carried out many studies on PEM water electrolysis technology [74]. The 10 MW P2G project under construction in Guyuan, Hebei, is the largest P2G conversion demonstration project in China, and the hydrogen can be used in industries and refueling stations [75].

1.6.1.2 Energy Transmission Technology

The hybrid energy transfer line (HETL) enables long-distance transportation of electricity and cryogenic fuel, e.g., liquid hydrogen and liquefied methane, in a single transmission device. The basic structure of an HETL is similar to that of an ordinary superconducting cable, and the major difference lies in that the cooling medium of an ordinary superconducting cable is supercooled liquid nitrogen, while an HETL uses cryogenic fuels [76].

This means of sharing the same transmission device with different energy carriers can greatly improve energy efficiency and is especially economical for long-distance transmission. Meanwhile, this technology is also a critical support for future energy sharing applications in the transmission sector. As early as the beginning of this century, scholars proposed the idea of a similar hybrid energy transfer line [77]. With the maturity of the material technologies, pilot projects are continuously emerging. In July 2019, the Chinese Academy of Sciences successfully developed the principle prototype of a "superconducting direct current power/gas transmission integrated energy transfer line". However, this technology is still in the laboratory stage and has not yet been widely popularized in practice.

1.6.1.3 Energy Storage Technology

Energy storage technology is an essential means for the transformation of human energy structure from fossil energy to renewable energy, which can smooth the volatility of renewables. In recent years, transportation electrification has created potential for portable energy storage sharing. The Swedish government has declared that all vehicles must use non-fossil fuels by 2030 [78]. In September 2019, China began to set up strong transportation networks with wide coverage and high speed, which requires the optimization of the transportation energy structure and the deep utilization of roadside renewables.

At present, one of the lowest hanging fruit is vehicle-to-grid (V2G), which allows bidirectional power exchange between electric vehicles (EVs) and power grids. The essence of V2G is to share idle battery resources for various grid supports. According to forecasts, by the end of 2030, the number of EVs in China will reach over 100 million, and the aggregated capacity will exceed 1000 GW, which is equivalent to China's installed thermal power capacity [79]. Through effective aggregation technology, the aggregated electric vehicle can be treated as a single controllable storage device and respond to dispatch signals from the upstream power grid. Some of the existing literature has evaluated the benefits of V2G applications and designed related business models. In [80], the integration value of EVs in Midcontinent Independent System Operator (MISO) grid is evaluated based on a multiday optimization model. The results show that with the support of V2G technology, orderly bidirectional charging of EVs can provide flexibility for peak shaving and ramping. In [81], the feasible region of EVs aggregation is formulated and applied in microgrid bidding toward connected bulk power systems. In recent years, an emerging concept and technology termed fuel-cell hybrid electric vehicles (FCHEVs) has prompted the integration of transportation and energy systems. With the complementarity of hydrogen and power systems, it is possible to electrolyze water to produce hydrogen during peak hours and store it for further use.

In addition, energy storage has become a generic supporting technology in various industries, e.g., communication, data centers, architecture, robotics, manufacturing and national defense security, among which the concept of sharing economy will bring about novel business models. Uber announced a new sharing model, "UberAir", in Dubai and the Dallas-Fort Worth area that will launch in 2023 [82]. The maturity of all-electric helicopter technology can greatly reduce people's commuting and travel time while relieving traffic pressure and can serve as large-scale portable storage as well. On the other hand, Huawei has provided Pakistani operators with communication facilities that share lithium batteries as backup power to solve the problem of communication interruption caused by unstable power supply. Furthermore, some researchers have proposed business models of cloud energy storage (CES) [83]. In [84], a CES operator is supposed to invest in centralized storage and share virtual storage for individual customers when needed. By contrast, in [85], individual customers decide to invest in distributed solar and storage, which can be shared and utilized by a CES operator to hedge against wholesale market risks and achieve peak shaving.

1.6.1.4 Energy Consumption Technology

In recent years, the wide use of intelligent instruments and sensors and the application of the Internet of Things (IoTs) have created conditions for deeper energy sharing on the demand side and provided a platform and an effective way to decentralize energy