Community Integrated Energy System Trading: A Comprehensive Review

Lu Chen, Qingshan Xu, Yongbiao Yang, Hui Gao, and Weixiao Xiong

Abstract—**Focused on life, consumption, and leisure, communities have been regarded as the basic unit of energy use in a city owing to rapid urbanization, whose energy use density continues to increase. Moreover, community integrated energy systems (CIESs) in the rapid development stage have become embedded, small, and self-sufficient energy ecosystems within cities because of their environmental and economic benefits. CIESs face a competitive energy trading environment that comprises numerous entities and complicated relationships. This paper presents an extensive review of various issues related to CIES trading. First, the concepts, types, and resources of CIESs are described. Second, the trading patterns and strategies of CIESs are reviewed from the four perspectives of the trading objects: community-to-peer (C2P), peer-to-peer (P2P), community-to-community (C2C), and community-to-grid (C2G). Third, a tri-layer trading framework and the features of CIESs that participate in combined multienergy markets are proposed. Last, the key issues in CIES trading are summarized.**

Index Terms—**Distributed generation, community integrated energy system, multi-energy market, trading pattern.**

I. Introduction

WITH the acceleration of worldwide urbanization over the past few decades, communities that are mainly composed of residents, commerce, and electric vehicles (EVs) have become basic energy-use units in cities [1], [2]. These communities account for a large share of urban energy consumption [3]. They have different demands such as electricity, gas, cooling, heating, and hot water loads. These demands are large, complex, and relatively regular [4]. In addition, distributed generation (DG) [5] has recently undergone explosive growth on the user side, benefiting from eco-friendly generation, low-cost operation, and maintenance. In this context, an increasing number of communities are adopting photovoltaic (PV) arrays, energy storage (ES), and combined heating and power (CHP) systems [6] because they are economically and technically feasible.

In this scenario, a community integrated energy system (CIES) [7], [8] is regarded as an effective option for aggregating DG, flexible loads, and energy management systems, which enables all energy elements to concurrently operate in an environmental and economic manner. There have been many research efforts and applications of CIESs [3], [7], [9] that can upgrade energy efficiency, increase multi-energy manageability, reduce energy dependence on external grids, avoid vast transmission losses, and minimize carbon emissions. Furthermore, numerous pilot projects are currently being developed worldwide, including the Brooklyn Microgrid in New York [10], [11], the Valley Housing Project in Australia [12], the Enerchain Project in Europe, and the Sino-Singapore in China.

Within this context, the effective utilization of CIESs to satisfy both the business and operational objectives of community operators and consumers is becoming an immense challenge that requires research attention. Energy trading is considered as an efficient way to facilitate diversified energy resources, and it has recently motivated studies on energy trading that allocates the multi-energy resources of a CIES. A tri-layer multi-energy day-ahead market framework and an operation mechanism that allows the simultaneous trading of electricity, heat, and natural gas were proposed in [13]. The economic dispatching and trading of smart buildings in a grid-connected community were discussed with respect to the impact of the air temperature [14]. With the growth of CIESs, energy markets have evolved from a hierarchical structure to a more decentralized state [15]-[17]. In [18], a model that enables periodic energy trading among communities was developed considering the future forecasting and its errors: one community could periodically buy/sell energy from/to other communities in the same district. In [19], one mechanism for distributed energy trading in communities was proposed for a competitive market, which was solved using the multi-leader multi-follower Stackelberg game. On this scale, the CIES, as an essential market entity, will further cause decentralized multi-energy markets to prosper because of the strong coupling between different energy grids in both the flow and market.

To date, there has been some reviews of research on peer-to-peer (P2P) energy trading in the community [20], [21],

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business models of diverse distributed renewable energy trading [22], [23], and energy trading among EVs [24]. However, a review of energy trading from the community's perspective is still lacking. In view of this, the purpose of this paper is to provide a survey of the energy trading and development prospects of CIESs. First, the types and resources of CIESs as well as the different roles of community operators are summarized. Then, the research status of CIESs and knowledge gaps are discussed from the perspectives of community-to-peer (C2P), P2P, community-to-community (C2C), and community-to-grid (C2G) energy trading. Subsequently, a tri-layer energy-trading framework is proposed. Finally, the features of CIESs that participate in combined multi-energy markets and the key issues that need to be addressed are identified.

The remainder of this paper is organized as follows. Section II briefly introduces CIESs, including their concepts and types. The energy trading of CIESs, particularly trading mechanisms and strategies, is discussed from the four perspectives of C2P, P2P, C2C, and C2G energy tradings in Section III. The future energy trading for CIESs is discussed in Section IV, including the tri-layer trading framework and key issues for CIES trading. Finally, conclusions are presented in Section V.

II. CIESs: Concepts and Types

A. Concepts of CIESs

In general, a community is a social unit (a cluster of people) located in a geographical area (e.g., a neighborhood, village, or district) with commonalities such as culture, morality, values, and identity [7]. Here, a community represents a region of several square kilometers (but not limited to this size) that is composed of residential, commercial, and small industrial consumers with joint consideration of its social and geographical attributes. Accordingly, a CIES can be regarded as a smaller version of an energy system that covers power generation, conversion, and clusters of different loads. One characteristic of CIESs is the strong emphasis on the close geography of energy production and utilization, unlike the decentralized manner of the virtual power plant in [25].

The concept of a CIES under consideration is shown in Fig. 1, which comprises an energy center and homogenous multi-energy consumers. In Fig. 1, CM represents carbon market; EG represents electricity grid; HG represents heat grid; NGG represents natural gas grid; HS represents heat storage; NGS represents natural gas storage; GB represents gas boiler; WF represents wind farm; HP represents heat pump; EC represents electrical chiller; and EH represents electrical heater. The center has energy supply devices such as microturbines (MTs) or PV arrays [26], ES, and energy conversion devices (ECDs) such as power-to-gas (P2G) devices and heat pumps (HPs). Consumers can be divided into three general categories. The first category is residential buildings [27] with relatively stable and seasonal energy loads that may be deployed by home energy management systems [28]. The second category includes commercial buildings (hotels, shopping malls, and office buildings) with diversified energy demands that differ from business scenarios. Small industrial buildings belong to the second category. The third category is an EV station, the load of which is determined by the number of EVs, traveling demands, and user preferences. Some communities that contain one or two of these categories also belong to this category, such as residential and commercial communities [14].

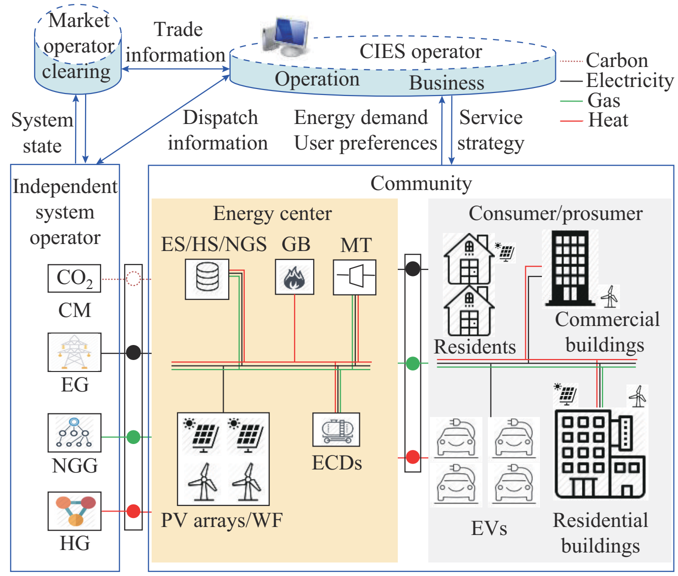

Fig. 1. Concepts of a CIES.

Here, the CIES operator is the serving entity in charge of business and operational optimization, e.g., integrated energy service providers and load-serving entities, with the goal of reducing the total cost and improving the reliability of the power supply. The CIES operator should provide both internal and external services. Internal services are responsible for a comprehensive and efficient energy supply, optimized operation of energy devices, and reasonable energy retail prices and energy-saving services for consumers. External services can aggregate all flexible resources to participate in competitive markets and obtain more energy profit or reduce costs, such as optimized energy buying strategies, peak shaving services, reactive power support services, black-start power supply services, and demand response services.

B. Types of CIESs and Resources

Owing to the effects of geographical environments, resource metrics, and other factors, CIESs will have different compositions and patterns. In terms of the energy self-supply level, we classify CIESs into three types: ① main grid supply communities; ② hybrid supply communities; and ③ micro-energy communities.

Main grid supply communities are the most common type supplied by external grids: ① no energy is generated within the community; ② the energy center contains only an energy distribution link; and ③ the energy demand for cooling, heating, or electricity is provided by ECDs on the demand side. For instance, regarding residents, the cooling and heating loads are provided by air conditioners, whereas hot water loads are provided by electric or gas water heaters. In commercial buildings, HPs or ECs provide cooling and heating loads, whereas electrical boilers (EBs) and GBs provide hot water loads. Thus, there could be two broad scenarios for the CIES operator. In the first scenario, the CIES operator is an intermediary agent that charges a service fee according to the distribution volume without operational risk. Its service range includes energy guidance, equipment maintenance, and other management services. In the second scenario, the CIES operator acts as a profit-oriented operator who purchases energy from external markets and resells it to consumers with retail rate schemes. These operators generally have and manage their energy assets, achieve the optimal trading price in the competitive market, and guarantee all the energy demands of the community while taking the corresponding risks. This type of community is the primary and most common form of community.

Hybrid supply communities are mainly supplied by external grids that account for a large proportion and are supplemented by DG units in the energy center. In most cases, these communities must interact with external markets because of the poor power-balancing ability of the energy center. There are generation, conversion, and distribution links in the energy center consisting of at least one DG approach. However, the generation output is small, uncertain, and incompatible with the full-time demand supply. The energy demand can also be provided by ECDs on the demand side, as determined by the corresponding economy and efficiency. Here, the CIES operator is mainly profit-oriented, as previously stated. These communities are currently prevalent worldwide, and example studies are provided in [29].

Micro-energy communities are supplied by an energy center without reliance on external grids and are known as the ultimate community type for the future. These communities can work in the islanded mode in emergency circumstances, and the CIES operator should be responsible for the supply-load balance [30]. A reliable microgrid with modified control techniques for residential communities was presented in [31] to achieve enhanced operation in the grid-connected, islanded, and resynchronization modes. Compared with other communities, the coordination and complementary application of different energies in the community greatly increase the flexibility of resources, which can adopt better trading actions according to different market rules and prices. Here, the CIES operator can obtain more profit by actively participating in external markets. Electricity, heat, and natural gas can be exchanged with external grids in insufficient or surplus scenarios. Currently, the North Customer Service Center of the State Grid Corporation of China is a typical micro-energy community.

Affected by local resources, space, funds, and user preferences, the energy center of a CIES has diversified and complex structural patterns that are difficult to represent by fixed structures. To systematically describe the energy components and structural characteristics of a community, its devices are divided into four types: generators, ECDs, ES, and loads. A bus-based structural map is employed to represent the universal structure of a CIES, as shown in Fig. 2, where an “R” in parentheses represents residents and a “C” represents commerce. Further, FC represents fuel cell; GH represents gas heater; HX represents heat exchange; HR represents heat recovery; EL represents electrical loss; HL represents heat loss; NGL represents natural gas loss; CPED represents community public electrical demand; ED represents electrical demand; CD represents cooling demand; HD represents heating demand; and HWD represents hot water demand. In Fig. 2, the connection and coupling relationships among various devices in the CIES can be intuitively shown, and the conversion process among different energies can be clearly displayed.

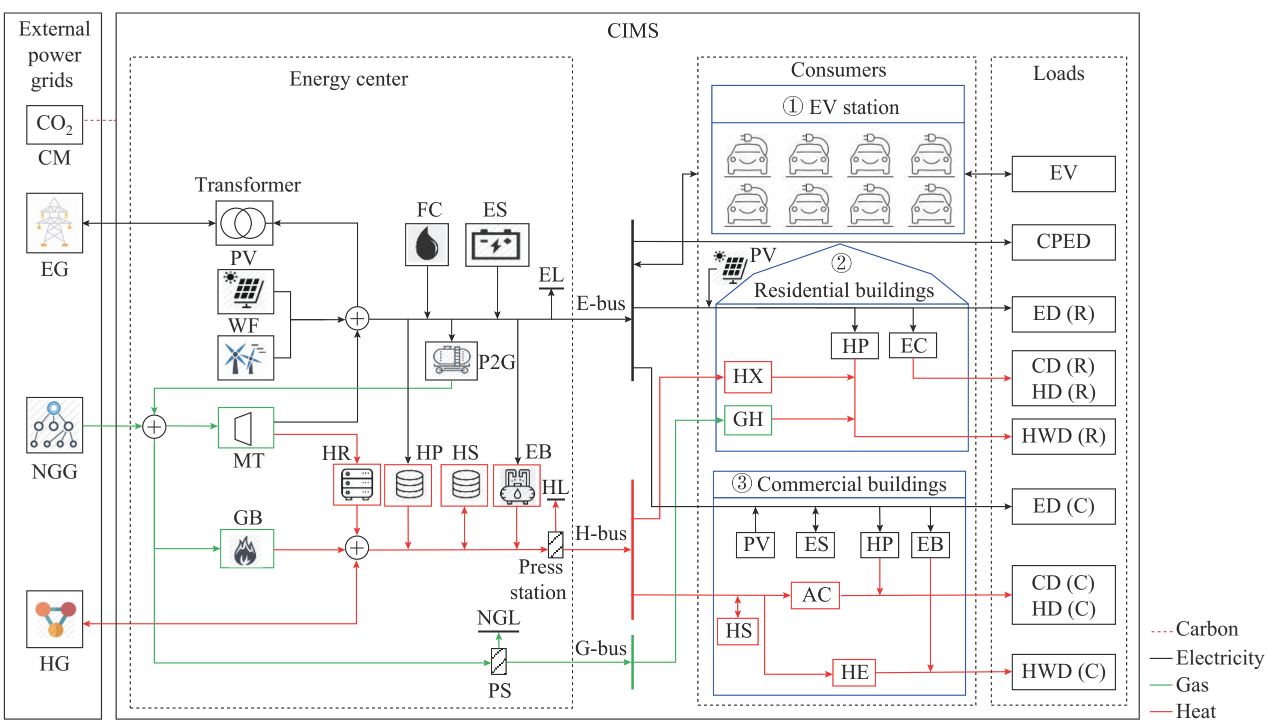

Fig. 2. Structure of a CIES.

Finally, the three types of CIESs are compared in Table I and Fig. 3.

TABLE I
COMPARISON OF THREE TYPES OF CIESS

Type	Energy supply	Function of energy center	Role of CIES operator	Resource flexibility
Main grid supply community in Fig. 3(a)	Completely supplied by external grids	Only power distribution	Intermediary agent/profit-oriented operator	Low, with adjustable loads
Hybrid supply community in Fig. 3(b)	Mainly supplied by external grids and supplemented by energy center within the community	Power distribution and small proportion of energy generation	Profit-oriented operator	Middle, with energy substitution/adjustable loads
Micro-energy community in Fig. 3(c)	Supplied by energy center within the community (self-sufficiency)	Power generation and distribution	Profit-oriented operator	High, with integrated demand response

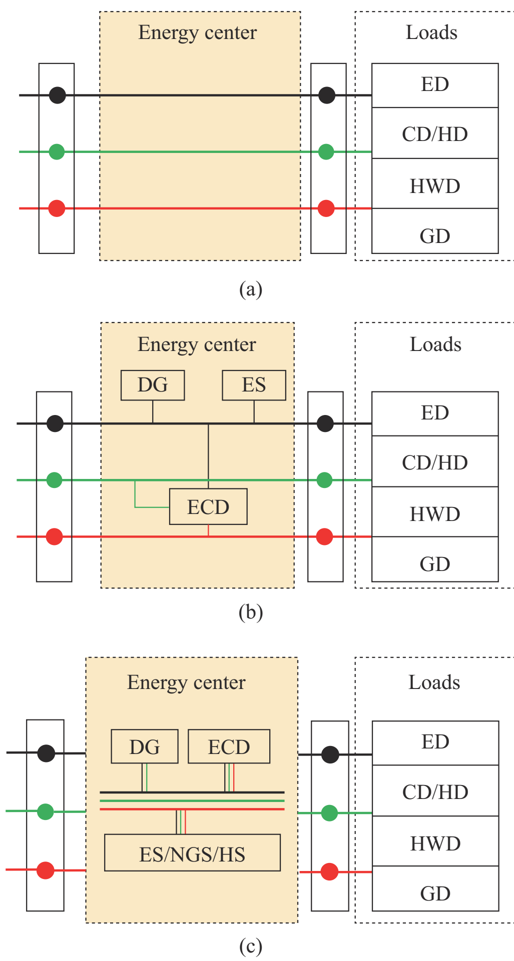

Fig. 3. Framework comparison of three types of CIESs. (a) Main grid supply community. (b) Hybrid supply community. (c) Micro-energy community.

Here, resource flexibility refers to the ability of communities to cope with uncertainties on the premise of meeting certain economies and reliability, including upregulation and downregulation. Upregulation refers to the community's ability to provide extra power, while downregulation refers to the community's ability to reduce excess power. Owing to differences in resource flexibility, the energy centers in the three communities have different supply capacities. The main grid supply community is supplied by external grids and has no internal supply ability with limited adjustable loads; therefore, its resource flexibility is evaluated to be low. The hybrid supply community has a proportion of internal energy generation but still depends on external grids in some periods; thus, its resource flexibility is evaluated as intermediate. The micro-energy community can be supplied by internal grids by an integrated demand response (IDR) during all periods, namely self-sufficiency. Hence, its resource flexibility is assessed as high.

III. ENERGY TRADING OF CIESS

According to trading objectives, the energy trading for CIESs can be divided into four types: C2P, P2P, C2C, and C2G, as shown in Fig. 4. For better understanding, we assume that P is an entity that can produce and consume energy; meanwhile, C is a CIES operator within the community that provides multiple forms of energy to customers according to the type of generator without energy consumption demand itself. The first two types, i.e., C2P energy trading between the CIES operator and consumers and P2P energy trading among consumers in the community, belong to intra-community trading. In the C2C mode, the surplus electricity, heat, and gas of the CIES and carbon quotas will be exchanged among communities to maximize the benefit. In the C2G mode, the generator, the CIES, and other entities jointly participate in multi-energy trading.

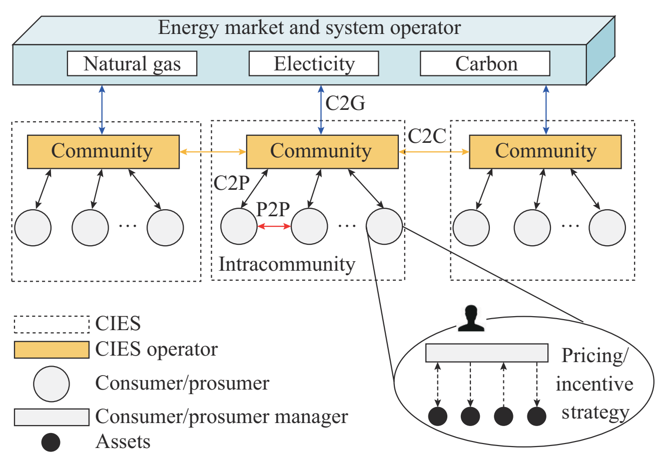

Fig. 4. Types of CIES trading.

A. C2P Energy Trading

In a CIES, various loads are traded as a commodity between the operator and multiple consumers to maintain the supply-demand curve at any time and achieve economic goals [32]. In this study, C2P energy trading involves three scenarios: multi-energy pricing, energy value-added services, and IDR.

In the first scenario, the CIES operator seeks to achieve the maximum benefit by considering the following measures: setting reasonable multi-energy pricing, referring to load forecasting and coupling, optimizing generation resources, and managing demand-side measures. Multi-energy pricing has various sophisticated forms such as time-of-use tariffs [33], progressive pricing, electricity plans (e.g., total consumption), and energy plans that contain heat and electricity. In [34], the electricity and thermal prices were formed by an optimization benefit model for the community operator, which included the energy buying payoff, the retail income of energy sold to consumers, and the income from surplus electricity fed to the power grid. A multi-energy price incentive model for an industrial park was designed for a low-carbon economic environment [35]. In [36], a type of real-time pricing was developed, whose float factor was determined by the ratio of the actual load to the average load. A novel nodal energy pricing strategy for a multi-energy system was proposed in [37] composed of two parts: nodal generation and a transmission fee. A combination of electricity and heat was sold to consumers in [4] by offering a series of energy package contracts based on consumer behavior.

In the second scenario, value-added energy services are the key measures that further expand the interests of CIES operators according to the discrepancies in the energy demands of consumers. The operators can utilize big data analyses and intelligent methods to ascertain the internal needs of multiple consumers, such as energy disconnection and connection services, the installation of new meters, integrated energy-saving services combined with big data and cloud platforms, the distributed power grid connections of proxy users, and uninterrupted power supply services by the ES. These measures improve consumer satisfaction and retention [38]. However, this trading scenario has a strong dependence on its business model, the local policy environment, and the level of data mining, and there is still room for development and exploration.

In the third scenario, IDR [39], [40], the goal is to motivate consumers to change their consumption profiles in response to incentives or price signals to assist CIES operators in external markets, such as encouraging lower energy use during periods of high market prices, or when the grid reliability may be jeopardized [41], [42]. In [43], an integrated load adjustment model considering price changes and incentives/penalties was developed. In [44], the proposed price-driven demand response could significantly improve the power stability of tie lines. Given complex physical and business aspects such as the demand aggregation effect, the relationships between the operator and consumers, and the geographical attributes of IDR resources, the model and assessment of the IDR in the CIES were not straightforward. A novel "transaction energy" model and assessment framework for CIESs were proposed in [45]. The framework addresses three aspects: a stochastic optimization model, a profit-sharing model, and an economic assessment model based on a fundamental cost-benefit analysis. This framework was introduced through an analysis of IDR business cases of some pilot studies in France. Certainly, the implementation of an IDR can impact consumer comfort levels and trading preferences because the ideal load profiles are modified [46]. For example, the adjustment of thermostatically controlled appliances may negatively impact thermal comfort [47]. Therefore, a novel two-stage control model for thermostat loads was proposed to participate in the IDR, which considers the different comfort sensitivities of various residents [48]. A comprehensive review of the IDR was conducted in [27]. The results showed that the IDR could utilize the complementarity of multi-energy carriers to improve their operational performance while securing customer comfort. On the basis of the enormous amount of research on IDR models for CIESs, it can be determined that the response behaviors of consumers are greatly simplified. For instance, some studies simply constrain the maximum/minimum values of loads to express the response behavior [45], [48]. Furthermore, some studies do not consider the price sensitivity, detailed physical models, or other factors. Thus, IDR models for CIESs must be further improved to realize real and normalized applications.

A summary of C2P energy trading is presented in Table II. Multi-energy pricing is the primary trading scenario in terms of energy sales, as determined by the market environment, pricing mechanisms, etc. Value-added energy services are supplementary trading forms to further expand the interests of the CIES operator, limited by user preferences and diversification levels. An IDR can strengthen the balance between supply and demand to become more economical, triggered by the external grid demand or the business strategies of the CIES operator.

TABLE II
ANALYSIS OF SCENARIOS OF C2P ENERGY TRADING

Scenario	Example	Objective	Constraint
Multi-energy pricing [33]-[37]	Time-of-use tariffs, progressive pricing, energy plans that contain heat or electricity, etc.	Maximize energy sale benefits	Power supply reliability and quality/ equipment output limits/price range/ market environment, etc.
Energy value-added services [38]	Energy disconnection and connection services, installation of new meters, integrated energy saving services, etc.	Further expand the operational interests	User preferences, diversification level dependent on business model, local policy environment and data mining
IDR [39]-[48]	Energy substitution and demand response (interruptible load, etc.)	Strengthen the balance between supply and demand to become more economical	Multi-energy complement/user response

B. P2P Energy Trading

Owing to the explosive growth of DG approaches, some residents are equipped with PV arrays and batteries, while some buildings have energy stations such as small CHPs, GBs, and ES. Thus, the concept of an energy prosumer in the community, namely an entity that produces and consumes energy, has emerged. Energy trading among prosumers within the community is referred to as P2P energy trading and is a new energy management paradigm that allows consumers with excess energy to pair with other consumers with inadequate energy, achieving balanced energy provision in the same region and reducing transmission losses. Here, the prosumer should be within the community and is an independent energy metering unit that can trade with other partners. Examples of trading objectives include high renewable energy utilization, electricity cost reduction [49], peak load shaving [50], minimization of network operation, and investment cost [12]. The following constraints are involved in the optimization processes of P2P energy trading [21]: flexible resource outputs, local balances, trading mechanism constraints, etc. A coordinator distributes the revenue of the entire P2P community following predefined principles such as determining the prices for calculating the revenue of each peer [22].

Undoubtedly, a fair and reasonable pricing strategy is a key part of P2P energy trading, which can be classified as a dynamic pricing strategy, a game theory strategy, and an auction mechanism.

The dynamic pricing strategy is a real-time price form that reflects the energy supply and demand relationship in the community [37], [51]; this relationship can be defined on the basis of the supply-demand ratio, the midmarket rate (MMR), or bill sharing. An electricity pricing model for P2P energy trading reduces the price variation in the real-time electricity market by introducing the supply-demand ratio to the pricing formula; thus, this model improves the benefits for prosumers considering the flexibility in energy consumption [15], [52]. Motivational psychology has also been identified as a novel tool for designing energy pricing. In [12], a detailed introduction of this concept was described to show how it could be applied to P2P trading with the MMR.

The game theory strategy is an analysis method for studying the phenomena of struggling and competition, which can be developed to describe the complex relationships between entities' businesses and technical schemes during the trading process [53], [54]. From a cooperative game viewpoint, the Shapley value is applied to model P2P trading and the decision-making process of prosumers by considering optimization and fairness among prosumers [55], [56]. From an uncooperative game viewpoint, the Stackelberg game is widely exploited to model and analyze trading problems in the market, such as capturing the interactions between the shared facility controller and residents [57]. Additionally, the Nash equilibrium is also suggested in [58].

The auction mechanism has been the cornerstone of many applications in energy markets. Similar to economic auctions, the main purpose of energy auctions is to obtain the lowest cost to match supply with demand, thereby maximizing economic efficiency. In [59], a general-purpose double-auction mechanism is specifically relevant to P2P trading because it obeys physical grid constraints without requiring agents' private information. Discriminatory and uniform k-double auctions were compared in [60] using case studies of 100 participants in a community that differed by PV penetration levels. Further, ESL represents electrical shiftable load; and EHS represents electric heating system. The above research on P2P energy trading within a community is compared in terms of mechanisms, objectives, and algorithms, as shown in Table III.

TABLE III
COMPARISON ON P2P ENERGY TRADING WITHIN A COMMUNITY

Reference	Resource					Mechanism	Objective	Algorithm
	DG	ES	EV	ESL	EHS			
[15]	√	√	√	√		Supply-demand ratio	Minimize cost	Interior-point-convex
[52]	√					Supply-demand ratio	Minimize cost	Distributed iterative
[50]			√	√	√	Supply-demand ratio	Maximize bids' use	Mixed-integer linear programming
[12]	√					MMR		Cooperative game
[55]	√	√				Shapley value	Minimize cost	Constrained nonlinear programming
[56]	√	√				Shapley value	Minimize cost	Standard linear programming methods
[57]	√	√		√		Stackelberg equilibrium	Minimize cost of the shared facility controller/maximize benefit of residents	Uncooperative Stackelberg game
[58]	√	√		√		Nash equilibrium	Minimize cost	Game theory
[62]	√	√				Pareto optimality	Minimize cost	Near-optimal algorithm
[18]	√	√				Equilibrium price	Maximize revenues	Hierarchical algorithm
[59]	√					Iterative double auction	Maximize social welfare	Adaptive algorithm
[60]	√					k-double auctions	Minimize cost	Game theory

In practice, numerous P2P pilot projects have emerged in Europe, North America, and Oceania to explore the possibility of P2P trading from various perspectives [61]. We recognize that extensive research on P2P electricity trading has been conducted, but that on P2P hybrid energy trading remains limited because it is difficult for ordinary consumers to generate multiple forms of energy such as heat and gas in the community. With an increase in the number of ECDs at consumer locations, this research will gain momentum in the future.

C. C2C Energy Trading

At a given time, some CIESs have surplus energy for sale or to retain in storage devices, whereas other CIESs wish to buy energy to satisfy load and storage demands. Energy sharing among CIESs, referred to as "C2C energy trading", is becoming even more significant owing to variations and mismatches between the internal demands in a community, which is more cost-effective and reliable and can reduce the energy loss incurred by long-distance transmission [63]. It may also yield savings for a CIES by avoiding selling/buying to/from external power grids [64], [65].

Specifically, an individual community involved in energy trading has its own interests to maximize without considering the interests of other communities. To encourage communities to contribute their superfluous energy to real costs, we need to build a trustworthy trading platform that enables all communities to engage in active trading. In [66], a multi-leader multi-follower dynamic game model, in which a scorecard model based on logistic regression was designed, was established to describe the credit ratings of prosumers. A new energy trading platform with a decentralized controller network of residential communities was proposed in [67], accommodating the energy trading of communities and improving the performance level of the community. In contrast, trading security and privacy are not negligible during C2C trading, and a decentralized trading system [68] using blockchain technology, multiple signatures, and anonymous encrypted messages was employed, all of which enabled participants to anonymously bid on energy prices while preserving the privacy of their identity.

In the early stage, electricity trading contributed to a large fraction of C2C energy trading [69], [71], and a reinforcement-learning-based energy trading scheme [72] was built to choose the optimized strategy according to the new energy predicted to be generated in the future, the estimated future power demand, and the ES level. Likewise, many efforts have been devoted to the concept of cooperation and games in interconnected communities in recent years to optimize their performance and gain benefits [73]. In [19], a unique equilibrium was demonstrated using a multi-leader multi-follower Stackelberg game to maximize the benefits of all participating communities. A two-layer game approach [74] was developed to achieve optimal and elastic energy trading for communities while improving the utilization of green energy. The trading prices and energy quantities were obtained using a proof double-auction mechanism in [75], [76].

With the growth of ECDs, hybrid energy trading is effectively included in C2C trading [77]. In [8], a three-step internal heat trading strategy was designed for optimal energy sharing among building communities to minimize the operational cost of the entire system. In [78], a hybrid energy sharing framework for multiple communities was proposed for a heat-electricity-integrated energy system with CHP and demand response. A more concise solution was presented to determine the fair prices for multi-energy trading [79] and generalized considering various supply- and demand-side energy management technologies.

Owing to energy redundancy, demand balance, and risk preferences, C2C trading and external trading can be simultaneously coordinated using a flexible pricing mechanism. In [80], a price incentive was proposed to coordinate trading between communities and the wholesale market and generalized considering prosumers' individual preferences for clean energy. An interactive two-level pricing mechanism that considers operational quality and intermittent generation [81] was designed for coupled communities in a power grid.

There are some similarities between P2P and C2C energy trading; both can be considered as point-to-point distributed trading at the corresponding network level. A comparative analysis between P2P and C2C energy tradings is presented in Table IV. Compared with P2P energy trading, C2C energy trading reduces the investment in communication equipment in the early stage and provides convenience to management. However, it requires consumers in the same region to form a community of interests, which causes new problems such as a reasonable distribution of trading income while satisfying the energy needs of all consumers [82].

TABLE IV
COMPARATIVE ANALYSIS BETWEEN P2P AND C2C ENERGY TRADINGS

Type	Entity	Content	Advantage	Disadvantage
P2P [12], [15], [44], [46], [52], [53]	Prosumers/consumers within the community	Electricity mainly	- Full trading freedom - Improve energy efficiency at the consumer layer	- Equipped with corresponding communication control equipment - Large early investment - Difficult to guarantee the safety and quality of energy trading - Sophisticated market management
C2C [67], [68], [75], [76], [82], [83]	Communities, DG approaches, energy aggregators, etc. (in a region)	Electricity, heating, cooling, hot water, gas, etc.	- Promote the rational allocation of energy resources at the community layer - Reduce the density of communication - Reduce early investment - Convenient market management	- Need to reach a consensus to form a community of interests - Acquire reasonable distribution of revenue, and form a community of interests

D. C2G Energy Trading

In most cases, a CIES must interact with external markets for balancing and sharing the surplus or shortage of power with outside power grids. This trading style is called C2G energy trading. Owing to physical characteristics, price regulations, and transmission ranges, the electricity market is the most active market, followed by the carbon and natural gas markets; the heat market is the least active. A comparison of the characteristics of multi-energy markets is presented in Table V. Here, the community can be regarded as an energy service provider or electric power company that participates in the electricity market. Considering that natural gas is a primary energy source, the community is not currently able to participate in the spot market for natural gas. Thus, the natural gas price of the community is considered to be the stable terminal retail price, and only natural gas in C2C trading is involved. The heat market is relatively closed because its products (such as hot and cold water) cannot be transported over long distances; thus, the heat market is treated as regional heat trading [84].

TABLE V
COMPARISON OF CHARACTERISTICS OF MULTI-ENERGY MARKETS

Energy market	Market activity	Trading cycle	Energy demand	Price characteristic	Transportation distance	Real-time balance
Electricity	High	Forward/day-ahead and intra-day/balancing market	Stable	Node marginal price, affected by generation, transmission, and congestion costs	Long distance	Yes
Natural gas	Middle	Forward/spot market (1 week)	Seasonal	Forward price, progressive price	Long distance	No
Heat	Low	Forward market	Seasonal	Affected by generation and distribution cost	Regional distance	No
Carbon	Middle		Affected by policy	Carbon quota		

1) Electricity Trading

CIESs have an advantage in the competitive and deregulated electricity market because of reasonable resource allocation and sufficient flexibility. In general terms, the main goal of these activities is to minimize the peak demand or electricity bill [85], [86] and to maximize profits [87] or social welfare [88], along with other objectives.

At the temporal scale, the electricity market can be divided into forward, day-ahead, intraday, and balancing markets. The roles, objectives, and challenges of CIESs in the electricity market are presented in Table VI. There are only a few studies on CIESs in the forward market [89], while more attention has been focused on the day-ahead or more recent time scales. A bilevel optimization problem [90] in the day-ahead market has been proposed, where the target of the lower level is to maximize the community's social welfare by solving for the power flow, and the target of the upper level is to maximize the profits of individual bidders. Apart from participating in energy markets, an alternative way of making profits is to participate in the ancillary service market. In [91], the technical approaches for providing frequency control reserves in balancing markets were investigated among a cluster of communities along with the potential economic profitability of the CIES. Considering the coupling of different markets, some studies have focused on the coupling between the energy and auxiliary service markets, such that the CIES participates in trading in the day-ahead and balancing markets [92], in which upregulated, downregulated, spinning, and nonspinning reserves are simultaneously employed. The EV [93]-[95] and ES [96] strategies were also obtained for the coupling markets.

TABLE VI
ROLES, OBJECTIVES, AND CHALLENGES OF CIESS IN ELECTRICITY MARKET

Time scale	Scenario	Objective	Main challenge
Forward market	Bilateral contract [89]	Minimize cost	- Forecasting accuracy of multi-loads and renewable energy sources - Assessment of energy and ancillary service price trend within a certain period of time
Day-ahead and intra-day markets	Peak regulation [85]	Minimize cost	- Integrating and optimizing large amounts of data provided by numerous devices and consumers
	Bidding [90], [97]	Minimize purchasing cost/maximize selling profit or social welfare	
Balancing market	Frequency control reserves [91]	Maximize profits	- Tracking of auxiliary service performance - Assessment mechanism of auxiliary service market
Coupling markets	Joint energy and ancillary service markets [92]	Maximize profits	- Coupling or pass-through relationship among markets, namely, day-ahead and real-time markets
	Avoid penalty fees for real-time differences and participate in the reserve market [93]	Maximize benefits of EV charging	
	Consider fluctuating costs of energy in day-ahead and real-time markets [96]	Maximize the revenues of ES	
	Bidding in wholesale and local flexibility markets [98]	Minimize operational costs	

In these works, the optimization models for the CIES in the electricity market are dominated by scheduling and supplemented by trading, and the market setting is greatly simplified such that the market environment is only employed as the input of the models and does not consider the impact of community decisions on the market price. The interaction and coupling between the CIES and the electricity market should be further strengthened for practicality.

2) Coupling Electricity and Carbon Trading

As global warming and energy shortages have become more pronounced, carbon trading has been regarded as an economic way to guide the transition of energy systems from higher-emitting activities to lower-emitting ones [99]. Carbon trading [100] is a trading mechanism for carbon emissions in which legal carbon quotas are established and traded. To achieve low-carbon goals, different countries have introduced emission trading systems with the goal of reducing carbon emissions, such as the European Union's Emissions Trading System [101], the United Kingdom's Emissions Trading System, the Chicago Climate Exchange [102], and the systems in Singapore [103] and the Netherlands, etc. Many studies have focused on the impact of carbon markets on energy prices or policies, such as [104], which investigated the effect of carbon trading on the real-time electricity market prices in California, USA, and [105], which analyzed the possible potential impact of the designed emission trading system on the affected generators by modeling the Australian National Electricity Market.

Owing to low pollution and high energy efficiencies, the CIES has an absolute cost advantage in carbon trading, which also has an indirect positive impact on the energy market [106]. Previous studies transferred the low-carbon effect as a single factor, variable, or constraint [107] to CIES scheduling and trading [108] as either flat [109] or ladder-type carbon prices. According to the carbon emission flow theory, the carbon footprint of communities is equal to the input energy multiplied by the corresponding carbon intensity [107], [110], and the constrained carbon emission cap can limit carbon emissions from the demand side, which is accounted for by multiple energy systems. Zero-carbon technologies such as PV arrays and WTs [106] and negative carbon technologies such as P2G facilities [111], [112] are also considered. P2G facilities in communities can efficiently reduce CO_2 emissions by synthesizing natural gas or using CO_2 as a raw material to generate methane [113]. In [114], a bilevel low-carbon optimal dispatching model was proposed for P2G plants in the power and natural gas markets. Additionally, the NO_x emission problem was considered in [111] to better match environmental goals. In [115], a fully decentralized blockchain-based P2P trading framework that couples the energy and carbon markets was proposed, and an incentive mechanism was designed for carbon emission reduction to achieve tax neutralization without market interventions in the trading process.

In most studies, the carbon market is introduced by adding the carbon cost to the total cost and assuming that carbon trading does not affect the clearing prices of the electricity market. However, this assumption does not consider the extent of carbon market pass-through in the real-time electricity market due to the greater involvement of the CIES.

3) Combined Multi-energy Trading

Owing to the limited interactive and settlement mechanisms among energy systems, many market entities have to participate in a single market rather than in coupling markets. However, this situation is changing owing to an increase in the number of cogeneration plants. As an important entity, the CIES purchases energy from electricity, gas, or carbon markets to maintain supply-demand curves and can feed surplus energy into external grids to generate revenue. Heat trading and electricity trading [4] are discussed in a generic framework. The optimal contract design, which involves coupled electricity and heat markets, is established with asymmetric information, whereas the heat price is determined by the optimal thermal flow [116]. A tri-layer multi-energy day-ahead market structure and an operation mechanism for the CIES are proposed [13], which allows the simultaneous trading of electricity, heat, and natural gas, and a new conditional value-at-risk approach is adopted to address the uncertainties in market prices.

Since the size of the considered CIES is not sufficiently large, it functions as a price-taker agent in wholesale markets, i. e., the behavior of the CIES will not affect market prices. Other forms of energy such as natural gas are treated as fixed sources or demands [117]. With the continuing increase in CIESs or their integrated energy aggregators, the market force of CIESs will become more prominent. Thus, a significant amount of information on how to exploit the influence of CIESs over multi-energy markets will be gained, which will further affect the design of the mechanisms of each market and form a closed influence loop.

IV. Future Energy Trading for CIESs

A. Tri-layer Trading Framework for CIESs

Based on the previous discussion, the CIES marketplace would be more complex because it is envisaged as a connection system that includes different types of devices and a wider variety of entities with diverse and changing demands. The CIES will enter a state of highly effective, normalized, and diversified trading in multi-energy markets, which strengthens the liquidity of regional comprehensive energy markets and closely interconnects with superior power grids by a long-distance transmission network, further promoting coupling and competition among grid layers (especially at short time scales). An optimization framework that supports a paradigm shift in urban energy systems considering DG is proposed in [118]. The market structure is designed with local energy trading from the perspectives of local energy trading, the retail market, and the wholesale market in [119], as well as the overall procedure of market design. The tri-layer trading framework of the CIES in combined multi-energy markets is shown in Fig. 5, where the intensity of the blue color represents the market activity.

1) First Layer: Community Energy Trading

The existing electricity retail market can be regarded as the embryonic form of energy trading in the first layer, but the problems of a single trading type and few trading packages hinder the role of optimizing the allocation of resources at the community level [27]. With improvements in multi-energy coupling and information trading systems, energy trading in the community layer will advance to diversified and customized energy pricing, while incentives will differ according to the energy demand. In addition, the CIES operator can consider offering green energy packages, discounts for paying on time, double online rewards, and other incentives to encourage consumers to wisely use energy.

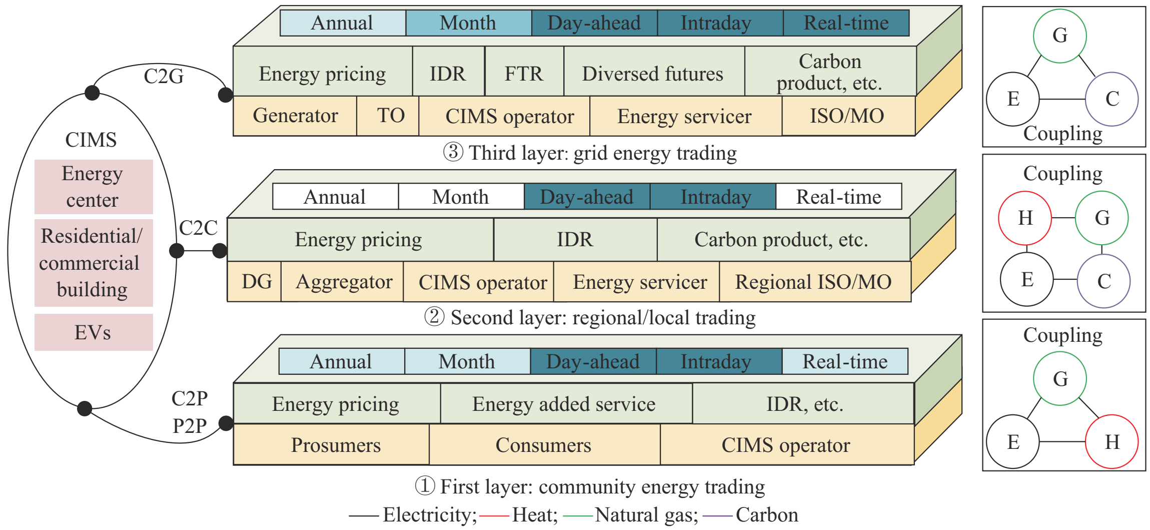

Fig. 5. Tri-layer trading framework of CIESs in combined multi-energy markets.

2) Second Layer: Regional/Local Energy Trading

Regional/local energy trading is certainly under the development of DG approaches and is likely to be the key to the local management of distributed resources. Triggered by regional demand, the trading period is concentrated in the short-term market to match the local balance in a short time and realize a multi-temporal multi-energy cooperative configuration and trading at a deeper level within the region. As the regional energy market gradually expands, CIES operators transfer part of the energy resources/demand from the grid energy trading layer to the regional energy trading layer [104] to inhibit deviations from the energy forecasting and to maintain the supply-demand curve, which may cause a proportional increase in natural gas trading on the day-ahead scale or volatility in heat prices and shorten the interval of natural gas and heat trading, which further activates the carbon and electricity market.

3) Third Layer: Grid Energy Trading

Energy trading in the third layer operates independently with weak coupling [68]. Owing to real-time power balance characteristics, the electricity trading cycle is relatively diverse and can be divided into several dimensions such as annual, monthly, day-ahead, intraday, and real-time. In contrast, other energy markets are relatively sluggish. For instance, natural gas is dominated by futures with a high entry threshold, and the heat price is relatively stable with inactive market entities. With the maturity of and interactions between all types of energy markets, market entities will extend to regional independent system operators, electricity/gas/heat transmission operators, CIES operators, energy generators, etc. These operators can run a single energy source and operate a variety of energy sources, which improve market liquidity and the use of energy commodities. In this context, energy trading products and even specific financial products will be diversified and combined, according to network congestion situations, supply and demand states, and asset investment market quotes. Such products include multi-energy prices, energy packages, incentive packages, financial transmission rights, natural gas futures, and carbon products.

In contrast, active CIES trading will also react to the planning and operation of CIESs to gain more profit space and encourage more main grid and hybrid supply communities to develop into micro-energy communities [120].

B. Key Issues in CIES Trading

1) Information Interaction Platform for CIESs

To ensure smooth trading, it is necessary to provide a benefit coordination mechanism and an information exchange platform for community entities. This platform should be operated and managed independently by regional energy providers, load aggregators, distribution system operators, etc. The platform operator can charge a certain percentage of trading service fees to ensure the balance of payments, but the specific business model is still worth discussing. All entities should be able to obtain sufficient information to effectively reduce asymmetric information or uncertainty and promote mutual understanding and optimized trading among entities [121]. During energy trading, a clear definition of market entities, their objectives, and the purpose of market clearing should be established.

Using computers and extensive data, the information platform has entered into an established stage [122] and includes methods such as blockchain-based energy trading, which achieves a good tradeoff between credit utility and operational overhead [123]-[125]. However, application problems such as the integration of all types of data sources, the reliability of real-time data, the personal privacy information and interactions among all types of stakeholders, and other operational patterns warrant further discussion in future research.

2) Precise Modeling of IDRs of CIESs

Flexible IDR resources form the trading premise of CIESs. Current modeling of IDR is greatly simplified with relatively simple classification or value constraints, which cause insufficient accuracy and calculation errors in the IDR model [25]. The IDR resources in CIESs are influenced by the types and characteristics of generators and devices, energy usage patterns, and energy coupling, and by the flexible demands of diversified consumers (pricing/incentive). Thus, they provide both diversity and uncertainty in terms of quantity and time.

This aspect deserves further in-depth investigation. A precise model of an IDR on a multi-temporal scale is shown in Fig. 6, which includes three-level optimization. The first step is to construct a joint operational strategy for the devices with the goal of achieving optimal efficiency. The second step is to build a complementary multi-energy strategy among consumers/prosumers with the goal of minimizing energy costs. The third step is to develop a collaborative optimization strategy for communities with the goal of maximizing benefits.

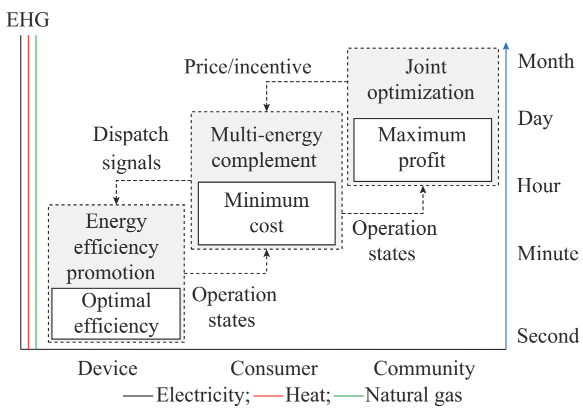

Fig. 6. Precise model of an IDR on a multi-temporal scale.

3) *Diversified Trading Pricing/Incentive Mechanism*

A diversified trading pricing/incentive mechanism catalyzes trading decisions and directly determines the degree of trading activity of a CIES. Hence, it is imperative to incorporate a well-designed pricing/incentive mechanism in the scheduling and trading processes of CIESs. The applications of trading mechanisms in most studies are still dominated by traditional demand response programs that are not up-to-date with the influence of the response characteristics and price sensitivity coefficient of diversified consumers after multi-energy complementarity. Thus, there are deviations in existing trading models or parameters. In addition, the heat and natural gas markets have been greatly simplified with obvious differences in the actual energy trading model. The design of the diversified and customized trading incentive mechanism based on real energy markets and consumer groups requires further in-depth study.

V. Conclusion

A CIES is important for achieving the sustainable development of future smart cities, and diversified trading is the key to aggregating related entities to satisfy the business and operational objectives of the CIES. This study innovatively conducts a systematic review of CIES trading. The basic concepts and types of CIESs are introduced. The research and gaps of trading patterns and strategies in CIES trading are summarized, which cover four aspects: C2P, P2P, C2C, and C2G energy tradings. A tri-layer trading framework and the features of CIES trading are proposed with increased multi-energy coupling and increasing number of entities. The key issues in CIES trading are also analyzed.

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