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Key Technology Analysis of Demand-Side Smart Energy System

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Abstract: As an important part of the Energy Internet, the demand-side smart energy system is considered an important form of energy system in the future. It is of great significance for realizing the distributed local consumption of renewable energy and improving the efficiency of terminal energy utilization. This paper discusses the characteristics of the demand-side smart energy system, listing the key equipment and technologies related to energy production, transmission, distribution, conversion, storage, and consumption of the demand-side energy system, as well as analyzing the industrial development model. Finally, the development prospects of the demand-side smart energy system are further elaborated in the stages of experimental demonstration, application promotion, general application, and complete marketization.
Keywords: smart energy system; key technologies; development model; development prospect

1 Introduction

Energy is necessary for the survival of human civilization. Because fossil fuels such as oil, gas, and coal are not renewable and pollute the environment, it is necessary to enhance energy efficiency and the utilization of renewable energy sources to resolve the energy and environmental issues faced by human civilization. The construction of an optimized, coordinated, and unified energy system via the integration of various energy systems eliminates the constraints of independently designed and operated energy systems, and it is an effective approach for promoting changes in the energy sector and resolving energy problems [1–3].

Owing to the increasing prominence of energy and environmental problems, research on new energy system technologies has received a high level of attention. In 2007, the United States (US) passed the Energy Independence and Security Act, which made smart grids part of the US national energy strategy. The objective of this provision is to construct a safe, reliable, cost efficient, energy efficient, and flexible smart grid using advanced information technologies. In the *Report to Parliament under the Energy Efficiency Act 2009–2010*, it was noted that Canada would construct a new community energy network that covers the entire nation, to meet their 2050 greenhouse gas emissions targets and solve their energy problems. Europe was one of the first regions to adopt integrated energy systems. Considerable importance has been bestowed upon research on the coordinated optimization (co-optimization) of integrated energy systems in the fifth *Framework Programme for Research and Technological Development* (FP5) of the European Union. In FP6 and FP7, further research has been conducted on energy grids and the co-optimization of integrated energy systems, and projects such as *Intelligent Energy Europe*, *Trans-European Networks*, and *Micrografts and More Microgrids* were implemented. Under the guidance of the Federal Ministry for Economic Affairs and Energy (BMWi) and the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety

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(BMU), Germany has invested 300 million euros per annum since 2011 to optimize the supply chains and industrial chains in its integrated energy networks.

In recent years, China has strongly prioritized the development of technologies related to the "Internet + Smart Energy" concept. In July 2015, China announced the *Guiding Opinions of the State Council on Vigorously Advancing the "Internet Plus" Action*, which made "Internet + Smart Energy" a key area for action [4]. During the national energy planning symposium of the Thirteenth Five Year Plan, it was emphasized that China's energy systems would be optimized over the course of the Thirteenth Five Year Plan to improve the peaking capacity of electrical and natural gas systems, develop distributed energy sources and smart grids, and implement the "Internet + Smart Energy" action plan. The aim is to significantly increase the smartization and efficiency of China's energy systems. In April 2015, the "Energy Internet Action Plan" was formulated in a meeting organized by the National Energy Administration of China. China's research institutes and manufacturers have dedicated significant efforts towards the research and implementation of smart energy systems and Energy Internet technologies. These endeavors have been rewarded by a series of important achievements.

The core objective of smart energy systems is to enhance the energy efficiency and environmental friendliness of energy systems, and to meet China's diverse energy needs using advanced energy technologies. In this article, the features, key equipment/technologies, industrial development modes, and prospects of demand-side smart energy systems will be described in detail.

2 Features of demand-side smart energy systems

Demand-side smart energy systems are a type of local energy systems that integrate energy production, supply, and distribution systems. This is achieved by the coordination and optimization of local/user energy production, transmission, dispatch, transformation, storage, and consumption. In these advanced energy systems, multiple energy sources (electricity, heat, cool, and natural gas) are physically interconnected through various energy conversion devices, forming an energy utilization and circulation system consisting of strongly coupled energy sources [1–3]. More specifically: (1) District-class smart energy systems are formed by the interconnection of various energy supply networks, including smart energy distribution systems, low-to-medium pressure natural gas delivery systems, and heating/cooling/water supply systems, thus providing a form of continuity between energy transmission, distribution, conversion, and balancing processes. The energy systems that make up these smart energy systems are strongly coupled to each other. (2) User-class smart energy systems consist of interconnected user-class smart power systems, distributed/centralized heating systems, water supply systems, and energy storage systems, with deep couplings between the various energy sources. User-level smart energy systems may also be called microgrids, and a district-class smart energy system contains many microgrids.

3 Key equipment and technologies for demand-side smart energy systems

The structure of a demand-side smart energy system is illustrated in Fig. 1.

3.1 Key equipment

3.1.1 Distributed power generators

Distributed power generators are low-capacity power generators that are installed in a dispersed manner, in locations close to

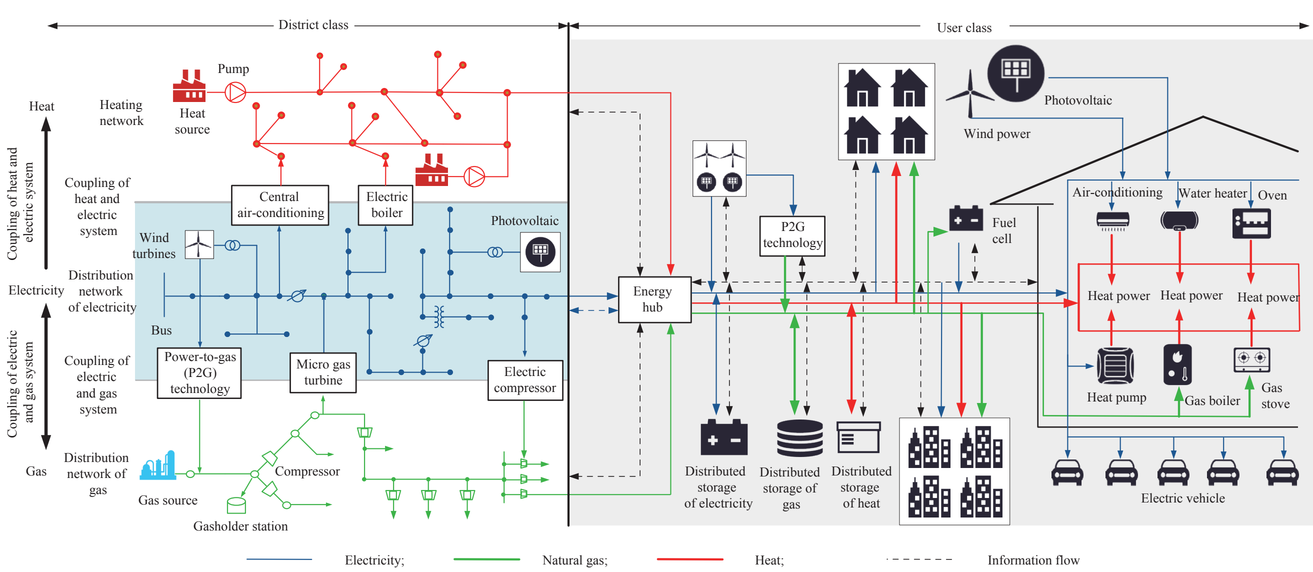

Fig. 1. Schematic of a demand-side smart energy system.

energy consumers. These include micro gas turbines, fuel cells, and renewable energy generation systems such as wind turbines and photovoltaics [5]. Distributed power generators generally produce little pollution, and are high in efficiency, small in volume, and straightforward to operate and maintain.

3.1.2 Energy storage equipment

Energy storage equipment refers to electricity storage systems (such as batteries, supercapacitors, compressed air energy storage, and flywheel energy storage) [6], as well as heat and gas storage systems. The existing technologies for gas storage include gas tanks and gas storage pipelines, while heat storage technologies include sensible heat storage, phase-change thermal energy storage, and chemical reaction heat storage [7]. In the future, novel energy storage technologies such as solidified natural gas (SNG) storage and underground thermal energy storage will drive the development of natural gas and thermal energy storage.

3.1.3 Energy conversion equipment

Energy conversion equipment is necessary for the interconversion of electricity, natural gas, and heat energy between different energy systems. Such equipment enables the diversification of energy supply modes and enhances the cost efficiency and reliability of energy distribution systems. The most common modes of energy conversion include power-to-gas conversion, power-to-heat conversion, and gas-to-heat conversion. A schematic of energy storage and conversion subsystems in a demand-side smart energy system is presented in Fig. 2.

Power-to-gas (P2G) technologies include power-to-hydrogen technologies, microturbines, and fuel cells. P2G conversion devices employ the excessive electrical energy produced by renewable energy sources during low power loads or output peaks to electrolyze water into hydrogen gas. This may then be stored or transferred, and ultimately utilized in end-user fuel cells for power generation or heating/cooling.

The existing technologies for power-to-heat conversion include electric water heaters and air-conditioners. The thermogalvanic cell, which is currently under development, can be used to convert heat into electricity at low temperatures.

Natural gas ovens are important energy conversion devices for natural gas systems and heating systems, as they can convert the chemical energy stored in natural gas into thermal energy, thus providing a supply of heat for consumers.

3.1.4 Energy transmission and distribution equipment

The transmission and distribution of electricity, heat, and natural gas is conventionally performed using mutually independent systems. The energy interconnector and energy hub concepts have been proposed to coordinate and enhance the efficiency of multi-energy transmission and distribution [8].

Energy interconnectors facilitate the long-distance transmission of electrical, chemical, and thermal energy in a single device. They consist of a hollow electrical conductor containing a gaseous medium (e.g., natural gas), as shown in Fig. 3 [8]. The heat loss generated by the electrical conductor is partially stored in the gaseous transfer medium, which enables the recovery of this heat energy at the end of the transmission line. The gas also helps to cool the electrical conductor. The characteristics of energy interconnectors are as follows: (1) They facilitate the interconnection of multiple energy sources, and are highly versatile.

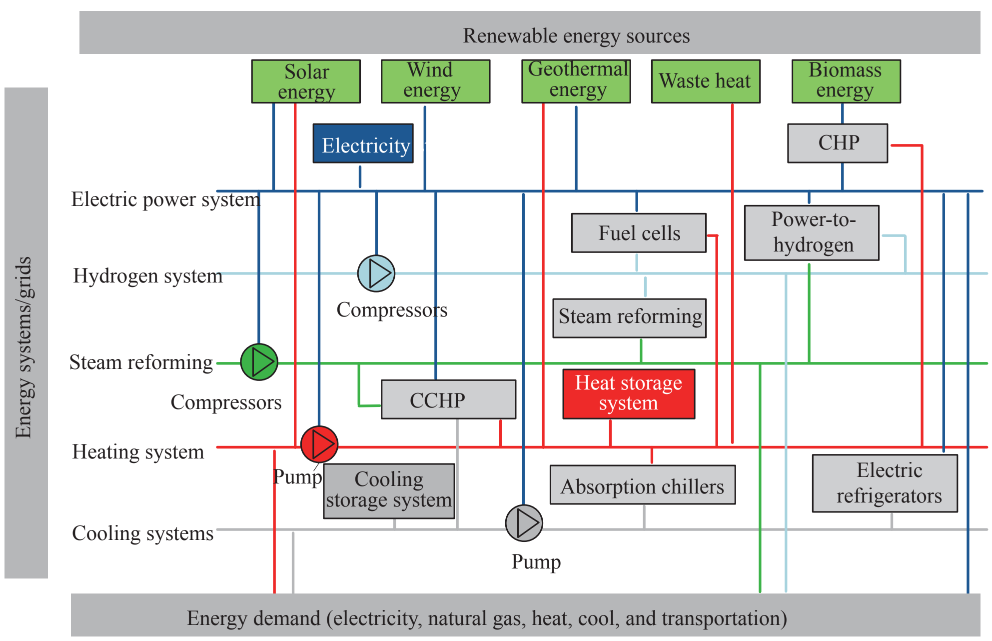

Fig. 2. Energy storage and conversion in a demand-side smart energy system.

Note: CCHP refers to combined cooling, heating, and power generation; CHP refers to combined heat and power generation.

(2) They simplify the layout of energy networks and terminals, and serve as convenient energy sources for multi-energy flow coupling devices.

Energy hubs are typical energy distribution devices. A typical energy hub is illustrated in Fig. 4 [8]. The characteristics of energy hubs are as follows: (1) The input/output relationships of the energy sources in an energy hub can be described in a standardized manner via coupling matrices. (2) In an energy hub, modularized physical systems can be constructed according to the requirements of the usage scenario at hand, thus standardizing the configuration and management of energy systems with complex couplings.

3.1.5 Smart metering equipment

(1) Smart meters

The functions of a smart meter include remote/local communication, two-way metering, multi-tariff billing, real-time data exchange, power quality monitoring, remote supply disconnection, user interaction, and automatic meter reading [9]. The requirements of load management, power trading, and power grid scheduling for distributed energy resources can be satisfied by constructing smart meter-based smart metering systems.

(2) Smart sensors

A mature set of theories and technologies already exists for conventional sensors such as inductive sensors and piezoelectric sensors. New sensor technologies, such as fiber optic sensors and charge coupled device (CCD) sensors, have also rapidly developed in recent years. These new sensors are technically superior to conventional sensors in most aspects: they are smaller, functionally superior, capable of withstanding high pressures, and resistant to electromagnetic interference. Therefore, new sensor technologies have a wide range of potential applications.

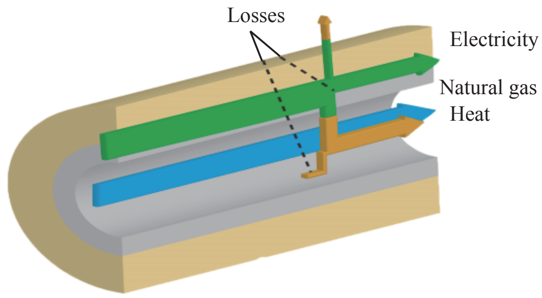

Fig. 3. Typical layout for energy interconnectors.

3.2 Key technologies

The key technologies of smart energy systems include planning and design techniques, information assurance technologies, operations optimization technologies, resilience enhancement technologies, and user-side resource usage optimization technologies.

3.2.1 Planning and design technologies for smart energy systems

The objective of planning and design is to configure the types and capacities of distributed energy resources in a scientific manner, and design grid topologies for energy distribution, in keeping with user requirements for energy supply reliability. The core techniques in this area include optimized planning and design methods, comprehensive evaluation systems, and support systems for planning and design [10,11]. For district-class smart energy systems, the primary task of planning and design is to maximally exploit the abilities of different energy sources to complement and supplement each other, based on the spatiotemporal characteristics and differentiations of user requirements for electricity/natural gas/cooling/heating. During the design and planning of district-class smart energy systems, the following steps are necessary: (1) Examine system control strategies for different spatiotemporal scenarios to obtain a comprehensive overview of the system's operational scenarios. (2) Study the

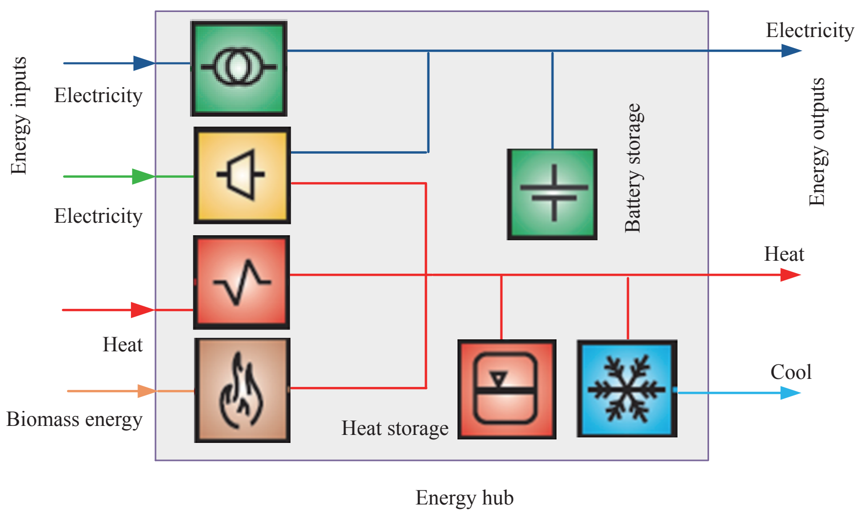

Fig. 4. Schematic of an energy hub

characteristics of each process and device in each scenario to obtain the operational constraints of each operational mode. (3) Design optimized system models based on the holistic consideration of energy efficiency, safety, user comfort, economic cost, and social benefits. (4) Apply collaborative optimization to solve multi-scenario optimization problems, based on the full life-cycle concept and the characteristics of the system's various operational stages.

3.2.2 Information assurance technologies for smart energy systems

Owing to the interconnection of information flows in the energy flow chains of smart energy systems, technologies for information communication between energy systems at different levels, situational awareness (SA), and information assurance (IA) technologies are necessary for cost-effective energy system operation in the presence of vast amounts of data [12]. The objective of IA technology is to facilitate efficient information communication and sharing between each cycle of an energy system, thus enabling the real-time acquisition, transmission, and storage of information in all energy system processes (i.e., every process from energy generation up to energy usage). The development of Energy Internet and cyber-physical system (CPS) technologies has given rise to deeply integrated information networks and physical energy networks, which provide a highly informatized, digitalized, and transparent operating environment for energy systems. The purpose of SA technology in multi-information fusion is to automate the control, management, and services of energy systems, based on information gleaned from a system's synchronous measurements, load characteristics, operational status, predictions, and risk assessments. Hence, SA is necessary for operational state optimization and other high-level applications in a smart energy system.

3.2.3 Operation optimization technologies for smart energy systems

In a smart energy system, different energy sources are coupled to allow each energy source to be utilized in a graded manner and supplemented by other sources. This effectively improves a system's efficiency. Operation optimization technologies are indispensable for achieving this goal. The optimization of a smart energy system's operations requires the consideration of various constraints to simultaneously balance multiple goals, as illustrated in Fig. 5. In essence, this process may be viewed as the combined scheduling of multiple energy sources, much like unit commitment and dispatch optimization in power systems. The difference is that a smart energy system involves a larger number of objective functions and constraints [13,14]. Operation optimization requires the consideration of many factors, and the balancing of a diversity of cost-benefit relationships, such as the contradictory needs of cost efficiency and safety, or those of energy sustainability, energy efficiency, and cost efficiency.

3.2.4 Resilience enhancement technologies for smart energy systems

Smart energy systems are complex dynamic systems with high levels of dimensionality, nonlinearity, and randomity, which operate on multiple time scales. The resilience of a smart energy system refers to its ability to withstand high-risk low-probability disturbances. In other words, it is the ability of a system to handle unavoidable perturbations in a flexible manner, using the resources it has at hand, to maintain a high level of operation and rapidly restore its performance [15,16]. The indices that reflect on the resilience of a system are called the 4Rs: robustness, redundancy, resourcefulness, and rapidity [17,18]. Robustness is the ability of a system to withstand external perturbations or pressure. Redundancy refers to the availability of backup devices in a system, or the usability of the system in disaster scenarios. Resourcefulness is the capability of a system to mobilize resources to maintain its key functions. Rapidity is the ability of a system to rapidly restore key functions and minimize energy losses. Smart energy systems are important for enhancing the resilience of energy supply systems. For example, if a malfunction occurs in the external power supply system, then micro gas turbines and fuel cells can be connected to energy conversion devices to rapidly produce power in order to mutually support other distributed power sources. If a problem arises in a heat and gas supply system, then electric-powered heat and electrolytic hydrogen can be utilized to rapidly convert electric power into other types of energy. In this manner, smart energy systems improve the ability of energy systems to restore power production and safeguard energy production capabilities in emergency situations.

3.2.5 User-side resource usage optimization technologies

In the conventional sense, user-side resource usage technologies refer to technologies for the demand-side management of electrical loads. These technologies are based on the user-side adjustment of electric loads, and therefore carry certain limitations. In a smart energy system, user-side resource usage optimization refers to the unified management of different energy systems from the user's side to effectively improve the comprehensive utilization level of energy sources and reduce user costs [19−21]. An example of a user-side resource optimization and management system for an ordinary household is illustrated in Fig. 6. The smart energy hub allows a user to monitor and control all energy equipment, and has self-optimization functions. A user may then participate in the planning of demand-side management by altering their amounts and types of energy consumption to fully exploit the supply, pricing, and coupling characteristics of each energy source.

4 Industrial development modes

In recent years, the government of China has assigned ever-increasing levels of importance and support to the energy

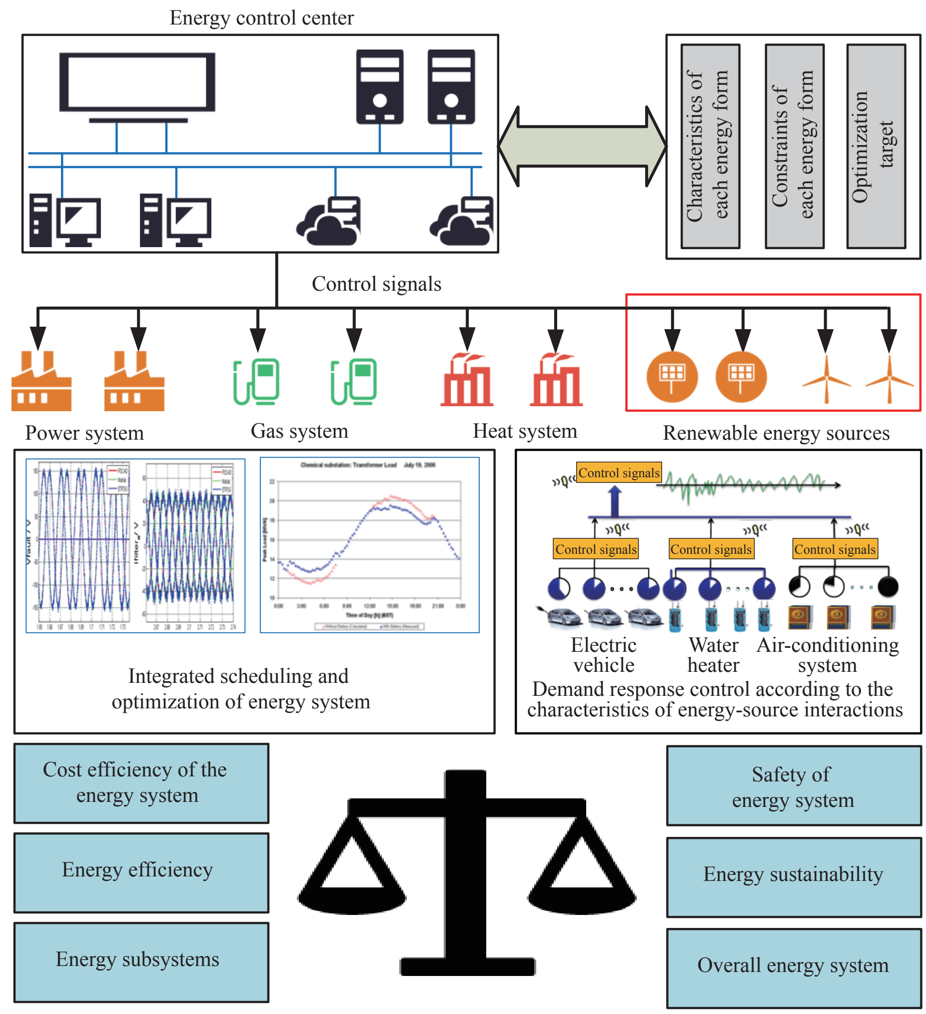

Fig. 5. Energy optimization and control in a smart energy system.

sector. In addition, the Chinese government strongly advocates the construction of a renewable-based demand-side smart energy system for the unification of energy generation, distribution, storage, and usage systems. To this end, we recommend the application of advanced Internet-information technologies in management approaches according to the Energy Internet concept, to bring about the smartization of energy production and usage, as well as the rapid development of all related industries. This approach manifests in the following aspects.

4.1 Energy structures

The energy supply process will gradually become environmentally friendly, efficient, safe, and reliable [22,23], and be characterized by multi-element energy structures and multi-carrier energy supply systems. In addition, distributed energy sources will develop rapidly. As low-capacity high-quantity distributed energy sources such as rooftop solar panels are geographically dispersed, the creation of a demand-side smart energy system capable of collecting, storing, and utilizing these resources will be crucial for the efficient and convenient usage of these resources.

4.2 Technological attributes

Information technologies and informatized management modes will continuously develop and mature in demand-side smart energy systems. This statement has two layers of meaning: First, information technologies are necessary for the realization of smart energy systems. The infrastructural foundations of a smart energy system are formed by the development of information technologies and the widespread application of sensors (e.g., current, voltage, flow, and temperature sensors) and embedded data acquisition devices. Reliable real-time communication networks then act as the medium that holds the system together, while efficient and intelligent control algorithms serve as the core of a smart energy system [24]. It is only on this basis that a smart energy system will be able to effectively integrate energy production data, operation data, user demand data, market data, and other types of data to optimize energy usage. Second, the

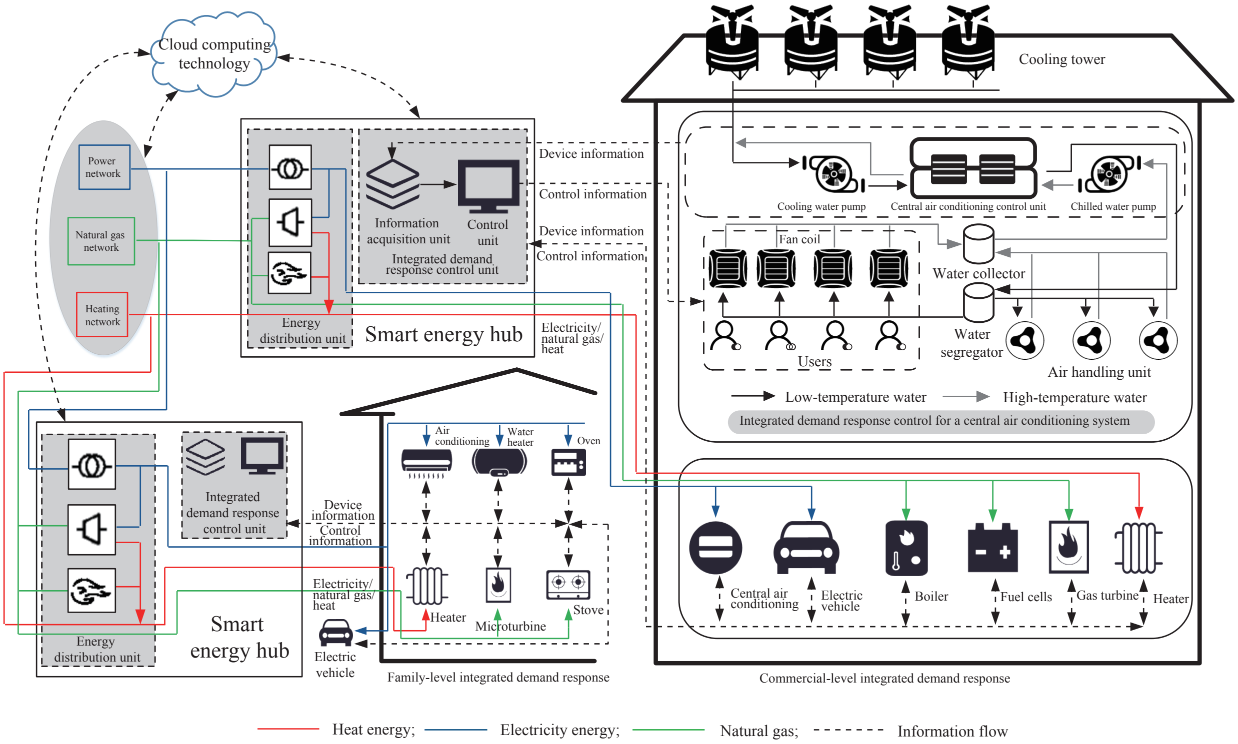

Fig. 6. User resource optimization and management system.

"informatized management" of energy is an effective approach for energy usage optimization and the balancing of supply and demand by smart energy systems [25,26]. For example, energy storage equipment is necessary to buffer the intermittency and randomity of distributed energy sources and user loads in energy production and usage processes. From the perspective of information theory, the incorporation of energy storage in the energy distribution process transforms energy from a continuous to a discrete quantity. This transformation allows smart energy systems to dispatch energy in a discretized manner, according to the information flows of the system's information network.

4.3 Market modalities

Technological advancements in energy-related industries have provided an opportunity for major breakthroughs and innovations in the business models of the energy industry [27]. Owing to diminishing barriers to entry, the number of participants in the energy market will increase, thus leading to the emergence of innovative business models with greater levels of flexibility. The Internet will tightly bind the dispersed users, differentiated energy sources, and diversified commercial entities of energy systems, thus expanding the range and frequency of interactions between members of the market, and reducing trading costs. This will significantly increase the participation of members in the energy market, and the convenience and presence of energy trading. The fusion of different energy sources and permeation of the Internet spirit will catalyze the creation of a new energy ecosystem that is competitive, multilateral, and participatory. The following recommendations have been proposed to provide users with open, flexible, and intelligent integrated energy supplies and value-added services: (1) Business model innovations for demand-side smart energy systems should be promoted. (2) The establishment of integrated energy service companies to commercialize energy supply and energy trading via holding shares or shareholding in power grid, natural gas, and heat energy companies should be encouraged. (3) Commercialization mechanisms, such as energy management contracting and comprehensive energy-saving services, should be actively promoted [28–30]. (4) The establishment of an Internet-based information service platform concerning smart energy should be accelerated.

5 Prospects for development

It is expected that the technologies of smart energy systems and their application will mature, and become fully commercialized by 2030. The development pathway of smart energy systems is described below.

The experimental demonstration phase: At present, the technologies associated with smart energy systems remain in the initial exploratory phase, and are gradually transitioning towards practical application. A number of experimental simulation systems and demonstration projects are currently being constructed. The continued development of smart energy system research will lead to the gradual maturation of smart energy system demonstration projects, and the propagation of these projects to society. In this stage, the key technologies of smart energy systems will gradually mature and become applicable to some real-world commercial projects. As the core technologies of smart energy systems propagate widely among companies on the market, the technical barriers to the smart energy area will quickly diminish. China and its government should still make preliminary investments in smart energy projects, or provide subsidies, to encourage investors to invest in smart energy systems and conduct smart energy-related business.

The propagation stage: The commercialization of demand-side smart energy systems in China is expected to develop vigorously in the period 2020–2025. In this stage, the core technologies of smart energy systems (equipment manufacturing, optimal control, and planning and design) should approach maturity, and meet the basic needs of actual projects. In addition, the technologies of smart energy systems will be validated through their application to actual projects. China's policies to promote the development of smart energy systems should be relatively refined by this point, which will further increase the vitality of the smart energy market. Energy contracting models and the construction of personal smart energy systems should be encouraged and developed.

Widespread application and full-scale commercialization: The key technologies for demand-side smart energy systems are expected to mature by 2025–2030, and the smart energy systems of China should be highly commercialized by this time. Other than energy supply companies, many independent commercial entities or even individuals will choose to invest in district-class and user-class smart energy systems, and the market is expected to adopt cost-based pricing. Because demand-side smart energy systems will be reasonably priced, and an adequate level of competition will exist, these systems will become a common mode of energy supply at all levels of society.

6 Conclusion

Smart energy systems are the future of the energy sector, and they are the foundation on which the Energy Internet will be built. The technologies associated with smart energy systems have already become hotspots for energy sector development in various countries around the world. The purpose of this work is to analyze and discuss the features, key technologies, industrial development modes, and development prospects of demand-side smart energy systems. With the rapid development of key equipment, and the advent of new energy storage, conversion, and transmission technologies, smart energy systems will be able to significantly improve the comprehensive utilization rate of energy sources and consumption capacity of renewable energies, through the complementary integration and graded utilization of multiple energy sources. This will enhance resource utilization levels, and the flexibility of energy supply systems. Furthermore, this will change energy production and consumption modes, thus driving the development of emerging energy markets and other related industries. Hence, demand-side smart energy systems hold the key to realizing the transformation of China's energy structures, and the attainment of China's emission reduction and sustainable development goals.

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