

Review Article

A Survey on Optimal Control and Operation of Integrated Energy Systems

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Received 18 July 2019; Accepted 19 August 2019; Published 25 December 2019

Guest Editor: Xiaoqing Bai

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At present, the transformation of energy structure is at a critical stage, and emerging renewable energy technologies and multienergy equipment have been widely used. How to improve the energy efficiency of integrated energy system (IES) and promote large-scale absorption of renewable energy is of great significance to the application forms of energy in the future. The development of new internet technology and sensor technology provides strong technical support for the optimal operation and coordinated control of IES. In recent years, the IES is experiencing unprecedented changes, which has attracted great attention from academia and industry. In this paper, the optimal control and operation behavior of IES are reviewed. Firstly, the research status of IES in recent years is summarized. Then, the modeling methods of different equipment in IES are analyzed in detail. The optimal operation of user, regional, and cross-regional IES are taken as typical research objects and the research status of optimization problems and operation modes, energy management planning, and power market allocation are summarized and analyzed. Finally, the key scientific issues and related frontier technologies in the IES are concluded, and the future research directions are prospected.

1. Introduction

The environmental pollution in the process of energy conversion and transmission and the requirement of sustainable development of energy urge human beings to seek diverse supply and efficient use of green energy. It is difficult to maintain the long-term development of human society due to the exponential growth of energy consumption and the insufficient reserves of nonrenewable energy. The development of renewable energy, such as solar energy, wind energy, hydro-power, geothermal energy, and biomass energy, makes it possible for sustainable use of energy [1].

Although the renewable energy-related technology has developed rapidly, the most important issue for power system is to ensure the reliable and secure operation. Due to the inherent intermittence and fluctuation of renewable energy, direct connection to power system will impact the voltage and frequency of the power grid [2]. Most of the renewable energy is connected to the power grid through power electronics devices. However, power electronics device itself is one of the main sources of harmonics in the power grid during the treatment of the power grid pollution. Although energy storage technology can directly solve the problem of renewable energy absorption, large-scale commercial application of energy

storage in power grid cannot be carried out for the time being due to the high cost, low efficiency of energy storage technology, and special requirements for engineering application sites [3]. The renewable energy is also facing the problem of effective connection with external power grid, the economic problems in long-distance transmission such as high cost of infrastructure construction and wheeling cost of power flow, and the lack of market competition, which is not conducive to the development and promotion of renewable energy technology. In order to solve these problems, the concept of integrated energy system (IES) has been proposed. IES is a highly abstract classification of energy supply and energy demand, which integrates multifunctional collaborative technologies such as P2G (power to gas) and CCHP (combined cooling, heating and power supply) in the process of planning, construction, and operation of energy systems, thus achieving multienergy conversion, scheduling, and storage.

As an important component of the energy internet and the main carrier of social energy, IES integrates power, natural gas, hot and cold system, instead of a single energy system in traditional energy supply form, which is an effective way to solve the problem of low energy efficiency and the coupling of various types of energy [4]. As a multisupply system, IES can alleviate or eliminate the inefficiency of energy equipment

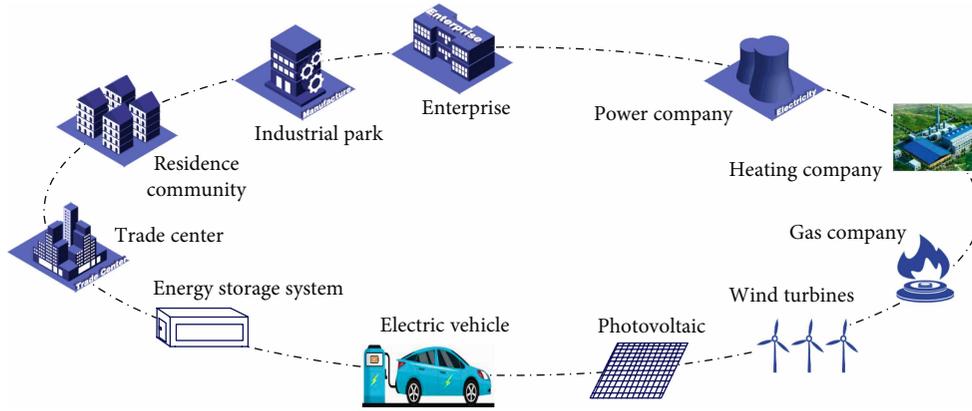


FIGURE 1: Open interconnection of multienergy systems.

through the coordination of subsystems [5]. It can also reduce the cost of system maintenance, realize the peak-valley interleaving of multienergy system, and fully absorb renewable energy through P2G technology [6]. IES can make full use of potential synergistic benefits, fully tap the potential of interconnected data and information networks, and achieve coordination, optimal scheduling, and synergistic utilization among different energy supply systems [7, 8].

The electricity, gas, heat, and other energy sources are complementary in IES to achieve time-sharing utilization of energy and improve the scope of renewable energy consumption, improve the utilization of social infrastructure and the flexibility of energy supply [9]. In the aspect of comprehensive use of energy, IES is regarded as one of the important development directions of the energy industry by all countries because of its advantages such as high energy efficiency and economy. IES can solve the shortcomings of traditional power system that cannot meet the energy demand under the new situation because of the one-way transmission of power load, and achieve the optimal allocation of resources through multienergy collaboration.

Many detailed researches on IES have been carried out in different countries, including modeling and planning for various scenarios, optimal operation, security assessment, and steady-state analysis of IES. This paper mainly reviews the related technologies of optimal operation and control of IES. Section 2 briefly introduces the main forms and development status of IES. Section 3 reviews the commonly used modeling methods of IES. Section 4 discusses the optimal operation and control methods of IES, Section 5 concludes the whole paper and summarizes the key scientific issues in IES research, and proposes future challenges and development trends of IES.

2. Brief Introduction of IES

2.1. Structure and Characteristic of IES. The inputs of IES are a variety of energy sources and the outputs are electricity, heat and cold energy, to meet the energy demand of different users. With the existence of electricity and gas distribution system, heating and water supply pipelines, and other related energy supply network, a coupling system is formed. The

coupling between gas and electricity distribution system and the complementation of various energy sources result in the complexity of energy combination and the diversity of energy utilization. According to the size of geographical area and energy characteristics, IES can be divided into three types: park (building) level, city level, and cross-regional level [10]. Figure 1 illustrates the typical open interconnection of multienergy systems.

IES of building level mainly considers the coordination and complementation of multiple energies of buildings or users, and takes demand response, forecasting of demand load, electric vehicles, and cloud computing as the core technologies. There is a deep coupling relationship among energy networks [11]. IES of park level covers energy systems with various forms and characteristics [12], including underlying equipment, energy system units and systems with multienergy coupling, which has the characteristics of complementary utilization of energy, deep integration of physical information and coordinated interaction of source, network and storage. Regional IES mainly plays a connecting role of energy transmission, distribution, conversion and balance [13]. It takes hybrid energy storage system, energy conversion and active distribution network as the core technologies, and there is a strong coupling among energy systems. Cross-regional IES takes power electronics technology, information physics system, transmission, and energy router as its core technologies [14]. It mainly considers such factors as management, operation, scheduling (transmission) time between cross-regional energy systems.

Based on the energy management and control platform, IES in the park (building) level covers many controllable resources, such as cold, heat, electricity, gas, and water, so as to realize the complementation of multiple energies. Based on the interaction between multiple decision makers, regional IES and cross-regional IES study the operational efficiency and economic cost of distributed and centralized decision makers (joint dispatching center). At the same time, the optimal power flow problem in the process of multienergy flow transmission should be considered to ensure the safe and stable transmission of energy. Electric power system, natural gas system and thermal system are composed of different stakeholders. It is necessary to analyze the economic distribution

among different stakeholders, focusing on game theory and other related theories, so as to enhance the coupling relationship between multienergy flows.

2.2. Current Development Status of IES. Energy Internet is the product of the deep integration of traditional energy system and internet thinking. In the book “The Third Industrial Revolution”, Jeremy Rifkin, a famous American scholar, first put forward the vision of energy internet, and believed that the third industrial revolution with energy internet as its core would subvert the use of traditional energy [15]. IES, as an important physical carrier of energy internet, focuses on collaborative optimization among different energy sources. Energy Internet emphasizes the deep integration of energy systems and the ICT (information and communication technology), which is marked by the technologies of internet, computer, automatic control, communication, data processing and network [16]. IES is not a new concept. In the field of energy integration, there are long-term cooperative optimal operation among energy sources, such as CHP system and CCHP system, which use heat energy in different levels to reduce energy waste; P2G technology uses wind power and solar energy to generate Hydrogen by electrolyzing water, which is then supplied to the existing gas pipeline network, or to produce methane by utilizing water and CO₂ in atmosphere to provide gas, so as to solve the problem of renewable energy absorption [17, 18].

IES has been extensively studied and developed based on the needs of energy strategies of various countries. In 2007, the U.S. incorporated IES into the energy sector, and promoted the construction of IES by means of additional funds, unified energy production, and distribution suppliers; in 2013, the National Renewable Energy Laboratory established the “Energy System Integration Research Group” [19], and IBM established “Smart City” and other projects. In 2014, the EU adopted the target of “40-27-27” in 2030. By 2030, greenhouse gas emissions will be reduced by 40% compared with 1990, 27% of energy consumption comes from renewable energy sources, and energy efficiency will be improved by 27% [20]. Since 2015, China has issued a number of IES-related policies and carried out a series of demonstration and practical projects, such as the demonstration project of Shanghai Disneyland Resort, which uses centralized energy control to make the primary energy utilization rate above 80%. The Chongming Island demonstration project in Shanghai builds a three-tier energy utilization framework for renewable energy, which realizes the joint optimization of wind farm running independently and megawatt container energy storage system in distribution network [21].

2.3. IES Related Technology. The development of IES needs the support of related technical fields such as renewable energy generation, energy storage, power electronics, new transmission, stability analysis and control of multienergy flow system, and artificial intelligence.

Renewable energy power generation has triggered the energy revolution, led to the large-scale development of emerging ecological industries, laid the foundation for the

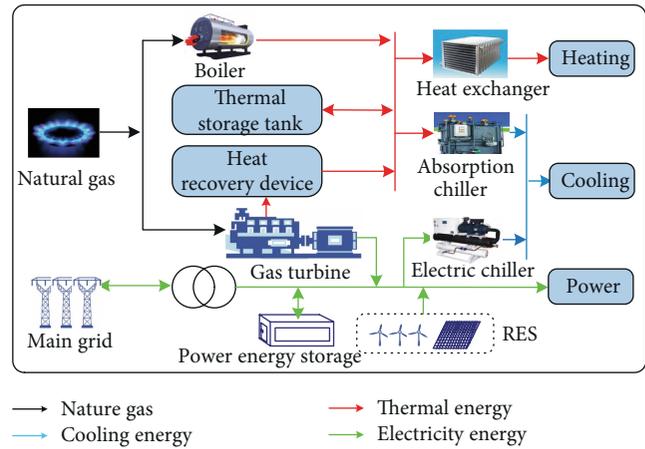


FIGURE 2: Basic structure of IES.

promotion and application of IES. The development of power storage, heat storage, cold storage, and hydrogen storage plays an important role in the absorption of renewable energy. The development of power electronics technology has improved the security and controllability of energy transmission and distribution, and promoted energy interconnection. Power flow calculation of multienergy flow system is the basis of the research of multienergy flow system and the premise of the related control technology research. Faced with the uncertainties, randomness and complexity of energy systems, the new generation of artificial intelligence technology needs to carry out a lot of research work in such areas as comprehensive perception, reliable transmission and intelligent processing of data information, machine learning algorithms, and artificial intelligence platform for power and energy applications.

3. Modeling of IES

IES is composed of power system, natural gas system and thermodynamic system and the basic physical equipment of these systems is modeled in this section, which includes the equipment in the process of production, transmission, storage, and consumption of various energy sources such as electricity, heat, cold and gas. The basic physical structure of IES is shown in Figure 2.

3.1. Modeling of Independent Power Equipment. The traditional power equipment in IES mainly include PV, transmission and distribution network, energy storage battery, and electric vehicle, which are the core components of IES.

3.1.1. Model of PV Power Generation. PV power generation is the direct use of photovoltaic effect of semiconductor materials to convert solar energy into electricity. PV power generation system has short construction cycle, flexible installation, and wide application scenarios and will not cause disturbance to human living environment. The mathematical model of PV power generation is generally shown as follows [22]:

$$I = I_{sc} - I_{sc} D_1 \left\{ \exp\left(\frac{U}{D_2 U_{sc}}\right) - 1 \right\}$$

$$\begin{cases} D_1 = \left(1 - \frac{I_m}{I_{sc}}\right) \exp\left(-\frac{U_m}{D_2 U_{oc}}\right), \\ D_2 = \left(\frac{U_m}{U_{oc}} - 1\right) \left[\ln\left(1 - \frac{I_m}{I_{sc}}\right)\right]^{-1}, \end{cases} \quad (1)$$

where U and I are the voltage and current of a single PV module respectively; I_{sc} , U_{oc} , I_m , and U_m represent short-circuit current, open-circuit voltage, current and voltage at maximum power point, which are provided by PV cell manufacturers; D_1 and D_2 are intermediate variables. These parameters will vary with the environment and need to be determined according to the actual light intensity and temperature.

Then the output power of PV array in k period can be expressed as:

$$P_{PV}^k = U^k \times I^k \times C_a \times C_b \times \eta_{pv}, \quad (2)$$

where U_k and I_k are the voltage and current of a single PV module in k period, respectively; C_a is the number of PV modules in series; C_b is the number of PV modules in parallel; η_{pv} is the loss factor.

3.1.2. Model of Wind Power Generation. Wind power generation is the conversion of kinetic energy of wind into electricity through wind turbines. Wind energy is proportional to the cubic of wind speed and the mathematical model of wind power output is as follows [23]:

$$P_{wt} = \begin{cases} 0, & v_k < v^{ci} \text{ or } v_k \geq v^{co}, \\ P^r \frac{v_k^3 - (v^{ci})^3}{v_R^3 - (v^{ci})^3}, & v^{ci} \leq v_k \leq v^R, \\ P^r, & v^R \leq v_k \leq v^{co}, \end{cases} \quad (3)$$

where v_k is the actual wind speed in k period; v^{ci} , v^{co} , and v^R are cut-in, cut-out and rated wind speed, respectively; P^r is the rated power of wind turbine.

3.1.3. Model of Transmission and Distribution Network. The power model of transmission and distribution networks is usually expressed by [24]:

$$P_L = U_L I = P_{Lin}(1 - \eta_{line} - \eta_{sub}) = U_{Lin} I (1 - \eta_{line} - \eta_{sub}), \quad (4)$$

where P_L and P_{Lin} are the output and input power of the transmission and distribution network, respectively; U_{in} and U_{il} are the input and output voltage of the transmission and distribution network; I is the operation current; η_{line} and η_{sub} are the tie-line loss of the transmission and distribution network and the substation loss, respectively.

3.1.4. Energy Storage Battery. The typical model of energy storage battery is expressed as [25]:

$$S_B(t) = (1 - \delta_B) \cdot S_B(t-1) + P_B^{in} \cdot \Delta t \cdot \eta_B^{in},$$

$$S_B(t) = (1 - \delta_B) \cdot S_B(t-1) - \frac{P_B^{out} \cdot \Delta t}{\eta_B^{out}}, \quad (5)$$

where $S_B(t)$ represents the remaining electricity of the energy storage system in t period; δ_B is the energy consumption rate in the energy storage process; P_B^{in} and P_B^{out} are the charging and discharging power, respectively.

3.1.5. Charging Pile. The typical model of charging pile is expressed as [26]:

$$P_{cp}^i = \sum_{n=1}^n S_{ta}(k) P_{cha}^n, \quad (6)$$

where P_{cp}^i is the total charging capacity of charging piles in area I ; n represents the total number of charging piles in area I ; $S_{ta}(k)$ is the charging state of k^{th} charging pile, whose value is 1 when charging and 0 when discharging; P_{cha}^n is the output power of n^{th} charging piles.

3.2. Modeling of Equipment with Electro-Thermal Coupling

3.2.1. Model of Gas Turbine. As the core equipment in electro-thermal coupling, Gas Turbine converts natural gas into electric energy and recovers waste heat for heating and refrigeration. The mathematical model of gas turbine is as follows [27]:

$$P_{gt}^t = F_{gas}^t \gamma_{gt} \eta_{gt} \lambda_{gas},$$

$$Q_{gt}^t = F_{gas}^t \lambda_{gas} (1 - \eta_{gt} - \eta_{loss}) \eta_{rec}, \quad (7)$$

where P_{gt}^t , Q_{gt}^t , and F_{gas}^t are the output power, recovery power of waste heat, and natural gas consumption of gas turbines in t period, respectively; γ_{gt} is the gas consumption rate of gas turbines; η_{gt} , η_{rec} , and η_{loss} are the efficiency of power generation, recovery efficiency of waste heat, and energy loss rate of gas turbines, respectively; λ_{gas} is the calorific value of natural gas.

3.2.2. Model of Heat Pump. Heat pump is mainly composed of heat exchanger, compressor, throttling device, hot water storage tank and temperature acquisition device, which can convert low-grade heat energy into high-grade heat energy by using a small amount of electricity. The typical model of heat pump is as follows [28]:

$$Q_{HP}^t = C_{HP} \rho_{HP} \Delta T_{HP}, \quad (8)$$

where Q_{HP}^t is the heating power of heat pump in t period; C_{HP} is specific heat of heat pump fluids; ρ_{HP} is the density of hot water; ΔT_{HP} is the temperature difference of fluids before and after a cycle.

3.3. Modeling of Equipment with Electro-Gas Coupling. The main coupling parts between power system and natural gas system are gas turbine and P2G, which realizes a bidirectional coupling of electro-gas system.

P2G equipment is mainly composed of electrolytic water device, methanation reaction device, and pressure-adding device [29].

3.3.1. Model of Electrolytic Cell. At present, there are three main electrolytic technologies, which are alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis. The alkaline electrolysis technology is mature, but its efficiency is low. High temperature electrolysis has strict environmental requirements, which needs to work in environment with high temperature and pressure, so the high cost is high. At present, the PEM technology has attracted wide attention because of its flexibility, better mechanical strength and chemical stability [30].

The PEM electrolysis model is:

$$\begin{cases} E_{\text{eh}_2}^t = f(\eta_{\text{eh}_2}) \pi_{\text{eh}_2, \text{rated}}, \\ f(\eta_{\text{eh}_2}) = a_{\text{eh}_2} \eta_{\text{eh}_2}^2 + b_{\text{eh}_2} \eta_{\text{eh}_2} + c_{\text{eh}_2}, \\ \eta_{\text{eh}_2}^t = \frac{P_{\text{eh}_2}^t}{P_{\text{eh}_2}^{\text{rated}}}, \end{cases} \quad (9)$$

where $E_{\text{eh}_2}^t$ is the amount of hydrogen produced by the electrolyzer in t period; $f(\eta_{\text{eh}_2})$ is the efficiency function of the electrolyzer; η_{eh_2} is the operational efficiency of the electrolyzer; $P_{\text{eh}_2}^t$ is the input power of the electrolyzer in t period; $P_{\text{eh}_2}^{\text{rated}}$ is the rated input power of the electrolyzer; a_{eh_2} , b_{eh_2} , and c_{eh_2} are three coefficients of efficiency function of the electrolyzer.

3.3.2. Model of Methane Reactor. The hydrogen generated by P2G is sent to the methane reactor. The operating efficiency of the reactor is affected by the composition of syngas, the ratio of hydrogen, working temperature and pressure [31]. The methane reactor model is expressed as follows:

$$P_{M,g,t} = \frac{\eta_m E_{M,H_2,t} \lambda_{\text{gas}} * 4}{\kappa}, \quad (10)$$

where $P_{M,g,t}$ is the natural gas power generated by methane reactor in t period; $E_{M,H_2,t}$ is quantity of hydrogen injected into methane reactor at t period; η_m is operational efficiency of methane reactor; λ_{gas} is calorific value of natural gas; κ is quality of gas corresponding to each m^3 of natural gas pipeline.

3.4. Modeling of Equipment with Other Coupling. Electric refrigerator is a typical electro-cooling coupling device; electric heating boiler is a typical electro-thermal coupling device; gas boiler is a typical gas-thermal coupling device; and adsorption refrigerator is a typical thermal-cold coupling device.

When the heating of gas turbine is insufficient, the gas boiler supplements the heating. The mathematical model of a gas boiler is expressed as [29]:

$$Q_{\text{gb}}^t = F_{\text{gb}}^t \eta_{\text{gb}} \lambda_{\text{gas}}, \quad (11)$$

where Q_{gb}^t and F_{gb}^t are the output heat power and consumption of natural gas of gas boiler in t period, respectively; η_{gb} is the operating efficiency of gas boiler.

The main coupler of the thermal-cooling system is the adsorption refrigerator, the main coupler of the electric-cooling system is the electric refrigerator, and the main coupler

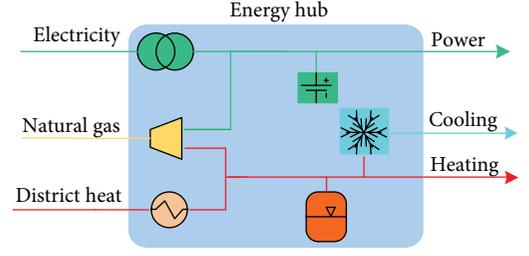


FIGURE 3: Basic model of energy hub.

of the electric-heating system is the electric-heating boiler. The details of these modeling can be found in [27].

3.5. Modeling Based on Energy Hub. Geidl and Andersson from Zurich Federal Institute of Technology firstly proposed the energy hub, which represents the interface between different energy infrastructures or loads [32]. It uses cogeneration technology, transformer, power electronic equipment, heat exchanger, and other equipment to convert and adjust the output of energy. In this model, the internal equipment is highly abstract, the static relationship of energy in the transmission and conversion process is considered, so it plays an important role in the planning and operation research of IES [33, 34]. Figure 3 shows a typical model of energy hub.

The energy hub represents the input and output of energy, which are connected by an energy coupling matrix as follows [35]:

$$\begin{bmatrix} P_{\text{out}}^{\alpha} \\ P_{\text{out}}^{\beta} \\ \vdots \\ P_{\text{out}}^{\zeta} \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & C_{\beta\alpha} & \cdots & C_{\zeta\alpha} \\ C_{\alpha\beta} & C_{\beta\beta} & \cdots & C_{\zeta\beta} \\ \vdots & \vdots & \ddots & \vdots \\ C_{\alpha\zeta} & C_{\beta\zeta} & \cdots & C_{\zeta\zeta} \end{bmatrix} \begin{bmatrix} P_{\text{in}}^{\alpha} \\ P_{\text{in}}^{\beta} \\ \vdots \\ P_{\text{in}}^{\zeta} \end{bmatrix}, \quad (12)$$

where P_{in} is the original energy input to the energy hub; P_{out} is the energy output after the energy hub; $C_{\zeta\zeta}$ is the coupling matrix between input and output energy of the system to characterize the coupling relationship between energy.

The advantages of energy hub are as follows: (1) It highly abstracts energy transmission, conversion, and scheduling processes, which are only related to energy input and output, and has good practicability and scalability. (2) It simplifies complex problems and provides a new way of thinking for the optimization of joint operation and scheduling of cross-regional and city-level IES, and for market trading mechanism, benefit distribution and other issues.

Disadvantages: (1) It cannot describe the dynamic behavior of the system well, and only considers the static analysis of energy. (2) When the coupling matrix is singular, the model cannot be solved. (3) With the development of various energy storage technologies, renewable energy technologies, demand response, and P2G technologies, the expansion of energy hub is required.

4. Optimal Operation of IES

At present, according to the size of geographical areas and energy characteristics, the research objects on optimal operation of IES are divided into three categories: park, region and

cross-region. Regional IES is mainly aimed at a certain region, which can be a part of a city or a region; cross-regional IES mainly refers to multiple cities or regions.

Park-level IES is mainly aimed at energy management of industrial parks and large buildings. The core research contents are energy equivalence and optimal allocation. The complementary forms and optimal coordination methods of IES are explored so as to realize flexible scheduling of the whole process of “source-network-load”.

Optimization problems of regional and cross-regional IES mainly focus on energy interaction analysis with hybrid optimization of power flow as the core, exploring coordination and optimization among multiple IES. The optimization results provide theoretical guidance for large-scale optimization and transaction operation of IES.

The research related to optimal operation of IES in the park, region and cross-region will be reviewed in the following sections.

4.1. Optimization Objectives and Optimal Operating Constraints of IES

4.1.1. *Optimization Objectives of IES.* In park-level IES, there is only one IES that generates, transmits and distributes energy in a certain area. The optimal operation problem of IES is generally expressed as follows:

$$\begin{aligned} \min \quad & f(P, E, x), \\ \text{s.t.} \quad & \begin{cases} L_{\text{out}} = (C S) \begin{bmatrix} P \\ E \end{bmatrix}, \\ P_{\min} \leq P \leq P_{\max}, \\ E_{\min} \leq E \leq E_{\max}, \\ 0 \leq x \leq 1, \end{cases} \end{aligned} \quad (13)$$

where $f(P, E, x)$ is the objective function related to energy input P , energy storage system E and energy allocation coefficient x ; the constraint is the balance of energy input and output; P_{\min} and P_{\max} are lower and upper limits of energy input; E_{\min} and E_{\max} are lower and upper limits of energy storage system output; x is the energy allocation coefficient of IES, which generally refers to the proportion of a certain energy output to total energy output.

The optimization objectives of a single IES can be summarized as follows:

- (1) Most of the optimization objectives of IES are to minimize the total operating cost of the system or maximize social welfare [36–39].
- (2) There are also some studies whose optimization objectives are optimal carbon emissions or environmental benefits, to achieve the proportion of green energy in the operation of IES system [40–42]. There are still a few studies whose optimization objective is maximal absorption of renewable energy, to improve the proportion of energy supply from renewable energy in IES, so as to achieve better environmental benefits [43].

For regional and cross-regional IES, multiple IES are connected by power transmission network, natural gas

transmission network, and thermal transmission network. The overall optimal dispatch of IES is mainly a problem of optimal hybrid power flow of multienergy.

Appropriate interconnection can reduce consumption and reserve capacity of generation, and make full use of power generation equipment, which is a method that can make the energy equipment the most effective in any region. There will be various forms of energy exchange between IES [44–47] and the concept of energy hub is constructed. Each energy hub is regarded as a generalized node in the network, and the energy flow on the transmission line is similar to the optimal power flow of the power system, which is called the optimal power flow of multienergy system [48]. Figure 4 shows a typical cross-regional IES schematic.

On the basis of the optimal hybrid power flow, the problem of IES at the regional and cross-regional levels is to calculate the optimal hybrid power flow of the system, thus revealing the operation mechanism of multiple IES, and providing theoretical guidance for the optimal operation and energy dispatch of IES at regional and cross-regional levels. Moreover, the optimal hybrid power flow calculation generally chooses the system operation economy as the optimization objective, and its constraints are energy flow equation constraints of IES, energy production and consumption constraints, conversion and energy storage equipment constraints, while considering the energy constraints of multienergy coupling equipment of IES [49–53].

The basic optimization model is shown as follows:

$$\begin{cases} \min f(P_i, F_j) \\ \text{s.t.} \quad L_i = C_i P_i \\ G_\alpha(P_i) = 0, \\ F_j^{\min} \leq F_j \leq F_j^{\max} \\ P_i^{\min} \leq P_i \leq P_i^{\max} \end{cases} \quad (14)$$

where $f(p_i, F_j)$ the function related to energy input and power flow of energy network; the first and second constraints are energy flow equation constraints in energy networks and upper and lower limits in networks.

4.1.2. *Optimal Operating Constraints of IES.* In the research of optimizing constraints, besides the independent units of conventional power system, natural gas system and thermal system [54], the coupling system has also been discussed in previous studies [55]. The specific constraints are shown in Figure 5.

4.2. *Optimal Operation of IES considering Electro-Thermal Coupling.* As an important part of IES, electro-thermal coupling system connects power system and thermodynamic system through coupling elements such as CHP units and electric boilers to realize the conversion between electric energy and thermal energy. However, there are mutual restrictions between electric output and thermal output among electro-thermal units, which in some cases will affect the peak regulation of power system and absorption capacity of wind power, so some research introduces heat pumps and heat storage devices to increase the flexibility of the electro-thermal coupling system.

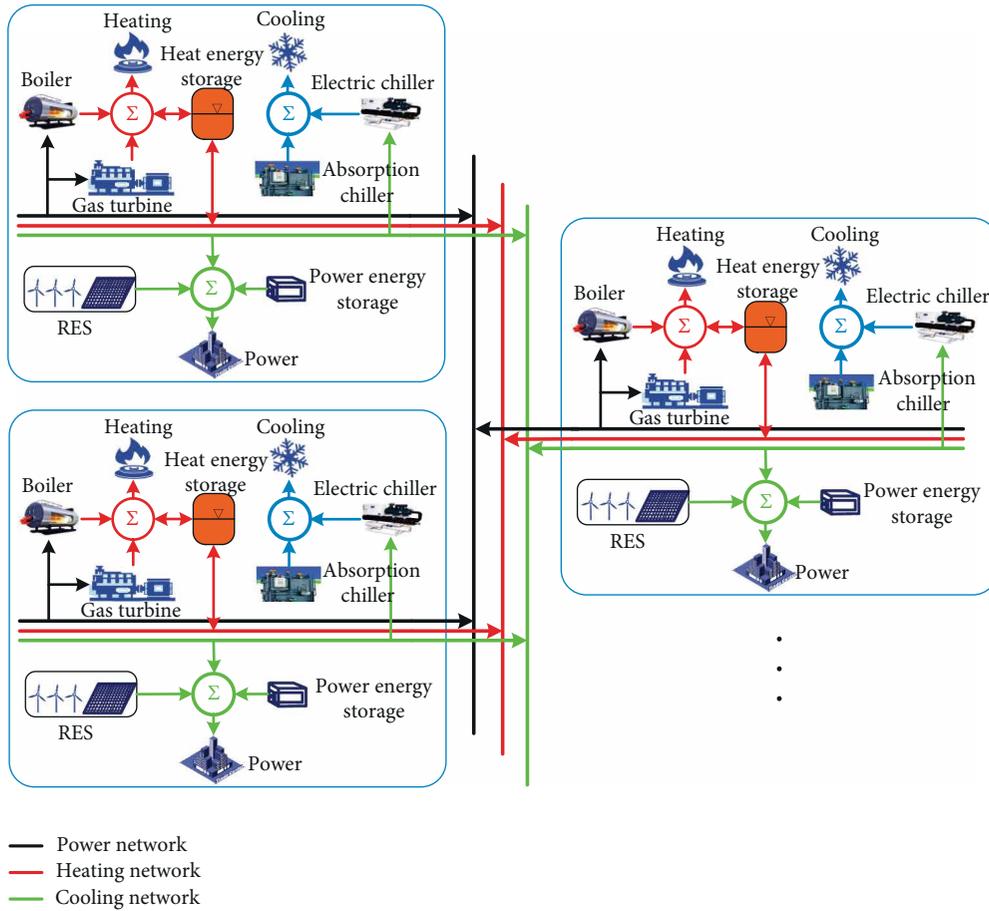


FIGURE 4: Schematic of cross-regional IES.

Park-level IES mainly considers the optimal dispatch of cogeneration units. Good et al. [56] chooses the optimal operation strategy for CHP system considering energy demand and integrated performance criterion under two operating modes of “electricity by heat” and “heat by electricity”. The emergence of heat pumps and heat storage devices provides a powerful support for the flexibility of electro-thermal coupling systems. Fang et al. [57] presents a physics-based model which is applicable to both electricity generating ETTs (aggregated residential electro-thermal technology), the presented model determines the expected energy and discomfort costs for a variety of cases.

Research on CHP and CCHP has been mature. Power cycle that efficiently converts low-grade thermal energy into power combining organic Rankine cycle (ORC) has become a hot research topic. In [58], the ORC turbogenerator is used in cement industry to improve economy and energy efficiency by recycling heat.

The researches considering the characteristics of heat network and temperature variation of heat medium, and the connections of heat pump and heat storage into systems have also attracted extensive attention. Wang et al. [59] proposes an IES with solar energy heat pump, which shows that increasing solar energy heat pump can effectively reduce the cost of central heating supply of cogeneration unit. In addition, some

scholars have refined the loss model in the process of heat energy transmission, and the thermal energy storage (TES) device is proposed in [60], which proves that TES device can provide flexibility for the electro-thermal coupling system. Sauter et al. [61] analyzes the impact of electro-thermal storage (ETS) system on the operation of community microgrid in northern China, and proved that ETS can significantly reduce the operating cost of the system and better absorb wind and solar energy. Pan et al. [62] develops an integrated quasi-dynamic model of integrated electricity and heating systems, a simulation method is proposed and quasi-dynamic interactions between electricity systems and heating systems are quantified with the highlights of transport delay, results show that both the transport delay and control strategies have significant influences on the quasi-dynamic interactions.

Some researches focus on demand response technology. The energy consumption behavior of users is influenced by demand response technology in [63], which shows that demand response can improve the regional wind power consumption. In [64], the Energy PLAN is used to model IES, and analyses the application of heat pump, heat storage equipment, and demand response technology in different scenarios. Results show that the total operating cost and carbon dioxide emissions of the system can be minimized, and the introduction of heat pump improves the operating efficiency of the system.

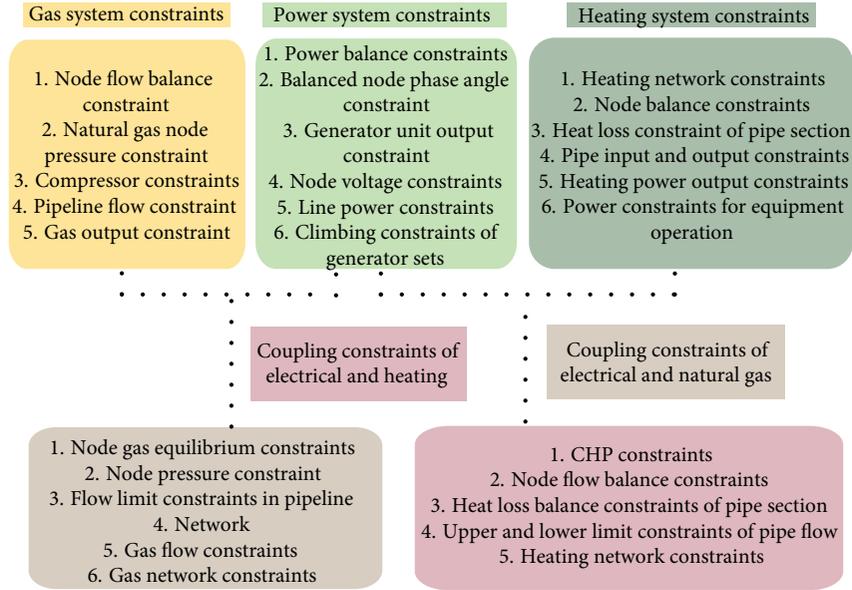


FIGURE 5: The specific constraints of IES.

Cooperative optimal operation of power system and thermal system can break the traditional mode of “electricity by heat” and improve the level of energy utilization. Relevant research has proved that large-scale thermal storage system can effectively improve the flexible dispatching ability of the system. However, new materials such as thermal storage or phase-change thermal storage need to be further studied [65]. At present, the related research of solar thermal power generation technology [66] has attracted wide attention. However, due to the high cost of power generation, related technologies need to be further studied.

4.3. Optimal Operation of IES considering Electro-Gas Coupling. The coupling relationship between power system and natural gas system is mainly caused by P2G equipment and gas turbine. For power system, P2G equipment is a load, and for natural gas system, it can be used as a gas source for transmission. The coupling between power system and natural gas system can make these two systems stand by each other and improve the flexibility of the system [67]. One-way transmission of energy between natural gas network and power grid is carried out by gas turbine. P2G device makes the power grid and natural gas network interconnected, and energy flow becomes bidirectional. As for the coupling relationship between power grid and natural gas system, the following literatures make positive exploration.

Clegg and Mancarella [68] evaluates multienergy systems considering the short-term flexibility provided by natural gas power generation. Chen et al. [69] considers the problem of optimal energy flow, gives the method of solving the optimal power flow, measuring the feasibility margin and the infeasibility of energy flow. It also proposes three models to solve the optimal energy flow, studies the identification method of solvability of optimal multienergy flow, and verifies the effectiveness of the proposed models through case studies.

Khani and EI-Taweel [70] considers the problems of reverse power flow of feeder, additional heating of transformer

or incorrect operation of protective device caused by power generation of high-penetration renewable energy. This study reveals the application of bidirectional converter in integrated electric-gas system, and proposes a new real-time algorithm, which is verified effectively by simulation with real data. He and Shahidehpour [71] proposes a robust security-constrained unit commitment model to enhance the operating reliability of integrated electro-gas system against possible transmission lines outages. Zhang et al. [72] considers the N-1 accident of natural gas system and power system, a mixed integer linear programming (MILP) method is developed, and the experimental results show that the proposed method has good computational performance.

4.4. Optimal Operation of IES considering Electro-Gas-Thermal Coupling. IES with electricity, gas, and heat is composed of power system, thermal system, and natural gas system with various coupling units such as CHP, gas turbine and gas boiler. Energy hub is the key to the coupling of multienergy. The optimal operation and power flow with energy hubs as the core have attracted wide attention.

The coordinated optimization objectives of multienergy hubs are generally the optimal economy of own system, optimal overall economy or the least carbon emissions. Zhong et al. [73] establishes a multiobjective model for scheduling optimization of IES with the objective of minimizing the operating cost and pollutant emission. The improved bacterial population chemotaxis algorithm is used to optimize the comprehensive energy system scheduling model. The simulation verifies the effectiveness of the optimized scheduling model and the improved algorithm. Zhong and Yang [74] proposes a distributed auction mechanism with multienergy control. The energy hub uses dual consensus ADMM algorithm to distribute energy for users with the objective of maximizing social welfare. Finally, it organizes and builds load data, analyses and evaluates the performance of energy scheduling and verifies the compatibility of incentive mechanism.

Li et al. [67] uses cooperative game theory to optimize multiple IES systems by adjusting the existing IES control algorithm, and proves that the cooperative game has a balanced distribution point of economic benefit. Clegg and Mancarella [68] proposes an optimal operating framework for intelligent areas with multienergy devices and integrated energy networks. The framework is based on two-stage iterative modeling, involving linear approximation of MILP and nonlinear network equations. Practical cases in England prove that the proposed model can eliminate uncertainty to a certain level and has important reference value for evaluation of system flexibility.

4.5. Optimal Control and Operation of IES. Power flow calculation of multienergy flow in IES is to determine the power flow distribution of each subsystem, which is an important prerequisite for exploring coupling characteristics and optimizing scheduling.

Power flow calculation of multienergy flow in IES is expressed as follows:

$$\begin{cases} 0 = F(x_e, x_g, x_h, x_{eh}) \\ 0 = G(x_e, x_g, x_h, x_{eh}) \\ 0 = D(x_e, x_g, x_h, x_{eh}) \\ 0 = E_H(x_e, x_g, x_h, x_{eh}), \end{cases} \quad (15)$$

where x_e , x_g , x_h , and x_{eh} are variables of power system, natural gas system, thermal system, and energy hub; $F(\cdot)$ is the equation of power flow; $G(\cdot)$ is algebraic equation of natural gas system, including equations of gas pipeline and compressor; $D(\cdot)$ is the equation of thermal system, including equations of heat flow continuity, pressure loop, node flow and node mixed temperature; E_H is the input-output conversion equations of energy hub.

The gas distribution system mainly includes two parts: node and branch. Nodes are divided into pressure-known nodes and flow-known nodes [75], in which the pressure-known node is generally the gas source point with the pressure known and the flow to be calculated; the flow-known node is generally the load node with the pressure to be calculated. Because of the pressure drop at both ends of the pipeline, especially in the medium and high pressure gas transmission network with long distance and large capacity, it is necessary to configure a compressor to increase the pressure of the gas transmission pipeline [76].

The steady-state model of IES mainly includes AC power flow model of power system, natural gas pipeline model with compressor and steady-state model of thermodynamic system.

4.5.1. Energy Flow Analysis

Electric Power Network. Similar to the power flow model of traditional power system, the classical AC power flow model is generally used for IES. The power equation of the node is expressed as follows:

$$S_i = P_i + jQ_i = \dot{U}_i I_i^* = \dot{U}_i \sum_{j=1}^{n_i} Y_{ij}^* U_{ij}^*, \quad (16)$$

where P and Q are the active power and reactive power of the node, respectively; I_i is the current injected into node i ; U_i and U_j are the voltage of node i and node j , respectively; n_i is the number of nodes; “*” is the conjugation of complex numbers; V is admittance matrix of the node and U is voltage vector of the node.

Thermal Network. Thermal network is composed of hydraulic model and thermal model. Generalized Kirchhoff's law should be satisfied at each node, i.e. injected flow should be equal to outgoing flow [77–80], that is

$$\begin{cases} A_h m = m_q \\ B_h h_f = 0 \\ h_f = Km|m|, \end{cases} \quad (17)$$

where A_h is the node-branch correlation matrix of heating network; m is flow of each pipeline; m_q is outgoing flow of each node, i.e., consumption flow of heat load node; B_h is the loop-branch correlation matrix of heating network; h_f is loss vector of pressure head; K is the resistance coefficient vector of pipeline.

The thermodynamic model is used to calculate the heating and regeneration temperature of heating network nodes. Heating equipment converts energy into heat energy through natural gas and other fuels, and transmits energy through heat network. For each heat load node, the thermal power and node temperature are expressed as follows:

$$\begin{aligned} \Phi &= C_{shc} m_q (T_{strat} - T_{end}), \\ T_{end} &= (T_{start} - T_g) \exp\left(-\frac{\lambda_{pipe} L}{C_{shc} m}\right) + T_g, \\ (\sum m_{out}) T_{out} &= \sum (m_{in} T_{in}), \end{aligned} \quad (18)$$

where Φ is the thermal power of the thermal network node; T_{start} and T_{end} are the temperature vectors at the beginning and end of the pipeline; L is the length of the pipeline; C_{shc} is the specific heat capacity of water; T_g is the environmental temperature; λ_{pipe} is the heat conductivity of the pipeline; m_{out} and m_{in} are the outflow and inflow of hot water, respectively; T_{out} and T_{in} are the temperature of outflow and inflow of hot water.

Natural Gas Network. The air flow through the pipeline depends on the pressure at both ends of the pipeline and is expressed as follows:

$$\begin{cases} f_r = \text{sgn}(\Delta p) \cdot K_r \cdot \sqrt{\text{sgn}(\Delta p) \cdot (p_n^2 - p_m^2)} \\ \Delta p = p_n - p_m \\ \text{sgn}(\Delta p) = \begin{cases} +1, & p_n > p_m, \\ -1, & p_n < p_m, \end{cases} \end{cases} \quad (19)$$

where f_r is the flow value of natural gas pipeline from node m to node n ; Δp is the pressure difference between node n and m ; $\text{sgn}(\Delta p)$ is the flow direction in pipeline; “1” means from node n to node m ; “-1” means from node m to node n ; K_r is the constant of pipeline, and generally calculated by

$$K_r = 7.57 \times 10^{-4} \frac{T_n}{p_n} \sqrt{\frac{D_r^5}{FL_r T_a Z_a G}}, \quad (20)$$

where T_n and p_n are the temperature and pressure under the standard condition; D_r and L_r are the diameter and length; F is the undirected friction coefficient; T_a is the average temperature of natural gas; Z_a is the average compressibility coefficient; G is the relative density. Both (19) and (20) do not consider the temperature change of natural gas during transmission.

4.5.2. Solution of Optimal Power Flow of Multienergy. At present, Newton-Raphson method is mainly used to solve the problem, which can be divided into unified solution method and decomposition solution method [81–83]. Based on the power flow calculation of power system, the unified solution method takes the variables of natural gas system and thermal system as extended variables, and solves the problem in a unified way. The iterative process of solving the unified power flow model by Newton-Raphson method is expressed as follows:

$$\begin{cases} \Delta x^{(k+1)} = (J^{(k)})^{-1} \Delta F^{(k)} \\ x^{(k+1)} = x^{(k)} - \Delta x^{(k+1)}, \end{cases} \quad (21)$$

where ΔF is the deviation value of power flow equations; J is the Jacobian matrix; k is the number of iterations; $x^{(k)}$ and $\Delta x^{(k)}$ are the state variables of the system and its deviation value in k^{th} iteration, respectively; J is expressed as follows:

$$J = \begin{bmatrix} J_{ee} & J_{eg} & J_{eh} \\ J_{ge} & J_{gg} & J_{gh} \\ J_{he} & J_{hg} & J_{hh} \end{bmatrix}, \quad (22)$$

where the diagonal elements J_{ee} , J_{gg} , and J_{hh} represent the relationship between the energy flow and the state variables of individual electrical, gas, and thermal systems, and nondiagonal elements represent the coupling relationship between different systems.

The decomposition method, also known as sequential solution method, solves the power flow equation separately from the natural gas system. In the current power flow program, the coupling nodes of natural gas system and thermal system are represented by PV nodes or PQ nodes. When solving natural gas system or thermodynamic system, the nodes coupled with other systems are equivalent to source nodes or load nodes.

To solve the hybrid power flow problem of multienergy flow in IES, the corresponding coupling model is first established, and different solving methods are adopted according to different application scenarios. In [15], a collaborative optimization method of adaptive robust day-ahead energy reserve for urban energy systems is proposed, which proves the economic benefits of the proposed adaptive robust framework. Cesena and Mancarella [4] introduces an optimal operation model of intelligent multienergy region constrained by internal energy network, and considers the relevant uncertainties. The results show that the physical constraints of the integrated network and the uncertainty of specific energy sources (such as PV) reduce the flexibility of the region. Nistor and Antunes [84] proposes an integrated energy management method using Markov process to reduce energy costs while maintaining

consumer satisfaction. The results show that the proposed method can significantly reduce the system operation economy.

4.6. Research Status and Existing Problems. In view of the current research status of electro-gas coupling system, there are mainly the following difficulties.

Firstly, the transform of the original system on the basis of the existing equipment of power system or natural gas system, and the correctness and economy of selected scheme considering the coupling relationship need to be further analyzed. Because the existing system construction is difficult to come up with a set of extendable and applicable expansion scheme, it is easy to have problems such as large investment and small income. Secondly, the analysis and calculation of multienergy flow of electro-gas coupling system is still in the initial stage of research, lacking fast, accurate and practical methods.

Because the power system and natural gas system are dominated by different subjects, whether there are conflicts of interest and how to distribute interests need to be studied by game theory and other methods. It also has problems whether different subjects will implement scheme according to the scheduled. In addition, the price of hydrogen or methane generated by excess power or renewable energy in power system through P2G technology and whether hydrogen or methane is allowed directly into gas transmission and distribution pipelines by the main body of natural gas still need relevant research and investigation.

The reliability of natural gas supply and power system supply still needs further study. The reliability of single natural gas supply is mainly affected by pipeline capacity and gas storage capacity. The reliability of power system mainly consists of the reliability of power generation system, transmission system, distribution system, and main electrical connection of power plant/substation.

Generally, the operation of IES needs to consider the dynamic characteristics of the system, such as the delay of pipeline transmission, the nonlinearity of equipment conversion efficiency, and power flow constraints, which are nonlinear programming problems [4]. Traditional algorithms such as sequential quadratic programming (SQP) and primal dual interior point or intelligent algorithms, such as particle swarm optimization (PSO), genetic algorithm (GA), evolutionary algorithm (EO), and reinforcement learning (RL), are used to solve nonlinear programming problems [85, 86].

5. Conclusion

This paper first describes the basic structure and formal characteristics of integrated energy system, and introduces the related technologies. This paper systematically summarizes the theory of multienergy coupling, economic analysis, operation optimization and optimal control operation, and pays attention to the problems concerned by academia and industry at present. The methods of physical equipment modeling, energy hub modeling, multienergy flow calculation, economic analysis, coupling relationship, and multienergy flow optimal

solution are described, and analyzed from three levels of user level, regional level, and cross-regional level respectively.

Considering that the integrated energy system plays an important role in the energy revolution, further research is needed to achieve large-scale absorption of renewable energy and efficient utilization of energy. The hot research issues include:

- (1) The general modeling theory of IES is the basis of analyzing and researching IES. Although the related physical models of IES system have been stated in the previous sections, due to the lack of in-depth research on control rules and optimization characteristics of new equipment in practical application scenarios, it is of great significance to explore the general modeling theory of integrated energy resources. How to embody the dynamic characteristics of multienergy system and how to build the wide adaptability of IES simulation platform still need to be further studied.
- (2) Energy storage system can realize single/two-way conversion and storage of electric energy and other energy in IES. With the wide application of energy storage technology, the dynamic response characteristics of energy storage technology, such as heat storage, cold storage, electricity storage, and gas storage should also be considered during system operation. The impact of adding various types of energy storage systems on the planning and operation of IES needs to be further explored.
- (3) Power flow calculation of multienergy flow is an important basic work for system planning, operation and control. How to sum up the general mathematical expressions about the power flow calculation of multienergy flow and achieve fast solution of model needs to be further studied. For the optimal power flow model of multienergy, the mixed integer nonlinear programming (MINLP) problem is solved by using related intelligent algorithms. The complexity of time and space in the optimization process still needs to be further studied.
- (4) Considering many uncertainties in IES, the modeling of probabilistic power flow and fast solution methods need to be improved in related applications; due to the different dynamic response characteristics of energy flows, the delay of heat network and gas-heat transmission pipeline need to be studied; optimization problems with multiobjective, strong nonconvex and multiuncertainty coupling need to be efficiently solved. Moreover, there is large fluctuation of the output of wind turbine and solar energy, and the related uncertainty needs to be fully considered.
- (5) At the same time, market mechanism and development mode are the direct driving force of IES development. It is necessary to establish a multilevel market mechanism and trading structure, including users, multitype energy producers, energy agents and energy service providers. Frameworks such as multienergy-coupled markets or decentralized trading

need to be further studied. According to the actual situation, the way to adjust the interest relationship between integrated energy supply and integrated energy services, and to establish the trading structure and operation model of the future energy market remain to be further explored.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Grant Nos. 51807179, 51777193, and 51967001.

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