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A comprehensive review of Energy Internet: basic concept, operation and planning methods, and research prospects

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Abstract With the intensifying energy crisis and environmental pollution, the Energy Internet and corresponding patterns of energy use have been attracting more and more attention. In this paper, the basic concept and characteristics of the Energy Internet are summarized, and its basic structural framework is analyzed in detail. On this basis, couplings between the electric power system and other systems such as the cooling and heating system, the natural gas system, and the traffic system are analyzed, and the operation and planning of integrated energy systems in both deterministic and uncertain environments are comprehensively reviewed. Finally, the research prospects and main technical challenges of the Energy Internet are discussed.

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1 Introduction

In the 21th Century, traditional patterns of energy use based on centralized conversion of fossil energy have been facing many challenges such as the energy crisis and environmental pollution [1]. It has been recognized that solutions mainly include two aspects, i.e., developing renewable energy sources (e.g., solar, wind and biological energy) and improving the efficiency of energy use. As shown in the "EU Energy Road Map 2050" [2], it was forecast that more than 55% of global energy demand is expected to be satisfied by renewable energy sources by 2050. In such an era, a sustainable energy supply system with high energy efficiency is required. Therefore, it is urgent to create an integrated energy system to optimally coordinate various renewable energy sources and different energy systems [3]. Combining this context with Internet technology, Jeremy Rifkin proposed the vision of the Energy Internet (EI) in 2011, which can make full use of distributed renewable energy, and improve energy efficiency and electric power system reliability [4]. The ultimate goal of the Energy Internet is to realize distributed and renewable energy systems [5]. The concept, framework and composition of the Energy Internet have been continuously developed since then.

Compared with the existing energy system, the Energy Internet can be regarded as a peer-interconnected sharing

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network with advanced power electronic technology, new-energy technology and information technology. With those technologies, the coordination and two-way energy and information flow can be realized [6]. Also, the Energy Internet can be interpreted as an integrated energy supply system, i.e., the electric power system tightly coupled with other energy networks such as the natural gas network, the traffic network and the information network [7, 8], as shown in Fig. 1. In this figure, the electric power system is the conversion hub between various forms of energy and is the core of the EI, since it owns significant advantages in energy transmission efficiency and it carries the most convenient form of energy for end-users. In the Energy Internet, different energy systems are coupled through energy transformation devices (e.g., micro-turbine, electric vehicle (EV), power to gas (P2G), or vehicle to grid (V2G)). For instance, using P2G technology, surplus renewable energy can be transformed into methane, and then used to supply natural gas load [9].

In contrast with traditional energy supply systems, the EI generally has such characteristics as utilizing renewable energy [10], plug and play (PnP) of distributed devices and EVs [11], and balancing energy supply and demand via wide-area energy sharing, energy router and efficient information management [12, 13]. Therefore, many developed countries have carried out related research on the EI. In the US, the Future Renewable Electric Energy Delivery and Management research center was built to develop a high-efficiency distribution system with high penetration with PnP of distributed generators (DGs) [14, 15]. In Germany, the "E-Energy" project was proposed, which aimed at establishing an intelligent energy system based on information and communication technology [16, 17]. In Switzerland, the Vision of Future Energy Networks project proposed two key elements of the EI: a hybrid energy hub and an energy interconnector [18, 19]. However, research about EI exploration and practice is still in the preliminary stage, and a deep and comprehensive survey on the EI is needed.

In this paper, we will first give a comprehensive review of the concept, characteristics, framework and development of the Energy Internet. Then, Sects. 2, 3 and 4 analyze different EI systems, i.e., a combined cooling heating and power system, an integrated natural gas and electric power system, and an integrated electric and traffic system respectively. In those sections, state-of-the-art research on operation and planning methods for such integrated energy systems are reviewed from the perspectives of deterministic environment and uncertain environment. Finally, the research prospects and main technical challenges of the Energy Internet are discussed in Sect. 5.

2 Operation and planning optimization of CCHP system

2.1 Combined cooling heating and power system

As an important type of distributed generation, combined heat and power (CHP) plants can supply heat energy and electric energy at the same time. Compared with separate generation of heat and electric power, the fuel economy and overall efficiency of CHP are higher [20]. As refrigeration technology has advanced in recent years,
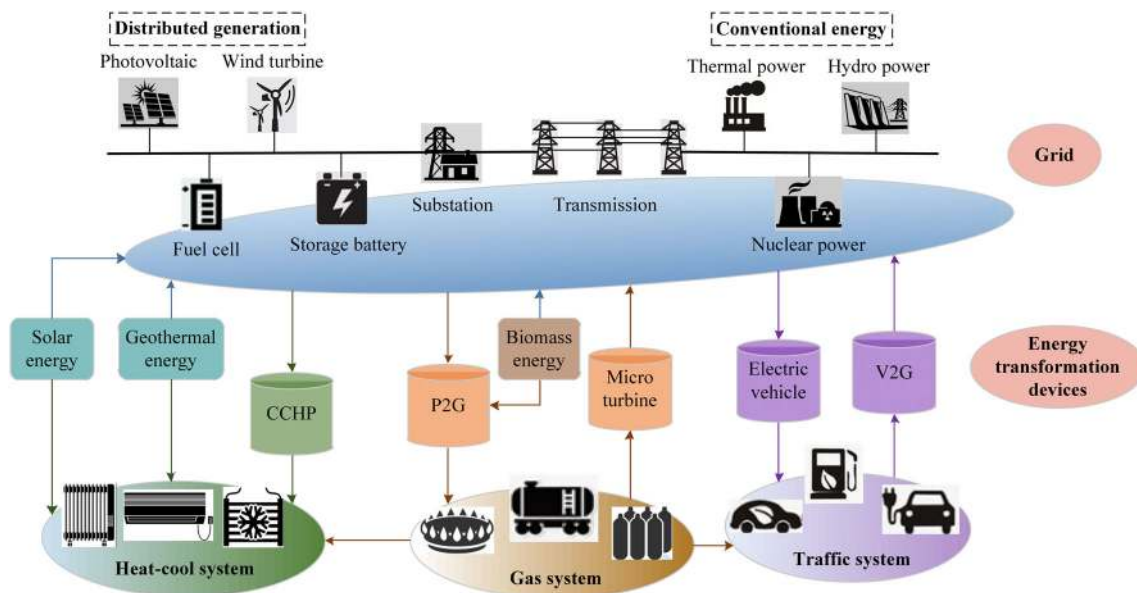

Fig. 1 Basic structural framework of Energy Internet

combined cooling heating and power (CCHP) plants have become one of the most promising, practical and flexible resources in electric power systems [21]. A CCHP system includes electric power generation, heating and cooling [22], and the production of heating, cooling and electric energy can be balanced with load requirements to improve the overall energy efficiency from 40% to 70%–90% [23]. In addition, a CCHP system has the advantages of emission reduction and cascaded energy use.

As shown in Fig. 2, a CCHP system generates electricity by means of a micro-turbine (MT) or a reciprocating engine. It recycles waste heat through the heat recovery unit and bromide absorption refrigerator; then the waste heat is used to satisfy thermal demands.

Mathematically, the MT-based CCHP model can be formulated as follows [24]:

$$\begin{cases} Q_{MT} = P_e(1 - \eta_e - \eta_1)/\eta_e \\ Q_{he} = Q_{MT}K_{he} \\ Q_{co} = Q_{MT}K_{co} \end{cases} \quad (1)$$

where Q_{MT}, P_e, η_e and η_1 represent heat discharge allowance, output power, generating efficiency and heat loss coefficient of the MT, respectively; Q_{he}, Q_{co} are the total heating and cooling generation; and K_{he}, K_{co} are equivalent thermal coefficient and refrigeration coefficient considering losses and the typical average daily temperature.

2.2 Objectives and constraints

The integration of CCHP into electric power systems has significant effects on branch power flow and nodal voltages. The conversion of heat energy is tightly coupled with electric power generation in a CCHP system, thus affecting the electric power balance. Therefore, much research has addressed electric power system optimization with CCHP.
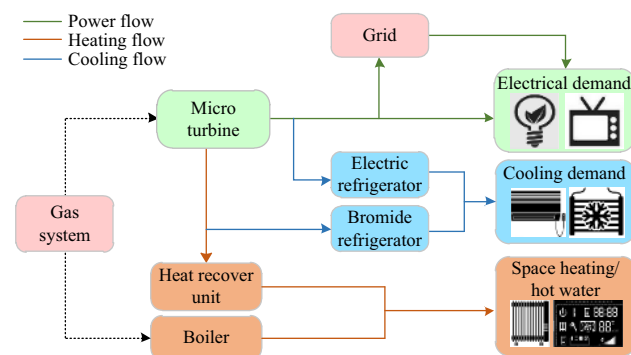

Fig. 2 Configuration of CCHP system with indicated electrical and thermal power flow

2.2.1 Objective function

As shown in Table 1, considering different factors, the objective function of CCHP optimization problems generally includes the following aspects:

1) Maximizing the economic benefits. This requires minimizing the power generation costs and satisfying the energy demands in the most economical way [24–29]. In general, the significant costs are the power generation costs of DGs and conventional energy sources, the operational cost of the MT, and the costs of power exchange between the CCHP system and the electric power system.

2) Maximizing the overall benefits including the economic benefits, the environmental benefits, and the heating and refrigeration benefits [24]. The use of fossil fuels can produce greenhouse gases and harmful gases (e.g. nitrogen oxides, sulfur dioxide), thus it is necessary to calculate pollution costs when considering environmental factors. Moreover, since heating and refrigeration can make profits, the overall benefits should consider the heating and refrigeration profits. The objective function can be formulated as:

$$C = C_0 + C_{po} - C_{he} - C_{co} \quad (2)$$

where C_0 is the total cost including power generation costs, operational costs and power exchange costs; C_{po} is the total pollution cost of different energy sources according to the formulae that can be found in [28–30]; and C_{he}, C_{co} are the heating and refrigeration profits, calculated based on the heating/cooling power and unit price.

2.2.2 Constraints

Since CCHP system is a power plant combining cooling, heating and electric generation, the constraints applying to electric power system optimization with CCHP generally includes the following aspects:

1) Electric power system constraints. They can be derived from the constraints in typical electric power system optimization models, including voltage constraints, current constraints, electric power balance constraints, maximum installed capacity constraints and active power constraints of DGs [31, 32].

2) Cooling and heating system constraints. They mainly refer to the heating/cooling load balance constraints and the operational constraints of heating/cooling units [32, 33]. The latter generally comprises the generation, transmission and storage constraints of the cooling and heating system, e.g., the heat constraints of the gas

Table 1 Summary of objective functions and constraints for integrated energy systems

System	Major objective functions	Major constraints	
		Other system constraints	Electric power system constraints
CCHP-related system	Economic benefits Overall benefits including economic benefits, environmental benefits, and heating and refrigeration benefits	Heating/cooling load balance constraints Heat constraints of the gas boiler Output constraints of bromide refrigerator Heating/cooling storage constraints Capacity constraints of heating/cooling transmission lines	
Integrated natural gas and electric power system	Capital benefits Energy benefits	Gas flow balance constraint Gas transmission constraints Natural gas capacity constraints P2G constraints	Electric power balance constraints Voltage constraint Current constraint Electric generator constraints
Integrated electric and traffic system	Stabilize the fluctuations of electric power system Optimal planning of charging stations	Capacity constraint of charging lines and substations Constraints of charging devices EVs batteries capacity constraints Charging power constraints of EVs V2G power constraints Traffic network constraints	

boiler, the output constraints of the bromide refrigerator, heating/cooling storage constraints, and the capacity constraints of heating/cooling transmission lines.

2.3 Planning and scheduling methods

Since uncertainties exist in operation, e.g. the uncertainties of load and renewable power output, the operation and planning of electric power systems with CCHP can be divided into two parts.

2.3.1 Deterministic methods

In deterministic approaches, uncertainties are neglected, and planning and scheduling algorithms are relatively simple. Linear programming (LP) [34, 35], nonlinear programming (NLP) and mixed integer linear programming (MILP) [36, 37] have been widely applied to the CCHP optimization problem. Rong *et al.* modeled the hourly trigeneration problem as a LP model considering the joint characteristic of three energy components and proposed the Tri-Commodity Simplex (TCS) algorithm to minimize the total production and purchasing costs, as well as CO_2 emissions costs [34]. Although LP offers significant advantages, it requires linearization of non-linear constraints in systems with CCHP, which introduces calculation errors. Thus, mathematically, NLP seems to be a more rigorous and accurate method, especially when considering the logistical constraints for the equipment [38, 39]. A notable example is [38], which proposed a non-linear cost-minimization model to obtain the optimal operational strategy for a CCHP system. These deterministic approaches provide important insight into the operation optimization of electric power systems with CCHP, however, they cannot deal with uncertainties such as load uncertainties.

2.3.2 Methods for handling uncertainties

The uncertain parameters can be generally classified into two categories including technical parameters and

economical parameters [40]. Specifically, in the operation and planning of a CCHP system, the former includes outages of lines and generators and uncertain demand and generation, and the latter includes the uncertainties of fuel prices and environmental policies. Due to the complexity of optimization under uncertainties, it is necessary to adopt more effective methods to analyze the operation and planning of a CCHP system [41]. Up until now, state-of-the-art methods can be generally categorized into three main classes as follows.

a) Probabilistic methods

In probabilistic methods, the random variables are modeled by probability density functions, and applicable methods include the chance-constrained programming method and the two-stage stochastic programming method [42]. For chance-constrained optimization, the constraints are formulated in probabilistic terms and thus decision-makers can know the likelihood of meeting the constraints [43]. In [44], Niknam *et al.* proposed chance constrained programming to handle multi-objective economic load dispatch using a jointly distributed random variables method. For the two-stage stochastic programming method, the effects of decisions after uncertain variables are realized can be well represented. A specific case in [45] shows that this method could handle uncertainties in the optimal sizing of cogeneration systems, where it firstly calculates the optimal capacities of CHP and boiler before uncertainties such as errors of the electrical and thermal loads are realized, and secondly determines the operational strategy by using realized scenarios.

b) Fuzzy methods

In fuzzy analysis methods, the uncertain parameters are described by using the membership function, and fuzzy membership can be obtained by subjective investigation [46, 47]. These methods are commonly used to quantify uncertain factors such as social and other qualitative indices, for which probability distributions are not available. For instance, Jing *et al.* [48] proposed Fuzzy Multi-Criteria Decision Making and evaluated the complex relationship between CCHP systems and society, economy, and the environment. Fuzzy set theory has also been widely applied to deal with insufficient data and uncertain load demand [49]. In [50], a multi-objective model based on fuzzy programming was proposed to minimize cost and maximize demand satisfaction. Combined uncertainties of price and load have been dealt with using fuzzy programming [51, 52]. In [47], uncertainties associated with electrical demand, thermal demand, and the prices of electricity and natural gas were modeled by using fuzzy sets as a percentage change from their nominal values. Then a hybrid optimization method was used to determine the desired optimal CCHP configuration.

c) Robust optimization

Robust optimization uses intervals to model uncertain variables and thus does not need accurate probability distribution functions and fuzzy membership functions. In [53], a model based on robust optimization was presented to consider uncertain load and price in the context of Energy Analysis-Based Optimization of Trigeneration (EABOT). The goal of [53] was to achieve optimal operation with high probability. However, up until now, research in this field is still limited.

In summary, useful research ideas have been presented for CCHP-related optimization. With the increasing numbers of highly-coupled distributed devices, more focus should be given on different random and fuzzy factors in electric power systems. Although a hybrid "possibilistic" and probabilistic model has been proposed [54], most of the current research adopts a probabilistic model or fuzzy model to deal with all uncertainties, calling for deep and comprehensive research.

3 Coupling of electric power system and natural gas system

3.1 Integrated natural gas and electric power system

An integrated gas and electricity network is one of the most important energy systems in economic and environmental terms. The coordinated operation and planning of the gas network, electricity generators, and transmission and distribution networks can reduce energy consumption and lead to an optimal structure for the combined systems. Up until now, a large number of studies have been done to analyze the interaction of the gas and electric networks in joint planning. For example, the study towards coordinated planning has been undertaken in the United States [55, 56], and some common problems related to the development of natural gas and electricity networks (operation costs, network expansion costs, optimal placement of gas-fired generation plants) have been analyzed in Europe [57]. Although the research in this area starts late in China, related concepts and models have been already proposed, such as a smart energy network based on multiple energy sources [58].

With the development of shale gas reserves and P2G technologies [59, 60], and the potential roles of gas in clean energy systems, the proportion of gas energy and gas-fired power generation in energy systems has seen significant growth, and the power network and gas network become
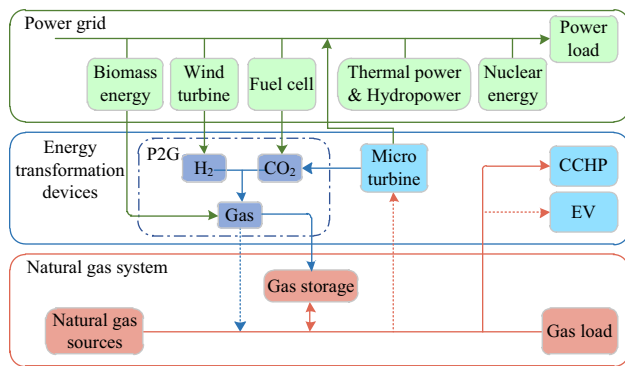
Fig. 3 Configuration of an integrated natural gas and electric power system indicating electrical and gas power flow

more tightly coupled. Referring to [9], the surplus output of renewable energy sources can be transformed into methane using P2G technology, and then used to supply natural gas load, as shown in Fig. 3. This achieves bidirectional energy flow between the electric power system and the natural gas system. Since natural gas is easy to store, the large-scale storage of renewable energy can be realized.

3.2 Objectives and constraints

3.2.1 Objective function

Generally, the objective function includes the following aspects.

1) Maximizing the capital benefits. This is the main research direction for the coordinated planning of natural gas and electric power systems. It can minimize the total cost of two energy systems, which include investment costs and operational costs of all generator units and natural gas production, storage, and transportation [61, 62].
2) Maximizing the energy benefits. As the energy supply network of the EI, minimizing losses in the natural gas system and the electricity system is also an important optimization objective in their coordinated planning [63].

3.2.2 Constraints

In the integrated natural gas and electric power system, besides the electric power system constraints described in Sect. 2.2.2, the following constraints related to natural gas systems are considered.

1) Gas flow balance constraint [66, 67]. This constraint requires that the sum of gas production is equal to the total consumption including any losses.

2) Gas transmission constraints, mainly referring to the strength and stability constraints for pipelines and their gas flow constraints [64].
3) Natural gas capacity constraints, i.e., the capacity constraints of gas production units and gas storage [62].
4) P2G constraints, mainly including the cost and technical constraints of P2G facilities. The former comprises investment costs, operational costs and maintenance costs of P2G. The latter mainly includes the constraints related to carbon dioxide and hydrogen, such as hydrogen storage constraints and carbon dioxide capture constraints. Although P2G technology is costly at present, it may become one of the cheapest ways to produce energy in the future [65].

3.3 Planning and scheduling methods

3.3.1 Deterministic methods

In the field of deterministic optimization, state-of-the-art models are mainly aimed at minimizing the investment and operational costs and optimizing the capacity and location of new facilities. Different methods and models have been presented based on MILP [66–69]. For instance, a long-term and multistage model for supply and interconnection expansion planning of integrated electricity and natural gas networks was proposed in [67] to determine the optimal location of new facilities; Unsihuay *et al.* presented another integrated planning approach for hybrid power and natural gas systems [69]; and an energy hub and coupling matrix were proposed in [70–72] to achieve the optimal energy conversion between gas and electricity. The goal was to minimize the operational costs of the two networks. Particularly, this method can be used for more than two energy systems and a notable example is shown in [72], in which optimal operation of multi-energy systems was investigated through the coupling matrix method.

3.3.2 Methods for handling uncertainties

Besides the uncertain factors of the electric power system, the uncertainties of the integrated natural gas and electric power system also include the failure of pipelines, gas production and gas demand, and the gas price. As shown in Table 2, the operation and planning of this integrated system is approached mainly by two methods. The first one is the probabilistic method. For instance, a two-stage stochastic programming method was proposed in [73] for optimal security-constrained unit commitment in hybrid hydro and natural gas systems. Also, this method was used in [74] to evaluate the effect of emergencies in integrated power and natural gas system. Sun *et al.* adopted a three-point estimate

Table 2 Summaries of the methods in the integrated energy systems

System	Deterministic method	Major methods for handling uncertainties		
		Probabilistic methods	Non-probabilistic methods	
			Fuzzy method	Interval based method
CCHP-related system	[34–39]	[42–45]	[46–52]	[53]
Integrated natural gas and electric power system	[66–72]	[73–75]	\	[76]
Integrated electric and traffic system	–	[91–95]	[96, 97]	[98, 99]

method based on the Nataf transformation to tackle the uncertainty of and the correlation between different energy loads to minimize total cost [75]. The other one is the interval optimization based method. In this context, Bai *et al.* [76] proposed an operating strategy based on interval optimization for integrated natural gas and electric power systems to improve the overall system operation and optimize the energy flow. In the proposed model, wind uncertainty and demand response were also considered and wind power uncertainty was represented using intervals.

Since most optimization models just take the sum of investment costs and operation costs of the two systems as the objective function, and rarely consider the stability of the integrated system, their optimization results are not comprehensive enough to assure secure as well as economic operation.

4 Operation and planning of integrated electric and traffic system

4.1 Integrated electric and traffic system

EVs and charging facilities are becoming an important part of city planning and infrastructure in many countries, and the plug-and-play of EVs has a significant impact on the Energy Internet. Taking EVs and charging facilities (e.g., charging piles and charging stations) as the bridge, the interaction between the electric distribution system and the traffic system is deepening constantly. On the one hand, EVs in aggregation can act as large-scale distributed energy storage devices to contribute to system regulation such as stabilizing the fluctuations of DGs [77] and shifting peak load [78], and on the other hand, the randomness of EV charging can compromise the stability of the electric power system [79, 80].

Up to now, many studies have been carried out and different mathematical models have been developed for the operation and planning of integrated electric and traffic systems. This research mainly focus on two major aspects. One is the coordinated operation of EVs and the power grid. It generally includes investigating the impact of EVs on the electric power system, the optimal scheduling of EV charging, stabilizing the fluctuations of DGs, peak demand and frequency control through EVs, and so on [78–80]. The other aspect is the coordinated planning of integrated electric and traffic systems, which mainly refers to planning of charging stations [81–84] and power system planning with EVs and charging stations [85–88]. Since the optimal location and sizing of charging stations could minimize the total costs of charging stations while satisfying the charging demands of EVs and supporting the optimal distribution network expansion planning, it could be one of the most important research topics to be studied in depth for the EI.

4.2 Objectives and constraints

4.2.1 Objective function

As discussed above, different models have been established for the operation and planning of integrated electric and traffic systems, and the objective functions generally aim to achieve:

1) Stabilizing the fluctuations of the electric power system [80]. This mainly refers to stabilizing the renewable power generation fluctuations and load fluctuation. Although the randomness of EV charging can compromise the stability of electric power system, the aggregated impact of EVs can contribute to system regulation as large-scale distributed energy storage to stabilize the fluctuations of DGs and shift peak load, using V2G technology.

2) Optimal planning of charging stations [83, 84]. This refers to the optimal locating and sizing of charging stations and includes both the total costs and the social benefits. Therefore, the objective function includes the investment costs, operational costs and maintenance costs of charging stations, the cost of network losses, and charging costs to users. In general, it can be formulated as:

$$C_A = C_1 + C_2 + C_3 + C_4 \tag{3}$$

where C_1 is the investment cost of charging stations; C_2 is the operational costs and maintenance costs of

charging stations, including the staff salaries, equipment depreciation costs, and equipment maintenance costs; C_3 is the network loss costs; and C_4 is the charging costs to users, which can be measured by the journey to charging stations and the waiting time at them. It measures the service capacity of charging stations, and is influenced by the traffic network and traffic flows.

4.2.2 Constraints

Corresponding to the objective functions mentioned above, the integrated electric and traffic system constraints include electric power system constraints (similarly to Sect. 2.2.2) and traffic-related system constraints, with the latter including:

1) Charging station constraints. These include the capacity constraint of charging lines, the capacity constraint of substations, and the constraints of charging devices [84].
2) Electric vehicle constraints. These include the capacity constraint of EV batteries, the charging power constraints of EVs, and the V2G power constraints [89, 90].
3) Traffic network constraints. The traffic system and the electric power system have complex mutual influence. Traffic flows can affect the planning of charging stations and the construction of the power system. In turn, the distribution of charging stations also influences traffic flows. Traffic flows are also greatly affected by user behavior and charging strategies. Therefore, the operation and planning of integrated electric and traffic systems is mainly constrained by traffic flows, traffic congestion levels, the road conditions and the potential to extend the road network, user behavior, weather conditions, and other factors [84, 85].

4.3 Mathematical methods

The randomness of EV charging behavior introduces inherent uncertainty to an integrated electric and traffic system, and deterministic planning methods cannot be used. Methods for handling uncertainties in an integrated electric and traffic system can be classified into two major categories as follows.

4.3.1 Probabilistic methods

Probabilistic methods have been widely used in optimizing integrated electric and traffic systems, such as the two-stage optimization method [91, 92], the chance constrained optimization method [93, 94], and the point

estimate method [95]. For instance, a two-stage optimization method was proposed in [91] to minimize the energy losses in a microgrid with different penetrations of hybrid EVs (HEVs). In the first stage, a convex quadratic objective function was established for active power management of HEVs, and the daily energy requirement of HEVs was calculated from a stochastic model of their owners' behavior. Then, the second stage managed reactive power of HEVs when employed as capacitors. In addition, Waqar et al. presented a multi-objective chance constrained programming model to investigate the economic implications of V2G on microgrids containing renewable energy sources and to optimize their operational planning [93].

4.3.2 Non-probabilistic methods

Fuzzy logic methods are often used to account for uncertain factors when determining the location of charging facilities and strategies for energy management [96, 97]. In [96], the fuzzy TOPSIS method was applied to select optimal locations for EV charging stations. Using multi-criteria decision making, [96] established an evaluation index system for charging station site selection, which includes environmental, economic and social criteria.

Interval-based methods also play an important role in the optimization and scheduling of integrated electric and traffic systems. For instance, a new method based on robust optimization was proposed to plan sustainable integration of HEVs into the electric grid in [98]. Interval power flow analysis was used in distribution system optimization to achieve the dispatch of each electric vehicle charging based on the statistical model [99]. In that work, a cluster-based strategy was proposed for the scheduling of EV charging, in which uncertainties such as charging power were modelled by intervals.

Several analysis methods have been developed for planning charging stations and for planning distribution systems with charging stations. However, they are usually based on existing road networks and traffic flows, which may not be sufficient for practical application. Although the traffic flow, traffic density and road network models have been proposed in [84, 85], additional research is needed on implications for road network planning, the impact of weather conditions, and other issues.

5 Research prospects

Building on information technology trends such as the Internet of Things (IoT), Big Data, cloud computing, real-time user interaction, etc., the Energy Internet represents the evolution of an integrated energy system with diverse

structure, clean energy sources, electrified consumption and intelligent operation. Although the Energy Internet is promising and some of its operation and planning problems have already been investigated, there are still many crucial technical obstacles to be resolved, such as developing energy storage devices of large capacity and low loss, or an energy transmission system of high efficiency and low cost, or energy conversion and transformation components with the intelligence and flexibility of information system components [100–106].

In view of different technical issues and trends relating to the EI, the main directions of future research should be as follows.

1) Optimal coupling of multi-energy systems. The coordinated coupling between subsystems of the EI allows the synergy of different energy flows to economically and securely deliver heating, cooling, gas, traffic, and electric energy. Therefore, high-efficiency energy transformation devices and the interaction pathways they enable between different energy systems should be studied in depth, especially low-cost P2G technologies and impacts. Coordinated operation and planning models for multi-system coupling should be approached through quantitative analysis of energy balance, environmental impacts, and other societal benefits and costs. In this context, using realistic energy network topologies, the role of different subsystems and their uncertainties in corresponding interaction models among multiple systems should be evaluated; e.g. renewable DGs, traffic flow, weather conditions, energy markets and demand response.

2) Advanced information and communication systems for secure operation of the Energy Internet. For real-time optimization of integrated energy systems and for coordinating large numbers of distributed devices, a large computing capacity is needed to deal with huge amounts of diverse energy data. Thus, it is important to develop advanced information and communication technology (ICT) for application to integrated energy systems, e.g. Big Data, IoT, cloud computing, cloud storage, and block chaining for the Energy Internet. Since energy flow and information flow are tightly coupled, Energy Internet cyber systems should be further investigated to overcome technical obstacles in data association, information collection and secure dispatch, and real-time control in multiple energy markets.

3) Unified network codes and coordinated national management and promotion policies for a global cyber-energy system. In an open and competitive market, it is crucial to establish and develop a secure and highly efficient global Energy Internet. Therefore, international cooperation is required to unify network codes, planning standards, energy transformation devices and information system interfaces. The same cooperative process should also coordinate different national firewalls, energy laws, management systems, and development policies. Although the ideal of global energy interconnection has been established [107], more work is needed to strengthen international collaboration towards the Energy Internet. Because existing studies about the Energy Internet are at the stage of theoretical research, corresponding engineering standards for a global Energy Internet are necessary for further progress.

4) Demonstration projects of new functionality for the large-scale EI. Some practical demonstration projects have been already built to validate the feasibility of the Energy Internet, especially relating to the integration of DGs and EVs. For example, the Shenzhuang Industrial Zone distributed energy station in Shanghai [108] has been built as a micro-EI to provide heating, cooling and electricity for the industrial zone. The Tianjin Eco-City and Smart Grid Demonstration Project was established by State Grid Corp. of China in 2014 [109], in which the interconnection and sharing of energy and information has been achieved across DGs, CCHP, energy storage, EVs, demand response, an information network, and a data platform. These projects demonstrate the feasibility of developing the Energy Internet and provide a practical foundation of experience. However, they are micro-EIs based on distributed energy. In the future, using information technologies such as Big Data and cloud computing, some demonstration projects are needed to promote the development of the large-scale Energy Internet.

6 Conclusion

The supply structure is one of the most vital elements that influence the energy systems and environment. Through the continuous development of the Energy Internet, a convergence of distributed energy sources, diverse forms of energy including gas, heating, cooling, and electricity, and supported by the data internet, will lead to a sustainable multi-energy system. Based on the analysis of an Energy Internet framework, this paper focuses on three examples of coupled energy systems, and analyzes state-of-the-art operation and planning methods applicable to each. Four main directions of further research prospect address the key challenges of optimal coupling, cyber systems, unified standards, and large-scale demonstrations. Though

research into the Energy Internet has only just begun, it is one of the most important topics in energy nowadays and worthwhile for the research community to pursue.

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