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Energy internet: concept, structure and its potential future development in China

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Abstract

Traditionally, different energy systems are planned and scheduled individually. However, at present, with the pressure of energy crisis and the development of novel energy conversion technologies, such as natural-gas unit, combined heat and power (CHP), the concept of energy internet (EI), which combine different types of energy carriers, such as electricity, natural gas, and district heating (DH) networks, through cyber network, is proposed. The aim of this paper is firstly to introduce the definition, main components and its typical framework of EI. Then, this paper briefly discusses the application of EI in the whole world. After that, China is chosen as a typical country to analysis main features according to statistics. According to the features, the challenges of future energy development in China can be obtained. Finally, the paper explains the potential of EI for energy challenges in China and provides future EI development plan in China.

Keywords: Energy internet, Energy carriers, Cyber network, Renewable energy, Energy distribution

1. Introduction

In the 21th century, human production and activities have great demand on energy. However, the inefficient use of large-scale fossil energy has caused energy waste and huge pollution to the environment. The pressure of energy crisis and environment pollution has prompted people to reconsider the existing mode of energy generation, transmission and consumption [1-2]. Therefore, in the future, there will be a significant shift in the ways in which different types of energies are produced, transported and consumed.

Traditional methods of generation, such as large-scale dispatchable coal-fired units, are now complemented by a range of dispatchable low-pollution natural-gas units and non-dispatchable intermittent renewable energy sources. Primarily, this has been brought about by growing recognition of the health problems associated with environmental and air pollution [3]. A number of countries have set ambitious renewable energy targets. For instance, some countries, such as Sweden, aim to derive 100% of their energy from renewables by 2040 [4]. In China, the future development of China's renewable energy can be divided into three stages: the first stage is to realize the part of renewable energy technologies commercialization by 2010. In the second stage, by 2020, most of new energy technologies have reached the level of commercialization, which accounts for more than 18% of the total primary energy consumption. The third stage is to commercialize all the renewable energy and replace fossil energy on a large scale. By 2050, the total energy consumption will reach more than 30%.

However, most viable methods of renewable energy generation for power systems, including wind generation and solar PV generation, have several shortcomings. The first issue is their cost-effectiveness. This is being addressed through ongoing research and development into the design and deployment of renewable energy technologies. The second issue relates to the uncertainty and uncontrollability of wind and PV generation, which is more difficult to solve because of the intermittent nature of the wind and solar resources that these technologies attempt to harness [5-7].

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With the development of advent energy conversion technologies, such as natural gas-unit and power to gas (P2G) technology, different types of energy system are becoming increasingly strongly coupled. For example, in the transmission process, the gas-fired generators are constrained by capacity and transmission rate of gas pipelines [8] and power to gas (P2G) technology can transform the redundant electricity to natural gas, which set up the connection between electricity grid and natural gas network [9]. In the consumption side, different types of energy are optimally chosen to fulfil the consumers' demands with advent technologies, such as demand response and energy storage [10-11]. When the electricity price is high, gas can be used for cooking and heating instead of electricity [12].

Given the present situation, researchers from different countries have sought to explore new ways to combine different types of energy system, such as electric power system, heating system and natural gas system, to coordinate, reschedule and operate optimally the whole system, which can accommodate more renewable generation, and increase the efficiency of existing energy networks. Recently, a new concept, known as Energy Internet (EI) [13] is proposed to reform the energy industry in order to further enhance energy system efficiency, as well as flexibility. Under an EI, different types of energy systems can be co-scheduled based on the cyber network with supporting of energy storage and conversion technologies. As energy storage and conversion technologies developing, an integrated approach to the use of multiple energy resources may provide valuable opportunities, helping to increase the flexibility of modern energy systems. For example, combined heat and power (CHP) can be used to generate both heat and electricity at low gas price. P2G technology and energy storage can be used to store surplus electricity from intermittent sources. This has two key benefits. First, energy that may have otherwise been curtailed is utilized. Second, there is greater flexibility within the system to meet the load.

In this paper, a comprehensive review of the concept of EI is provided, along with its core elements and typical future framework, and the potential future development of EI in China is also discussed. The paper covers the following aspects: Section 2 gives an introduction of EI, its core elements including conversion and storage technologies, and information and communications technologies (ICT) for the monitoring and control of the system, and typical framework of EI system, which show the relationship between physical and cyber networks. Section 3 shows the application of EI in the whole world. Section 4 discusses main features of China's energy distributions including low per capita possession, reverse distribution of energy supply and consumption and lacking of coordination of different types energy system to analyze the its possible future energy challenges. Section 5 compares the main features of EI and China's energy challenges to illustrate the potential of EI in future energy development. And future development plan of EI in China are also discussed. Section 6 contains the concluding remarks.

2. The Structure and Concept of EI

The concept of EI come from smart grid proposed by EPRI in 2002. Then, in 2008, North Carolina, USA Lowry State University Research Center imitates the router technology in the information internet and proposes the concept "energy router". The prototype experiment is carried out, in which the power electronic technology is used to control the transformer and the routers are connected to each other to realize peer-to-peer synchronization based on communication technology. This is the first time to realize the interaction between information flow and energy flow at the level of distribution network. In 2012, the concept of "energy internet" was mentioned in the book "Third Industrial Revolution". In this section, we introduce the definition of EI and its core elements.

2.1. The concept and its main features of EI

An EI can be considered as a new and comprehensive network that unifies existing different types of energy systems, such as electrical power, gas, and heat networks etc., based on the cyber network [13]. On the supply side, this networked system facilitates higher levels of renewable energy penetration. On the demand side, it connects vast spatially distributed end-users who are capable of generation, storage and production of energy. An EI's ability to manage multiple energy resources can help solve some of the most pressing challenges facing today's energy systems, in particular the effective large-scale integration of renewable energy resources into existing energy systems. And the main features of EI are listed as follows:

- The Intelligence is integrated in the energy production, transmission, storage, consumption, and energy sale market.
- The distributed renewable energy, energy storage and micro energy grid are included in the EI.
- EI is a two-way energy sharing network. Power generation devices, energy storage devices and other loads can be accessed to the system at any time. The loads can be balanced in time.
- EI can realize the effective energy allocation in a large area and low-loss energy transmission.

2.2. Core elements in the EI

1) Multi-generation facilities

The main generators in the electricity grid of MES include coal-fired generator, hydraulic generator, wind generator, and photovoltaic (PV). Gas well is the main gas supply for natural gas network, which is constrained by output power limitation [14]. Coal-fired (gas-fired) boiler is one of the main heat sources for traditional district heating systems. However, because of its low energy conversion efficiency, small capacity and serious pollution, the boilers are gradually replaced by thermal power units, CHP and electric boilers [15]. The output of CHP and thermal power units are constrained by thermoelectric coupling characteristics [16-17] and electric boilers are constrained by output power limitation and energy conversion efficiency.

2) Energy storage

The storage technologies allow energy to be stored when supply exceeds demand and support energy to the system when demand is greater than supply. In effect, storage technologies increase the temporal flexibility of energy systems [18], and are particularly important in the context of an MES with high levels of intermittent generation from renewable sources. In the absence of storage, excess energy must be curtailed if supply is greater than demand. For example, in China, nearly 15% of wind generation are curtailed during a year [19]. The most commonly utilized storage technology in the world, comprising 99% of installed storage capacity, is pumped hydro storage (PHS). In the natural gas network, natural gas tank is the main energy storage, which can be used to adjust the gas congestion and store the redundant gas.

3) Conversion technologies

The energy conversion devices add connections in different types of energy system. Table 1 list the main examples of energy conversion elements.

Table 1. Typical energy conversion elements in EI

Energy conversion device	**Input energy**	**Output energy**
CHP	Gas	Electricity, Heat
CCHP	Gas	Electricity, Heat, Cooling
Renewable generator	Renewable energy	Electricity
Transformer	Electricity	Electricity
Gas boiler	Gas	Heat
Compressor	Gas	Gas
Electric heater	Electricity	Heat
Absorption chiller	Heat	Cooling
Compressor chiller	Electricity	Cooling

4) ICT framework

In the EI, information and communications technologies (ICT) will be the medium that links different energy systems, and helps coordinate and manage the use of energy by consumers. Similar to a smart grid, at the customer level, advanced metering infrastructure (AMI) will be employed with home area network (HAN) used to connect end-user devices. The information collected by AMI at the customer-level within a HAN can be used by distribution retailers, also known as load serving entities (LSE). Similarly, LSEs, large energy consumers, and energy suppliers can be connected through an optical fiber network, PLC and digital microwave technology. With respect to managing this information, a centralized control structure could be implemented, with information sent to a single data center that will control energy suppliers and consumers. Alternatively, information could be sent to multiple data centers using a distributed control framework to coordinate energy flows within the system. Overall, the whole EI converged information physics system is illustrated in Fig.1.

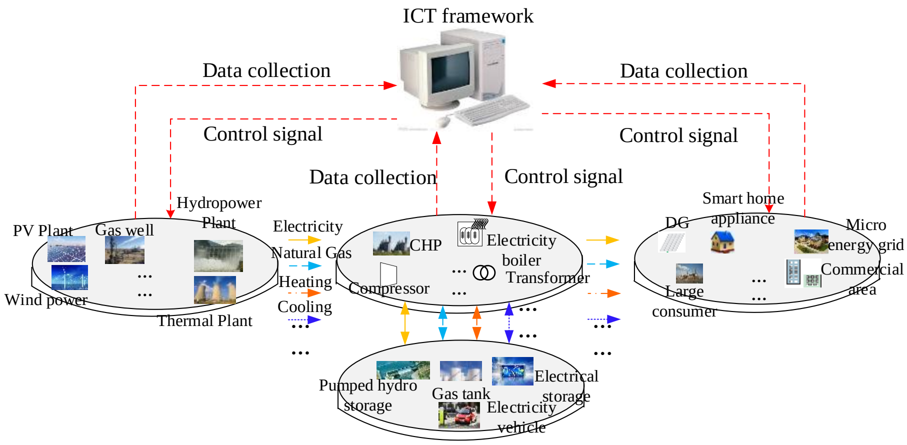

Fig. 1. Typical framework of EI system.

3. The Development of EI in the World

EI plays an important role in increasing energy use efficiency and exploiting a large scale of renewable energies. Many countries make their own plan for EI development according to their features. Up to 2019, there are at least 70 countries or regions in the world today start the research studies related to EI system with the aim of promoting sustainable energy supply in the future [20].

3.1. United States

In the past 30 years, the united states is in the forefront of internet industry and has rich experience in operating the internet. Therefore, the united states want to combine this advantage with energy industry to provide a solution for energy sustainable development. In 2001, the United States proposed an integrated energy system development plan with the aim to promote the distributed energy resource and CHP technologies [21]. In 2007, America promulgates Energy Independence and Security Act (EISA) to request the integrated resource planning (IRP) for energy supply and consumption in main sectors of the country [22]. President Obama put the establishment of smart grid into the U.S national strategy in his first term, aiming to build a high-efficiency, low-investment, safe and reliable EI on the basis of the smart grid.

3.2. Canada

Canada congress have issued a series of reports “Combining our energies: Integrated Energy Systems for Canadian Communities” [23] and “Integrated Community Energy Solutions: A Roadmap for Action” [24] for building integrated community energy solutions (ICES) for the whole country with the aim to address the energy crisis and achieve the 2050 annual greenhouse gas emission reduction target. At the same time, many research projects have been initiated: Equilibrium Communities Initiative, Clean Energy Fund, eco ENERGY, Building Canada Plan, etc.

3.3. Europe

From 2003, Europe start the related researches about EI, such as VoFEN, District of Future, Trans-European Networks and Intelligent Energy, etc. Apart from the research within the framework of the European Union, some countries have carried out their own special studies according to their own features. For example, Engineering and Physical Sciences Research Council (EPSRC) in Britain launch a large scale of research projects in this fields, such as Multi-Vector Energy [25], Future FM and SIES&D

(Systems Integration of Energy Supply and Demand) [26], etc. with the aim to study the coordination of different types of energies and exploit the renewable energy.

3.4. China

At present, nearly 55 EI pilot projects in China, such as EI of subsidiary administrative center in Tong Zhou, basically started or will be completed. According to Accenture's forecast, by 2020, the overall market size of China's MES will exceed 940 billion U.S. dollars, which take account of nearly 7% of GDP that year. By 2050, the cumulative investment in the global EI market will exceed 50 trillion U.S. dollars. Apart from pilot projects, many 973, 863 projects are launched to study the EI core technologies and its application. For example, in 2016, research project “Energy internet design: planning, market and mechanism” is initiated. The project has analyzed the energy load characteristics of large energy consumers and provide an optimization scheme that can help reduce 10%~20% energy consumption of local areas. Considering China is the largest energy consumption market in the world, in this paper, the main energy features in China and its potential future development is discussed in the following section.

4. Main Energy Features in China

China is a country with substantial regional differences in economic development, technology, energy mix and demographic composition. The main feature of energy distribution in China is different from other countries, which is list as follows:

1) The total amount of energy is abundant, but the per capita possession is relatively low

Coal, petroleum and natural gas are the main traditional energy in China. According to the Statistical Review of World Energy 2014, the proven reserves of petroleum, natural gas and coal only account for the 1.07%, 1.76% and 12.84% of world’s total reserves and remaining recoverable years are 12, 28 and 31 years, respectively [27-30]. Considering the huge population base of China, the traditional extensive energy use style is unsustainable.

2) Fossil fuel is distributed in the region around Beijing and Tianjin, while renewable energy is mostly distributed in the northwest of China

Coal is the main fossil energy source in China, while coal reserves are mainly distributed in the North and Northwest areas of China. And province Shanxi, Shaanxi and inner Mongolia have the most abundant reserves. The main clean energy sources in China are solar energy, wind energy and water energy. In China, the distribution of solar energy is mostly concentrated in the Qinghai-Tibet Plateau, Northern Gansu, Northern Ningxia and Southern Xinjiang. Wind energy distribution is mostly concentrated in the middle and high latitudes of north and northwest regions, while water energy distribution is mostly concentrated in the Southwest area, Middle-south area and Northwest area of China. Table 2 lists statistical results of the top and last five provinces of energy resources distribution in China.

Table 2. Distribution of natural resource in China

Nature resources		Distribution and Percentage
Coal	Top 5 (71.6%)	Shanxi (30.2%), Inner Mongolia (27.6%), Xinjiang (5.3%), Shaanxi (4.3%), Guizhou (4.2%)
	The last 5 (0.12%)	Shanghai (0%), Tibet (0%), Zhejiang(0.02%), Hainan(0.03%), Guangdong(0.07%)
Petroleum	Top 5 (70.5%)	Heilongjiang (19.9%), Xinjiang(18.7%), Shandong(12.6%), Heibei (10.2%), Shaanxi(9.1%)
	The last 5 (0%)	Beijing (0%), Shanxi (0%), Shanghai (0%), Zhejiang(0%), Fujian (0%)
Natural gas	Top 5 (85.7%)	Xinjiang (24.6%), Inner Mongolia (20.4%), Sichuan (19.3%), Shaanxi(16%), Chongqing(5.5%)
	The last 5 (0%)	Beijing (0%), Shanxi (0%), Shanghai (0%), Zhejiang(0%), Fujian (0%)
Hydraulic power	Top 5 (73.5%)	Tibet (29%), Chongqing(20.7%),Yunnan(15%), Xinjiang(5.5%), Sichuan(3.3%)
	The last 5 (0.5%)	Beijing (0.1%), Tianjin (0.1%), Hebei (0.1%), Guangxi (0.1%), Fujian (0.1%)
Solar	Top 5 (60.3%)	Xinjiang(18.3%), Tibet (15.9%), Inner Mongolia (12%),Qinghai (9.2%), Sichuan(5%)
	The last 5 (1.4%)	Beijing (0.2%), Tianjin (0.1%), Shanghai (0.1%), Hainan (0.3%), Ningxia (0.7%)
Wind	Top 5 (73.4%)	Inner Mongolia (20.8%), Xinjiang(20.5%), Tibet(17.9%),Qinghai (9.3%), Heilongjiang (5%)
	The last 5 (0.8%)	Shanghai (0.1%), Beijing (0.1%),Tianjin(0.1%), Hainan(0.2%), Chongqing(0.3%)
Biomass	Top 5 (38.6%)	Sichuan (10.8%), Heilongjiang(7.5%), Yunnan (7.3%), Tibet (6.9%), Inner Mongolia (6.2%)
	The last 5 (1.6%)	Shanghai (0.2%), Beijing (0.3%),Tianjin(0.3%), Hainan(0.4%), Ningxia (0.4%)

3) The energy consumption center is located in the Central and Eastern district of China, especially eastern coastal province

The eastern and central regions of China have the most population of the whole country, and also accounts for the largest proportion of the whole economic output of the country. From the perspective of energy consumption, the central and eastern region of China concentrates 75% of the coal-fired power units, and the regional energy consumption accounts for more than 75% of the national energy consumption. Table 3 lists the GDP rank of provinces in China, which can be considered as a reference index of energy consumption.

Table 3. GDP data for all provinces of China in 2018

Serial number	Province	GDP/Billion (RMB)	Serial number	Province	GDP/Billion (RMB)
1	Guangdong	9727.78	17	Chongqing	2036.3
2	Jiangsu	9259.54	18	Guangxi	2035.2
3	Shandong	7646.97	19	Tianjin	1880.9
4	Zhejiang	5619.7	20	Yunnan	1788.1
5	Henan	4805.5	21	Inner Mongolia	1728.9
6	Sichuan	4067.8	22	Shanxi	1681.8
7	Hubei	3936.6	23	Hei Longjiang	1636.1
8	Hunan	3642.5	24	Jilin	1507.4
9	Hebei	3601	25	Guizhou	1480.6
10	Fujian	3580.4	26	Xinjiang	1219.9
11	Shanghai	3267.9	27	Gansu	824.6
12	Beijing	3032	28	Hainan	483.2
13	Anhui	3000.6	29	Ningxia	370.5
14	Liaoning	2531.5	30	Qinghai	286.5
15	Shaanxi	2443.8	31	Tibet	147.7
16	Jiangxi	2198.4			

4) Reverse distribution of energy consumption center and resource center

Reverse distribution of energy resources and energy consumption area in China have resulted in the demand for large-scale energy dispatching. In the fossil fuel dispatching, the establishment of thermal plant near the energy resource and fossil fuel transportation are two tradition ways to solve the contradiction of energy supply, which cause the environment pollution and transmission losses. In the renewable energy, wind and solar abandonment phenomenon is obvious, because of the constraints from the capacity of transmission lines and local absorption.

5) Lacking of coordination in electricity, heat and cold system

In China, different types of energy systems operate separately. Compared to the power transmission network, power distribution network and heating system are relatively backward. Without intelligent and effective control devices, it is difficult to properly coordinate different types of energy systems. The central cooling schemes are rarely adopted in China's regions. However, as an advanced cooling mode, its high energy efficiency and low carbon emission has gradually aroused people's attention.

5. The Potential Future Development of EI

5.1. Potential future development of EI in China

According to the above analysis, the main challenges of China' s energy development includes four parts: a) The existence of geographical mismatch between energy consumption centre and energy resource centre, i.e., coal resources are close to densely populated areas, while clean energy is far from load centres. b) Although water, solar and wind energy are abundant, fossil fuels are dominant in the energy consumption. c) Clean energy and distributed generators (DGs) are difficult to access the energy system. A large amount of wind and solar energy are abandoned. d) Low energy efficiency. For the above problems, the EI is the efficient solution, as shown in Table 4.

Table 4. The features of EI correspond to China's energy challenges

Features of EI	Challenges in China's energy
Long-distance energy transmission	Geographical mismatch between energy consumption center and energy resource center
Intelligent load adjustment	Clean energy and distributed generators (DGs) are difficult to access the energy system
Multiple end users	Fossil fuels are dominant in the energy consumption
Energy allocation based on market-oriented method	Low energy efficiency

5.2. Future EI development plan in China

In the future EI, the development of EI includes three aspects: a) **Energy flow**: improving physical layer including energy converters and multi-energy generations. b) **Information flow**: establishing high efficient and intelligent ICT layer including data acquisition monitoring system, cloud-based data analysis and mining, artificial intelligent energy flow management and safety assessment and control management (information). c) **Value flow**: constructing a new EI finance including multiple trading entities, multiple energy transaction modes and multiple energy consumption areas. In the future, China will establish a novel three-layers EI basic framework including energy flow, information flow and value flow.

6. Conclusions

Under the situations of the global energy crisis and environment pollution, the development of EI will inevitably lead to significant changes in the process of energy generation, transmission and consumption. This paper firstly introduces the main features of EI and its core element including multi-generation facilities, energy storage, energy conversion technologies and ICT framework. Then, this paper summarizes the main application of EI in the world and mainly focus on the main features of China's energy. According to the China's energy features, the potential of EI can be concluded to solve the related problems. Finally, the future EI plan is provided including three layers: Energy flow, information flow and value flow.

Conflict of Interest

The authors declare no conflict of interest.

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