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Full-length article

Development of the interconnected power grid in Europe and suggestions for the energy internet in China

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Abstract: The European power grid is one of the largest regional interconnected power grids in the world. It realizes a multinational grid operation, which is rare. The total installed capacity of the European power grid is the largest throughout the world. In addition, the integration and utilization of renewable energy in this grid is a great benchmark for other countries and can help promote energy transformation and achieve a high proportion of renewable energy consumption. Based on the analysis of the existing status of the European interconnected power grid and the development history of this power grid, this paper summarizes four key development stages of the European power grid. In addition, the characteristics of each stage and the development prospect of the European power grid are analyzed. On this basis, this paper gives suggestions for the development and construction of China's energy internet; this can provide valuable reference for further studies on China's energy internet.

Keywords: European interconnected power grid, Energy Internet, Renewable energy.

1 Introduction

For a long period, the development of human civilization and industry was supported by fossil energy. However, it led to many significant challenges in terms of energy supply, environmental pollution, resource allocation, and efficiency. The achievement of a sustainable economic development under strict constraints of limited resources and environmental protection has become one of the most important topics in the world [1]. A power grid, as the transmission carrier of electrical energy, experiences hundreds of years of development to meet the growing demand of energy and electricity. The European power grid is one of the largest power grids in the world with the longest development history, the most interconnected countries, and leading development in renewable energy. It is a great model for other countries to promote energy transformation and achieve high proportion of renewable-energy consumption. Therefore, in-depth study is required on the development history, current situation, and future trends of the European power grid, and it can be a good reference for construction of China's and even global power internet.

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2 Current situation of the European power grid

The European power grid covers most European countries, including Germany, France, and other continental countries; Nordic countries such as Sweden, Finland, and Norway; and island countries such as the UK and Ireland. The European power grid, as one of the largest power grids, is composed of five main synchronous networks: the continental synchronous grid, Nordic synchronous grid, Baltic synchronous grid, British grid, and Irish grid. The five synchronous grids are DC interconnected to form the European interconnected power grid, which is managed by the European Network of Transmission System Operators (ENTSO-E). The coverage of each synchronous grid is shown in Table 1. The grid covers 34 countries, with a total area of about 5.11 million km^2, a population of about 513 million, total GDP of the approximately $18.8 trillion, and per capita GDP of about $36,600, as of 2018 [2, 3].

Table 1 Members and areas of interconnected power grids in Europe

Name	Members	Area (10^4 km^2)
Continental synchronous grid	France, Germany, Spain, and 21 other countries	344.9
Nordic synchronous grid	Norway, Sweden, Finland, and central Denmark	117.5
Baltic synchronous grid	Lithuania, Latvia, and Estonia	17.5
British grid	UK	24.5
Irish grid	Ireland	7

European countries are generally small, with higher load density and uniform load distribution; therefore, the structure of the European power grid is always relatively dense and compact. The voltage levels of transmission lines in most western European countries, such as Germany, France, and the UK, are mainly concentrated in 220 (225/275) kV and 380 (400) kV. Low-voltage transmission lines are still utilized in only a few countries such as Cyprus, Estonia, and Lithuania. In the eastern European countries near the Baltic Sea, the 330 kV voltage level is still reserved, as their power grid system is part of the former unified electric power system of the Soviet Union. By the end of 2018, the total length of the AC transmission lines above 220 kV was more than 310,000 km. Moreover, the lengths of the lines below and above the 380 kV transmission lines reach 132,000 and 181,000 km, respectively.

Except for Iceland and Cyprus (with independent power transmission systems), all the member countries of ENTSO-E exchange electricity with their neighbors. In 2018, the amount of total power exchange by the ENTSO-E (the sum of imported and exported power, including the power exchange between the members of ENTSO-E and peripheral non-ENTSO-E countries) was 902 billion kWh. Among the exchanges, the power imports and exports were calculated at 458 and 444 billion kWh, respectively, which results in a balance (import − export) of about 15 billion kWh [4].

3 Development history of the European power grid

Earlier, the networking process of the European power grid interconnection was driven by the economic situation, political factors, and energy-development strategy. The scale of the power grid constantly expanded from the power exchange between two countries to a multinational interconnection. The ability to optimize the allocation of resources has also been continuously strengthened. The development of the European power grid underwent four stages: the origin of the power-grid technology, gradual establishment of power grids in different countries, formation of the European transnational interconnected power grid, and realization of transcontinental interconnection.

3.1 Origin of the power-grid technology (late 19th century)

In the late 19th century, the development of the European economy promoted the innovation and breakthrough of science and technology and accelerated the advancement of the industrial revolution. In this period, the “age of electricity” replacing the “age of steam” was an important advancement in the new breakthrough of science and technology. With the arrival of the electric era, transmission technologies began to be developed.

In 1882, De Bolltes delivered 1.5 kW of electric power generated through the Miesbach coal mine steam engine to an area that was 57 km away through a DC 1500–2000-V transmission line, which led to the creation of a high-voltage European transmission line.

In 1891, Miller demonstrated the power transmission system from the Laufen valley to Frankfurt with a transmission voltage of 25 kV, power of 230 kW, and total length of 178 km, which fully showed the advantages of AC power technology. Subsequently, the three-phase AC power technology developed rapidly and dominated the field of power technology.

3.2 National grid: gradual shaping of weak transnational power links and small scale of power border trade (early 20th to mid-20th century)

3.2.1 Development of power grid

Since the 20th century, the European economy maintained high-speed development. In 1913, the European industrial production accounted for 48% of the world's total production, and electricity became the basic power for economic development. To meet the rapidly growing demand of electricity, reduce the cost of power supply and achieve the optimal allocation of resources, the development of an internal power grid in the European countries has gained considerable interest. For example, in the 1920s, the main load center of Great Britain was located near London. The electric power-generation structure was dominated by coal power, which was distributed throughout the coal mining areas in central England and Scotland. In 1926, the UK realized long-distance transmission of electricity from central England to London by using a 132 kV transmission line, thereby reducing the price of electricity in the London region by two-thirds of the original amount within 10 years. In 1930, a 132 kV grid was constructed in the UK that simultaneously implemented the standardization of operational frequency of the grid, specifying the AC power grid frequency to 50 Hz; this initiated the formation of the national AC synchronous power grid [5]. Fig. 1 presents the British 132 kV grid framework.

Fig. 1 Diagram of British the 132 kV power grid in 1932

With the establishment of internal power grids in various countries, the power trade between neighboring countries began to emerge. Some European countries started to consider interconnection with neighboring power grids. In 1906, Switzerland, France, and Italy built the earliest transnational lines in Europe [6]. In 1921, France, Switzerland and Italy realized preliminary interconnection between power grids in the adjacent border, allowing for the transmission of electricity from Nancy, France through Switzerland to Milan, Italy. In 1930, Belgium, Germany, Switzerland, France, and Italy began planning to build transnational interconnected power grids [7].

3.2.2 Characteristics of power-grid development

(1) The interconnection between power grids exists mainly within a country to meet the electricity demand of the load centers from the internal power supply. Power transmission was limited to a short distance and a small scale. To reduce the cost of power generation, large power plants were generally located in areas rich in coal, oil, and water resources. In addition, the electricity was transmitted to the load centers through domestic interconnection transmission grids, thereby satisfying the requirements of electricity consumption and realizing power-generation resource sharing, reduced investment, and low-cost electricity.

(2) The scale of the transnational interconnection grid was generally small. Furthermore, the interconnection was realized at the borders of different countries to meet the need of power trade. However, the power-exchange capacity was small owing to the limited interconnection scale.

(3) The institution and mechanism settings of the power cooperation organization had not been optimized. Many small power grids had been established as each European country built its own power grid around its own load center. Although some of these grids had small-scale interconnection, no coordinated multinational power cooperation organization and operation mechanism had been formed in terms of organizational management [8].

(4) Moreover, the electric power facilities were seriously damaged by Word War II, which retarded the power-grid interconnection process.

3.2.3 Characteristics of electrical power technology

As shown in Fig. 2, with the increase in transmission distance and capacity, the highest voltage level in Europe rose to 220 kV (225/275) during this period. In 1912, Germany built the first 110 kV transmission line, and in 1929, they developed the first 220 kV transmission line. In 1949, the first 275 kV transmission lines were implemented in the UK.

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Fig. 2 The update process of transmission voltage in Europe from the early to mid-20th centuries

3.3 Formation of European transnational interconnected power grid (mid- to late 20th centuries)

3.3.1 Development of the power grid

From the mid- to late 20th centuries, with the rapid growth in the economy, the transmission voltage level of the European power grid was further enhanced, and the capability and scale of the power-grid interconnection between countries were continuously improved. From 1960 to 1989, the per-capita electricity consumption in Europe increased by more than 3.7 times, from 1,400 to 5,200 kWh, as shown in Fig. 3 [9].

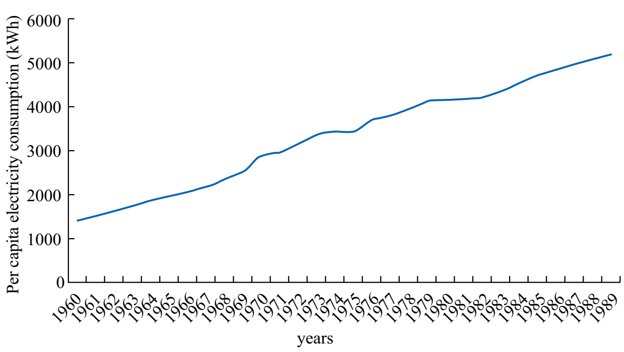

Fig. 3 Per-capita electricity consumption in Europe from 1960 to 1989

With larger-scale and longer-distance requirements for electricity transmission, to the end of the 20th century, major European countries implemented transmission networks of ⩾220 kV. The AC voltage level in some countries had increased to 400 (380) kV. In 1952, Sweden built the world's first 380 kV AC transmission line, successfully transmitting electricity generated by the northern Haas Prange hydropower plant to the southern load center in Stockholm. The length of the transmission line was 620 km with capacity of 450 MW. In 1957, Germany built the first 380 kV transmission line by boosting the voltage level, connecting the north-western Ruhr coal base and southern load center. From 1954 to 1960, to meet the demand of the electricity export of Tignes and Gynica hydropower groups in southeast France (via Lyon to Paris), France began to develop the 400 kV AC power-transmission technology.

Owing to a strong relationship between power supply structures in various countries, European countries developed a transnational power grid based on improved AC voltage levels [10]. After the oil shock in the 1970s, European countries changed their strategies for oil-fired electricity-generation replacement. France started developing nuclear power and built 13 nuclear power stations within two years. The UK focused on developing gas-fired power stations. Northern Europe kept increasing the proportion of hydropower. To realize the complementarity between generation structures, European countries had focused more on transnational interconnection. France developed transnational interconnection actively because of the high proportion of nuclear power, high pressure of peak load regulation, and low power generation cost. The 225 kV transmission line to Germany built in 1946 was the first grid interconnection line with surrounding countries. The first 400 kV transnational transmission line was built in 1964. Furthermore, the first DC transnational interconnection line was built in 1961 (with Britain; ±100 kV). By the end of the 20th century, France owned 46 transnational connections, 22 of which were of 400 kV, 20 lines were 225 kV AC, and 4 others were ±270 kV DC.

In 1951, France, Germany, Switzerland, Netherlands, Austria, Belgium, Italy, and Luxembourg (Union for the Coordination of the Production and Transport of Electric power, UCPTE) realized synchronous interconnection. In 1964, Spain and Portugal (Union for Franco-Iberian Production and Transport of Electric power) achieved synchronous interconnection with UCPTE through double-looped 400 kV AC circuits. In 1974, the former Yugoslav power grid was connected to the UCPTE through a single circuit with 380 kV AC transmission lines. In 1977, the Greek power grid was connected to the former Yugoslav, thereby allowing access to the UCPTE [11].

In the late 1980s, with the gradual expansion of the European continental synchronous region, 12 countries were interconnected, as shown in Fig. 4

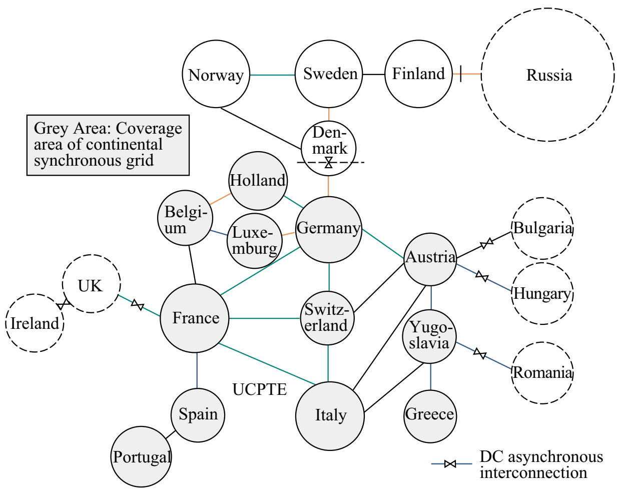

Fig. 4 Illustration of the power interconnection in Europe in the late 1980s

Within Europe, from the middle to end of the 20th century, the power grids of all European countries except those of Iceland and Cyprus, were interconnected and gradually formed five major synchronous grids, namely the continental synchronous grid, Nordic synchronous grid, Baltic synchronous grid, British grid, and Irish grid.

In the early 1990s, owing to the political influence of the disintegration of the former Soviet Union and the upheaval of Eastern Europe, the interconnection pattern of the continental synchronous grid was adjusted. From 1993 to 1995, the central European Union (EU) power grid, consisting of the grids of Poland, Czech Republic, Slovakia, and Hungary, disconnected from the former Soviet Union Power System and operated in sync with the UCPTE through nine newly built 400 kV AC transmission lines. In 1992, the former Yugoslav power grid was split into two synchronous regions: Croatia and Serbia. Romania, Bulgaria, and Hungary were connected to the continental synchronous grid via DC lines.

Restricted by geographical factors, such as the channel, the continental power grid was interconnected with the Nordic power grid, European continental grid, and British power grid through submarine cables. DC submarine cables were utilized to ensure transmission capacity and reduce difficulty in voltage control. From the 1960s up to the end of the 20th century, asynchronous interconnection among the five largest simultaneous grids in Europe was gradually established.

3.3.2 Characteristics of power-grid development

(1) The internal transmission networks were becoming increasingly interconnected. The rapid growth in the electricity demand accelerated the development of power grids. At this stage, the main network of each country's grid was enhanced, the AC voltage level was further improved, and the transmission grid was optimized.

(2) European countries placed immense importance on resource-allocation optimization, and considerable efforts were made for developing a multinational interconnected power grid. Considering the energy-development strategy and structure characteristics of each country, the development of the interconnected power grid was preferentially focused on the optimization of resource allocation among countries. At this stage, to meet the requirement of transnational transmission, Europe vigorously developed a transnational network.

3.3.3 Characteristics of electrical power technology

(1) Owing to the rapid growth of the power demand and the expansion of the power grid, efficient and large power-generation units were successively operated. The capacity of the single generation unit was continuously improved. Unit 4 of the German Hayden thermal power plant, which was put into operation in 1979 with a designed maximum capacity of 911,000 kW, was marked as the first million-kilowatt-scale single unit in Europe. The capacity improvement of the single unit required for a larger power grid with higher voltage levels.

(2) High-voltage direct current (HVDC) technology was applied to the transmission lines and power exchange between the European countries. In 1954, the world's first commercial HVDC transmission project, namely the Gotland project, began operating on the east coast of Sweden with a total length of 98 km. This project used the mercury-arc valve technology, with the voltage level of ±100 kV and total capacity of 20 MW [12]. In 1970, a thyristor technique was introduced in this project, which caused the voltage to increase to ±150 kV and the delivery capacity to reach 30 MW. By the end of the 20th century, there were several HVDC transmission lines for transnational interconnection.

(3) The AC transmission voltage level increased to 380 (400) kV. In 1952, the Swedish grid was updated to the 380 kV level. In 1968, the voltage level of the grids in Germany, France, and Switzerland was increased to 380 kV. In the late 1950s, France built the first 400 kV transmission lines.

3.4 Realization of transcontinental interconnection (since 1997)

3.4.1 Development situation of power grids

In 1997, the European continental power grid had achieved synchronous interconnection with Morocco, Algeria, and Tunisia in North Africa across the straits of Gibraltar from Spain through a 400 kV AC transmission line. In 2006, a second 400 kV AC transmission line was operated between Spain and Monaco. In 2010, the Turkish power grid was connected to the European power grid by using the smart grid technology.

In addition, projects, such as the DESERTEC, are being put forward. It proposes that interconnections between Europe and northern Africa countries can transport the rich solar-energy resources of Algeria, Tunisia, Libya, Morocco, other North African countries to Italy and southern Spain through a cross-sea power grid.

In terms of international-power-grid interconnection development and operation coordination, the EU integrated a unified alliance of transmission operators of ENTSO–E in 2008 to strengthen the planning and coordination of power grids in all member states. In addition, they achieved effective cohesion of national power control rules. Development plans, unified power-grid-operation control standards, and power trading rules were also formulated.

3.4.2 Characteristics of power-grid development

(1) The receiving end grid was relatively strong. In general, European countries have a small area and large load density. In the process of rapid economic growth, a receiving end system was formed around the big cities. Along with the increase in power consumption, the interconnection of power grids was gradually implemented to form a more intensive European power grid.

(2) The interconnection between the power grids provided interconnection benefits and allowed for the realization of a large power grid with superior complementary, reciprocal, and peak shaving resource sharing.

(3) The scale of the power grid was expanded, and the economy kept improving constantly. The European power grid followed the technology roadmap of “from small to large,” “from low voltage to high voltage,” and “from domestic grid to multinational interconnection.”

(4) Next, several voltage level sequences were implemented. In the early development period, the European power grid was built by the Regional Electric Company (electric power operators) with no unified planning and complex voltage levels. The highest AC voltage level was 400 kV. The AC transmission voltage level varied at 110/150, 220/285, and 380/400 kV, and the DC transmission voltage levels were mostly ±270 and ±400 kV.

(5) Considerable focus was provided to clean energy. The clean-energy consumption of EU accounted for 18.9% of the total energy consumption [13].

4 Development trend of the European power grid

Based on a comprehensive analysis of the European power grid, a 10-year development plan was published by the ENTSO-E [14], EU energy market plan, and European super smart grid plan. The future development trend of the European power grid would include the diversification and cleaning of energy. The goal of constructing the European power grid is to create a clean and smart power network to optimize the energy structure and promote strategic transformation of energy. A new energy revolution is being promoted in Europe. The EU has promised that by the end of 2020, 20% of electricity would be derived from clean energy and 80% greenhouse-gas emissions would be reduced by 2050, paving the way for the formulation of a “2050 energy roadmap” (Energy Roadmap 2050). The EU would consider this as an opportunity to propose the construction of a strong power internetwork before 2050 to achieve transportation of up to 50 million kW from southern Europe and North Africa to Germany and France to meet the clean-energy-consumption requirement.

(1) The backbone of the clean-energy-consumption network will be constructed from the aspect of transmission network. The regional and international main grids must be reconstructed and strengthened to adapt to the large-scale power flow. Many countries have put forward transmission network planning to promote clean-energy consumption. After abandoning nuclear power, Germany plans to build 45 million kW of wind power plants in the northern coastal areas during the period from 2020 to 2050. To replace the southern nuclear power unit, Germany plans to build four HVDC lines with maximum capacity of up to 12 million kW to allow for the transportation of clean energy power from the north to the south. In addition, Britain plans to construct 25 million kW of offshore wind power by 2020 and build five HVDC projects to transport clean energy before 2025.

(2) The intelligent distribution network is being vigorously promoted from the aspect of the distribution network. To improve the safe access of distributed clean-energy power generation, the future development of European distribution network will focus on the intelligent aspect. According to the “Vision and strategy of the European future grid,” the characteristics of Europe’s future smart grid would include flexibility, secure access, reliable power supply, and economy. The future smart grid will realize the interaction between users and power systems. The power flow in the distribution network can flow in two directions. Moreover, in the future open-market mechanism

of network operation, power system dispatching can be achieved by the market and would be unified supervised and operated in the EU, leading to both decreasing the cost and enhancing the security of system.

5 Enlightenment into China's energy internet development

Throughout history, the European energy development shows a tendency toward low carbon, high efficiency, and wide range of resource allocation. The development of an interconnected power grid in Europe follows the basic rule of increasing voltage level from low to high, interconnection range from small to big, and allocation capacity from weak to strong. The growing demand for electricity and the need of optimal resource allocation are powerful drivers for the development of the European grid.

Recently, the pace of global-energy-transformation development has accelerated. All countries are promoting the replacement of fossil energy with clean energy to realize strategic transformation based on clean energy [15]. From the viewpoint of clean-energy development, European countries consider a large power grid and power market as the essential parts of energy transformation.

China has become the largest producer and consumer of energy in the world. The energy resources in China can be described as "large portions of coal with less oil and gas as supplements" [16]. A distinctive imbalance exists between the distribution of resources and energy consumption [17]. In 2019, China's total energy consumption amounted to 4.86 billion tons of standard coal, in which coal accounted for 57.7% and clear energy, including natural gas, hydropower, nuclear power, and wind power, accounted for 23.4% of the energy. Massive exploitation of fossil fuels results in problems, such as resource shortage, environmental pollution, and climate change, which pose a serious threat to the sustainable development of society. With the increasing rise in carbon emission and environmental pollution, the demand for energy transformation and development in China has become significantly urgent. Therefore, the requirement to build China's energy internet and promote a clean and low-carbon energy system in China has become inevitable.

The development process of the European interconnected power grid has enlightened the development of China's energy internet from the following three aspects.

First, the interconnection of the power grid must be strengthened to optimize the allocation of resources.

In Germany, the annual electricity export almost tripled from 1990 to 2018, i.e., from 2643 to 6919 ktoe, respectively [18]. By 2018, Germany possessed 50 international transmission lines (⩾220 kV). Its interconnections with Austria and Switzerland are even more intense if 110–150 kV lines are included [4]. This export cannot be realized without a strong physical interconnection with other countries, and could result in a severe problem in system stability or constrains on certain transmission channels, thus limiting the trading capacity [19, 20]. In addition to the technological perspective, resource optimization should lead to a more economic power market, which can be reflected by the decrease in electricity price. An earlier research has shown a general decrease in the electricity prices in Italy due to the future import of North-African electricity [21, 22].

The capacity of China's wind power, photovoltaic power, and hydropower was 210 million, 204 million, and 356 million kW in 2019, ranking first in the world [23]. The formation of an ultra-high voltage (UHV) backbone network is very important. The backbone network should cover most parts of the country and connect large energy bases and main load centers through UHV DC transmission channels. Resource optimization will be technologically achievable after achieving a wide interconnection of grids with guaranteed security and stability. It is also reasonable to expect decrease in electricity price after this optimization.

The second enlightenment is the promotion of clean energy and set up of flexible generation units.

In 2018, EU's clean energy consumption accounted for 18.9% of the total energy consumption [13]. EU member countries, such as Germany and Spain, set their respective development goals, and according to the prediction of the European Wind Energy Association, the capacity of the European wind power plants would reach 230 million kW in 2020, 190 million kW of which would be onshore, and the remaining 40 million kW would be offshore. At this time, the European wind power plants would supply 14%~17% of the generation capacity, and this could reduce 3.33 tons of carbon dioxide emissions and 28 billion euros of fossil-energy-import cost. To promote the development of clean energy scientifically, the clean-energy planning and interconnected grid operation management are continuously being strengthened in Europe. In Germany, for example, on the one hand, the scale of clean-energy development should be controlled reasonably by adjusting the electricity pricing mechanism of clean energy. On the other hand, the establishment of a strict clean-energy grid testing-and-certification system is necessary. Therefore, the study on the clean-energy standards and the management of interconnected grid technology should be strengthened [24].

The high proportion of flexible generation units is one of the foundations for the high utilization rate of wind and photovoltaic power in European countries. For instance, among the Spanish power installed capacity, the flexible generation unit (oil and gas) is about 1.7 times the wind power unit [25]. The new installed capacity maintains at least a 1:1 ratio of the capacity and wind-power installed capacity of the flexible generation units. In China, the installed capacity of "Three Northern" area is mainly dominated by coal-fired power and other renewables. The proportion of flexible power supply, such as a pumped storage and a peak regulated power station, is less than 2% [26]. In winter, nearly no peak shaving capacity is available because of the high proportion of heat-supply units. The lack of peak-regulation power plants has decreased the operating flexibility of the power grid and hindered the large-scale clean-energy consumption.

The final enlightenment inferred from the European power grid is the coordination of the development of China's power grid and clean energy.

In Europe, the distribution of load centers and renewable energy development varies from country to country. For instance, in Germany, the wind- and solar-energy resources are widely distributed, and the development of photovoltaic and wind power is mainly dispersed and connected to a distribution system of $\leqslant$10 kV. However, most wind and photovoltaic power can be used domestically because of the strong distribution network and its high reliability. The wind-energy resources in Spain are mainly concentrated at the coastal regions in the north and south. The development of wind power is mainly focused on large- and medium-scale wind farms, while the Spanish load centers are mainly concentrated in Madrid, which is located in the center of Spain, and Barcelona in the eastern region. Spain therefore continues to strengthen the construction of its 400 kV backbone frames to meet the needs of large wind-power trans-regional transport.

The Chinese power demand and energy resources present a reverse distribution. To satisfy the development and export requirement of a large clean-energy base, long-distance and large-scale transmission is required. The construction of the Chinese energy internet based on the UHV AC/DC power grid can help realize the trans-regional and nationwide optimal allocation of energy resources. It can also improve China's energy structure, providing a strong support to guarantee the sustainable development of energy and electrical power. Additionally, for some particular provinces or regions, a relatively reasonable option is to develop distributed renewable energy together with long-distance transmission to create a more balanced and customized solution for these provinces or regions.

6 Summary

Based on the current situation of the European interconnected power grids, this paper reviewed their development history and analyzed the impact of the main drivers of the development of the European interconnected power grid in various periods. This paper also summarized the development of the power grid according to four stages. In addition, the paper provides a brief introduction to and analysis of the characteristics of different stages. Combined with the relevant planning, the future development trend of European power grid was predicted. Then, suggestions for the development of the energy internet in China were put forward. These overarching suggestions can be the reference for further study of the Chinese energy internet.

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References

[1] Liu K, Li J, Luo J, et al (2016) Synchronous power grid development trend and Chinese energy internet development research. Power Construction, 37(6):1-9

[2] World Bank (2020) European Union Population & GDP Database. http://data.worldbank.org/region/european-union

[3] World Bank (2020) United Nations Population Division Database. http://data.worldbank.org/indicator/SP.POP.TOTL

[4] Statistical Factsheet (2018) Brussel: European Network of Transmission System Operators for Electricity. https://www.entsoe.eu/Documents/Publications/Statistics/Factsheet/entsoe_sfs2015_web.pdf

[5] Wilson JC (2012) A history of the UK renewable energy programme, 1974-88: some social, political, and economic aspects, (Doctoral dissertation, University of Glasgow)

[6] Meisen P, Mohammadi C (2010) Cross-Border Interconnections on Every Continent. United State, Global Energy Network Institute

[7] Lagendijk V (2016) Europe's Rhine power: connections, borders, and flows. Water History 8:23-39

[8] UDI/McGrawHill. (2005). Electricity in Europe

[9] World Bank. (2020) Electric power consumption Database

[10] Verseille J, Staschus K (2015) The mesh-up: ENTSO-E and European TSO cooperation in operations, planning, and R&D. IEEE Power Energy Magazine 13(1): 20-29

[11] Wikipedia contributors. HVDC Gotland

[12] Saunders CT (1980) East and West in the Energy Squeeze: Prospects

for Cooperation. London: The MACMILLAN PRESS LTD

[13] EU (2020) Renewable energy statistics. Retrieved from Renewable energy statistics-Statistics Explained: https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics

[14] Ten Year Network Development Plan (2016) Brussel: European Network of Transmission System Operators for Electricity. http://tyndp.entsoe.eu/

[15] EU Energy trend to 2030(2009). EU publications office. https://ec.europa.eu/energy/sites/ener/files/documents/trends_to_2030_update_2009.pdf. Accessed 28 August 2019.

[16] Jiang K, He C, Xu X, et al (2018) Transition scenarios of power generation in China under global 2 °C and 1.5 °C targets. Global Energy Interconnect 1(4): 477-486

[17] Liu Z (2013) Study on the development mode of national power grid of china. Proc. Chinese Soc Elec Eng 33(7): I0001-I0026

[18] IEA (2020, 02) Data & Statistics - IEA. Retrieved from https://www.iea.org/data-and-statistics?country=GERMANY&fuel=Imports%2Fexports&indicator=Coal%20imports%20vs.%20exports

[19] Ruan Q, Wang W, Zhang Z (2007) Lessons learned from "11.4" blackouts in Europe. East China Electric Power, 35(1):5-9

[20] Tian S, Xhen X, Zhu C, et al (2008) Theory of electric power emergency management and its technological countermeasures. Power System Technology, 32(01): 26-30+55

[21] Martinez-Anido CB, L'Abbate A, Migliavacca G, et al (2013) Effects of North-African electricity import on the European and the Italian power systems: A techno-economic analysis. Electric Power Systems Research, Vol.96, pp:119-132

[22] L'Abbate A, Migliavacca G, Calisti R, et al (2013) Electricity exchanges with North Africa at 2030. In: The European and the Italian approaches: 225

[23] Wu C, Zhang X (2018) Economic analysis of energy interconnection between Europe and China with 100% renewable energy generation. Global Energy Interconnect 1(5):528-536

[24] Wang X, Li N, Sun W, et al (2018) Quantitative analysis of distributed and centralized development of renewable energy. Global Energy Interconnect 1(5):576-584

[25] Forte F (2019, August 26). Renewable energy: installed capacity Spain 2018. Retrieved from https://www.statista.com/statistics/1031674/installed-power-capacity-from-renewable-sources-in-spain/

[26] IEA (2017) World Energy Outlook 2017: China, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2017

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