Quantitative analysis of distributed and centralized development modes for renewable energy

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Abstract. Global renewable energy has maintained a steady growth in recent years under the support of national policies and energy demand. It is necessary to analyse the experience of renewable energy development mode in developed countries so as to provide reference and guidance for the renewable energy development in other countries. Firstly, the definitions of distributed generation in 18 typical countries or organizations are compared and summarized. On this basis, three basic characteristics of distributed generation are provided. Finally, Empirical analysis of Germany's renewable energy development mode is studied, which analyses the selection of development mode for wind and photovoltaic power. Moreover, the distributed photovoltaic generation accounts for more than 95%, and distributed wind power generation installations account for over 85% in Germany.

1. Introduction
In the present world, all governments attach great importance to the development and utilization of renewable energy. As of 2016, 173 countries around the world have set renewable energy development goals and 146 countries have adopted various supportive policies. Multiple cities, communities and businesses are pioneering the rapidly growing "100% Renewable Energy" initiative, which plays a crucial role in driving global energy transformation. Meanwhile, other factors also promote the development of renewable energy, such as financing incentives, energy security attention, environmental issues, and the growing demand for modern energy services in developing countries and emerging countries.

In 2016, renewable power generation (excluding hydropower) increased by 14.1%, created the largest increasing record (53 million tonnes of oil equivalent). More than half of renewable energy growth stems from the growth of wind energy. Although solar energy accounts for only 18% of all renewable energy, it contributes about one-third of the growth. As the largest market and producer of renewable energy in the world, photovoltaics and wind power in China have maintained a steady growth in recent years under the support of national policies. Renewable energy in China are mainly developed with the centralized development mode. However, due to the deficiency of power grid construction and transmission channel construction, the curtailment phenomenon of “wind, photovoltaic and water power” has become a prominent issue restricting the development of renewable energy [1]. Therefore, it is necessary to analyze the experience of renewable energy development mode in developed countries and
summarize the characteristics of different development modes, so as to provide reference and guidance for the selection of renewable energy development mode in China.

2. Definition of distributed development modes

2.1. The international definitions of distributed development mode.
Renewable energy development can be divided into centralized development mode and distributed development mode. The "distributed" is an opposite concept relative to the "centralized". However, there is no generally authorized definition of distributed generation about the maximum capacity, access methods, voltage levels, power quality etc. Not only different countries and organizations, but even different regions within a country propose different interpretations and definitions of distributed generation. Moreover, some institutions or organizations do not explicitly limit voltage or capacity.

(1) IEA
Definition: Serving for local users or local power stations, including internal combustion engines, small or micro gas turbines, fuel cells and photovoltaic power generation technologies, and energy utilization system of energy control and demand side management. Voltage limit: 10kV. Capacity limit: 10MW

(2) IEEE
Definition: Access to local power distribution equipment or energy storage via public connection points, without directly connected to the transmission grid, and total capacity does not exceed 10 MVA. Voltage limit: 7.2/12.5kV. Capacity limit: 10MW

(3) Denmark Energy Environment Department
Definition: Closing to the user, without connecting to the high-voltage transmission network, and installed capacity less than 1 kilowatts energy system. Voltage limit: 10kV. Capacity limit: 10MW

(4) WADE
Definition: Energy System of generating electricity and heat at or near the user's premises, primarily using for local users. Voltage limit: 48.3/69kV. Capacity limit: 100MW

(5) “Energy Policy Act” of USA, 2005
Definition: Power plants that distributed power points to nearing small users. Voltage limit: 7.2/12.5kV. Capacity limit: Some MW

(6) U.S. Department of Energy
Definition: System that located near the users and provides power or heat. Voltage limit: 34.5kV. Capacity limit: tens of MW

(7) EPRI
Definition: Small clean, efficient power of nearing loading with power supply. Voltage limit: 34.5kV. Capacity limit: 50MW

(8) UK
Definition: Power near loading with accessing to low voltage distribution network. Voltage limit: allow 66kV; but usually 33kV. Capacity limit: 100MW

(9) Germany
Definition: Power near loading with accessing to low voltage distribution network. Voltage limit: 20kV. Capacity limit: 10MW

(10) France
Definition: Access to low-voltage distribution network, supply power directly to the user. Voltage limit: 20kV; 30kV usually do not access. Capacity limit: 10MW

(11) Spain
Definition: Access to low-voltage distribution network, supply power directly to the user. Voltage limit: distribution network below 132kV. Capacity limit: 50MW

(12) Australia
Definition: Access to low-voltage distribution network, supply power directly to the user. Voltage limit: 33kV and below voltage level. Capacity limit: 10MW
(13) Portugal
Definition: Access to low-voltage distribution network, supply power directly to the user. Voltage limit: 30kV distribution network Capacity limit: 10MW
(14) Finland
Definition: Access to low-voltage distribution network, supply power directly to the user. Voltage limit: 20kV Capacity limit: 10MW
(15) India
Definition: Renewable energy accessing to low-voltage distribution network, supply power directly to the user. Voltage limit: 11kV Capacity limit: 10MW
(16) New Zealand
Definition: Power accessing to low-voltage distribution network. Voltage limit: 11kV Capacity limit: 5MW
(17) Sweden
Definition: Power accessing to low-voltage distribution network. Voltage limit: 10kV Capacity limit: 1.5MW
(18) Belgium
Definition: Power accessing to low-voltage distribution network. Voltage limit: 10kV Capacity limit: 10MW

2.2. Definition of renewable energy development mode in China
The definition of distributed generation in China has undergone many changes. Considering the renewable energy, the NDRC made a clear definition: “Access to the distribution network with various voltage levels of wind, solar and other renewable energy power generation”. Since then, the State Grid Corporation adjusted the definition to two types of services: Distributed power source with access voltage level of 10kV and below, and a single network with a total installed capacity of not more than 6MW; Distributed power source with access voltage level of 35kV, and the annual self-generated electricity more than 50%, or distributed power source with access voltage level of 10kV and a single network with a total installed capacity of more than 6MW, the spontaneous self-consumption of more than 50%[7].

Distributed photovoltaic: “Notice of National Energy Administration on Further Implementing Relevant Policies of Distributed Photovoltaic Power Generation” clearly stated:
Distributed photovoltaic power generation projects by using the construction of roofs and ancillary venues, can choose two modes: "Consume the generated electricity, and send the remaining electricity to the power grid"; or "send all of the generated electricity to the power grid" in the project record.
Photovoltaic power plant project installed on the ground or the agricultural greenhouses and other facilities without electricity consumption, access to the grid at voltage levels of 35kV and below. A single project not exceeding the capacity of 20,000kW and the main generating capacity of substations in the network dismissed, will belongs to the distributed photovoltaic power generation scale management and execute the local PV power station benchmark price. According to Article 17 of the "Interim Measures for Distributed Generation Management" and the "Green Channel", the power grid enterprises will follow the simplified procedures to handle grid access and provide relevant grid-connection services by the prefecture-level cities or county-level power grid.

Distributed wind power: “Notice of the National Energy Administration on Relevant Requirements for Accelerating the Construction of Distributed Wind Power Projects” clearly stated:
Distributed wind power project should meet 3 technical requirements: First, the access voltage level should not be more than 35 kV. Second, it should make full use of the existing distribution network facilities, giving priority to T or π access to the grid. Thirdly, the upper limit of the allowed wind power capacity should ensure the safe operation of the grid as a prerequisite, and takes the total capacity of installed distributed wind power plant at each voltage level into consideration and encourages multi-point access.
3. Characteristics of the distributed development mode

Based on the definitions of distributed generation in 18 typical countries or organizations, three basic characteristics of distributed power source can be summarized as follows:

1. VDG≤35kV, namely, distributed generation is connected to medium and low voltage distribution network [3]. Since the definitions of low voltage distribution network are different among countries, the access voltage levels of distributed power are also slightly different. In the 18 typical countries or organizations above, the access voltage levels in 8 countries are 10kV and below, 7 countries are 35kV and 3 countries are 110 kV or 66 kV. The distributed generations are limited to connect the mid-low voltage distribution network in Germany, France and Australia, in which the mid-low voltage is lower than 30 kV. The UK allows distributed generation connects to the 66kV voltage level, which is also medium level voltage in this country.

2. CDG≤10MW, namely, the capacity of distributed generation is less than or equal to 10 MW [4]. In the 18 typical countries or organizations above, the capacity of distributed generation in 13 countries are less than or equal to 10 MW, 3 countries are tens of MW, and 2 countries are 100MW. The United States, France, Denmark, Belgium and other countries limit the allowed capacity of distributed generation to around 10MW, while Sweden’s allowed capacity is limited to 1.5MW and New Zealand is 5MW. Due to the UK to allow the connection of distributed generation at higher voltage level, corresponding to larger allowed capacity, up to 100 mw. But in actual situations, the number of distributed generations connected to 66 kv voltage level is limited.

3. CDG/Pload≤1, that is, the generated generations sent power to the users [6]. This is the most essential feature of distributed generation, which requires that CDG<Pload, adapt to the local demand, and realize the power of local energy dissipate, which is more direct and close to users. National definitions refer to this feature as well.

4. The renewable energy development mode in Germany

4.1. German power grid development overview

The European interconnected power grid is an important support for the rapid development and high-level utilization of renewable energy in Germany. In the future of 2020-2030, Germany’s renewable energy development will also rely on its transnational interconnected power grid for consumption and resource allocation. It can be said that the transnational interconnected power grid in Germany is an important condition for its high-level utilization of renewable energies.

By the end of 2015, Germany has a total of 4 transmission companies and 817 distribution companies. The national transmission lines has a total length of 1.187 million kilometers. Among them, there are 133,000 km of high-voltage and ultra-high-voltage lines and 1,684,000 km of low-voltage lines. There are a total of 50.3 million users nationwide including 3.02 million non-resident meters and 47.28 million resident meters. Data show that civilian electricity meters are the majority [8].

| Table 1 Germany 2015 grid structure data |
|------------------------------------------|
|                                      | TSOs | DSOs  | Total         |
| Network operators(number)             | 4    | 817   | 821           |
| Total circuit length(km)              | 36001| 1,780,856 | 1,816,857   |
| Extra high voltage                    | 35610| 360 | 35,970        |
| High voltage                          | 391  | 96,267 | 96,658       |
| Medium voltage                        | 0    | 511,164 | 511,164      |
| Low voltage                           | 0    | 1,173,065 | 1,173,065   |
| Total final consumers(meter points)   | 535  | 50,298,514 | 50,299,049  |
| Industrial, commercial and other non-household customers | 3,015,426 | 3,015,426 |
| Household customers                   | 47,283,088 | 47,283,088 |
Via specific analysis of German power grid structure, it can be seen that the country use 380 to 400 kV transmission line as the network backbone. Supplemented it by 220 to 275 kV transmission lines as a support. In addition, distant wind power from the North Sea are transported to the mainland from the northern coast via the DC transmission system. The Ruhr district, a traditional industrial cluster, and the Baden-Württemberg state in the southwestern part of the country have the most developed industries and businesses, and the distribution of power grids is even more intensive[8].

Nine countries border Germany, namely Denmark, Poland, the Czech Republic, Austria, Switzerland, France, Luxembourg, Belgium and the Netherlands. Between these countries, the transnational transmission networks consist mainly of 380 kV to 400 kV lines, with 220 kV to 285 kV transmission lines serving as ancillary. Among them, the number of 380 kV to 400 kV lines is 28, and 220 kV to 285 kV transmission lines is 31.

4.2. Analysis of photovoltaic power generation development mode
Using influencing factors for analysis, according to the relevant statistics, about 70% of Germany’s PV capacity is connected to the LV distribution network (this capacity is less than 100KW), capacity of PV connected to medium-voltage power grid (usually 35KV) is about 25%. Therefore, it can be considered that 95% of the photovoltaic power generation capacity in Germany is distributed photovoltaic power generation. However, part of the PV connected to the medium-voltage grid is a centralized utility photovoltaic power plant (with a capacity of more than 1000 KW and constructed as a ground power plant). Due to lacking of access to detailed data, this part of the capacity is temporarily not be considered [10].

![Figure 1](image)

**Figure 1** Germany access to the voltage of photovoltaic power generation installed capacity

4.3. Analysis of wind power generation development mode
Wind power projects are mostly concentrated in the north of Germany. All the offshore wind power in Germany are connected to 110KV and higher voltage level. Besides, there is no detailed information about access voltage level and installed capacity of onshore wind power projects. Therefore, the first two characteristics of distributed development mode can not be used to analyze the development mode of the onshore wind power in Germany. The third characteristics is used to quantitatively analyze the onshore wind power development mode.

Inland areas in Germany, wind power installed capacity of 16 federal state and local load, considering the local non renewable energy power generation capacity, beyond the part of local average load state, that is the centralized wind power.

\[
C_{UC-wind} = \sum C_{wind} \times \rho_{wind} + C_{unrenewable} \times \rho_{unrenewable} - P_{load}
\]  

(1)
Among them, \( C_{UC\text{-wind}} \) is the centralized wind power capacity in Germany; \( C_{\text{wind}} \) is local wind power capacity in federal states; \( \rho_{\text{wind}} \) is wind power capacity coefficient (considering 0.2); \( C_{\text{unrenewable}} \) is generating capacity for non-renewable energy sources in federal states; \( \rho_{\text{unrenewable}} \) is non-renewable energy generation capacity (considering 0.6); \( P_{\text{load}} \) is local average load for all federal states.

In addition, the northern German offshore wind power plant is all connected to 110KV and above voltage level, with installed capacity exceeding 10MW. Therefore, all of the onshore wind power plants are in centralized mode [9].

According to the state power installation and the above formula, the scale of installed wind power plants in the 16 federal states of Germany is calculated, and the corresponding results are shown as follows:

### Table.2 Estimates of the size of wind power installed in 16 federal states in Germany

| The federal state | Wind capacity(GW) | non-renewable energy generation capacity(GW) | local load(GW) | centralized wind power(GW) |
|-------------------|------------------|---------------------------------------------|----------------|-----------------------------|
| BW                | 81.1             | 1190.6                                      | 1099           |                             |
| BY                | 201.0            | 1096.8                                      | 1363           |                             |
| BE                | 1.0              | 222.9                                       | 178            |                             |
| BB                | 643.5            | 565.9                                       | 303            | 164.9                       |
| HB                | 19.2             | 135.9                                       | 84             | 0.9                         |
| HH                | 7.0              | 199.4                                       | 191            |                             |
| HE                | 141.2            | 313.6                                       | 550            |                             |
| MV                | 313.7            | 84.1                                        | 99             | 13.9                        |
| NI                | 933.3            | 1068.8                                      | 847            |                             |
| NW                | 446.5            | 3261.2                                      | 2053           |                             |
| RP                | 320.9            | 204.3                                       | 423            |                             |
| SL                | 32.9             | 247.2                                       | 164            |                             |
| SN                | 128.1            | 609.1                                       | 340            | 50.8                        |
| ST                | 506.5            | 236.6                                       | 258            |                             |
| SH                | 632.1            | 293.5                                       | 237            | 65.6                        |
| TH                | 143.1            | 199.7                                       | 217            |                             |
| Total             |                  |                                             |                | 296.1                       |

According to the calculation results, about 2.29 million KW onshore and 4.13 million kw offshore wind power plants in German belong to the centralized development mode. In Germany, 7.09 GW wind power plants belong to centralized development mode, accounting for 14.3% of the total installed capacity of wind power plants. In conclusion, about 85.7% of the total installed capacity of wind power plants are developed based on the distributed development model.

### 4.4. Summary for the development mode characteristics in Germany

Firstly, Germany's renewable energy development mode is dominated by distributed development mode, where distributed photovoltaic power generation accounts for more than 95%, and distributed wind power installations account for over 85%.

Secondly, the largest proportion of renewable energy in Germany is concentrated in the northern states and the North Sea and the Baltic sea, which are away from the southern load center. All the northern offshore wind power adopts centralized development mode. In the northern states, the development of wind power development is centralized as well and cannot be distributed completely.
The development of distributed generation mainly focuses on the development of centralized development.

Third, the solar energy in southern Germany is rich and close to the load center, so the solar power is in distributed development mode, which is mainly used with high permeability access in the nearby area.

5. Conclusion
Based on the definitions of distributed power source in 18 typical countries or organizations, three basic characteristics of distributed power source can be summarized: 1) VDG ≤ 35kV; 2) CDG ≤ 10MW; 3) CDG/Pload ≤ 1. Empirical analysis results show that Germany's renewable energy development mode is dominated by distributed development mode. Since the largest proportion of wind resource is away from the southern load center in Germany, all the northern offshore wind power adopt centralized development mode. Correspondingly, the solar energy in southern Germany is rich and close to the load center, so the solar power is in distributed development mode. In general, the distributed photovoltaic power generation accounts for more than 95%, and distributed wind power installations account for over 85% in Germany.

In the future, the centralized and distributed should be promoted simultaneously in China. Local governments should actively support the distributed generation of renewable energy in central and eastern China, and reasonably grasp the pace of renewable energy development in severely restricted power areas. Moreover, governments should co-ordinate the development and consumption of renewable energy power.

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