A QUANTITATIVE COMPARATIVE STUDY OF

# POWER SYSTEM FLEXIBILITY

## in Jing-Jin-Ji and Germany

ENERGY RESEARCH INSTITUTE OF THE NATIONAL DEVELOPMENT AND REFORM COMMISSION

国家发展和改革委员会
能源研究所
Energy Research institute, NDRC, P.R.C

华北电力大学
NORTH CHINA ELECTRIC POWER UNIVERSITY

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

**IMPRINT**
This report, A Quantitative Comparative Study of Power System Flexibility in Jing-Jin-Ji and Germany, is published within the framework of the project German Energy Transition Expertise for China. The German Energy Transition Expertise for China project is commissioned by the Federal Ministry for Economic Affairs and Energy (BMWi) and implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in cooperation with the China National Renewable Energy Centre (CNREC), a leading Chinese think tank for advising the National Energy Administration (NEA) on formulating renewable energy and energy transition policies.

**RESEARCH INSTITUTES:**
Energy Research Institute of the National Development and Reform Commission (ERI of NDRC)
14-15 floors, Building B, Guohong Building, No. Jia11, Muxidi Bei Li, Xicheng District, Beijing, China
T +86-(0)10-6390 8491
F +86-(0)10-6390 8469

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
1-15-1 Tayuan Diplomatic Office Building, No.14, Liangmahe Nanlu, Chaoyang District, Beijing, China
T +86-(0)10-8527 5589
F +86-(0)10-8527 5591

North Chian Electric Power University (NCEPU)
No. 2 Beinong Road, Changping District, Beijing, China
T +86-(0)10-6177 1615
F +86-(0)10-6177 1611

**Project:** German Energy Transition Expertise for China
**Commissioned by:** Federal Ministry for Economic Affairs and Energy (BMWi)
**Project leader:** Wang Zhongying (ERI of NDRC)
**Author:** Zheng Yanan (ERI of NDRC), Wang Xinnan (Previous GIZ staff), Anders Hove (GIZ), Li Gengyin (NCEPU), Guo Zheyu (NCEPU)

**August 2020**

**Design/Layout:** Miro Design Company
**Photo credits:**

Please download the PDF version here or scan the QR code.

# EXECUTIVE SUMMARY

Implementing the Paris Climate Agreement requires a transition to carbon neutrality by roughly mid-century, which will require a rapid transition to a low-carbon electricity system. Developing a renewable-based energy system is an important aspect of the global energy transition and a core component of the low-carbon energy revolution in many countries. As early as the 1980s, Germany proposed a renewable energy development strategy. By the end of 2018, installed capacity of renewable energy in the country accounted for over 50% of the country's electricity generation capacity, making Germany a pioneer in renewable energy development in Europe. As a result of its energy transition, Germany now has rich experience in increasing power system flexibility, and system reliability has actually improved even as variable renewable energy has grown as a proportion of energy production.

Jing-Jin-Ji (Beijing-Tianjin-Hebei, or JJJ) is one of the areas with the highest energy consumption in China. The region's energy transition now focuses on developing renewable energy. Due to the variability of wind and solar power, this implies a greater need for local and regional system flexibility. However, the widely differing energy mixes and grid transmission capacity of provinces and cities within the Jing-Jin-Ji regional cluster challenge the system's ability to improve flexibility. By comparing the power system flexibility of Jing-Jin-Ji and Germany, this report aims to support Jing-Jin-Ji with flexibility solutions suitable for local renewable energy development that could also serve as a reference for other provinces and cities in China that seek to increase the share of renewable energy.

Power system flexibility is defined as the ability of a power system to reliably manage the variability of demand and supply across all relevant timescales. Flexibility resources are available on the supply side, the grid side and the demand side. Given recent technological and commercial advances, energy storage has also become a major new potential source of flexibility for power systems. This report first analyses different sources for providing power system flexibility in Jing-Jin-Ji and Germany, including from supply, grid, demand and energy storage. It then quantitatively compares flexibility of the two power systems, **finding that the present German power system offers substantially higher flexibility than that of Jing-Jin-Ji**. The report also reviews the cost-effectiveness of technologies for boosting system flexibility, **finding that flexibility retrofits of coal plants offer the greatest potential benefits given their cost, followed by flexible transmission operation, and followed by demand response and energy storage**. Based on a comprehensive analysis of the German power system flexibility, the report also offers recommendations for further enhancing this flexibility with a high ratio of renewables in the power mix.

# 1. A COMPARATIVE ANALYSIS OF JING-JIN-JI AND GERMANY ILLUSTRATES JING-JIN-JI'S RELATIVELY LOWER SYSTEM FLEXIBILITY

Despite similarities in the types of flexibility resources for power systems in Jing-Jin-Ji and Germany, the ability to flexibly dispatch resources varies considerably. **On the supply side, the flexibility of coal-fired power units in Jing-Jin-Ji has substantial room for improvement**. On one hand, the dispatchable power in Jing-Jin-Ji exceeds 75 GW, or 72.5% of the total installed capacity, which is much higher than the 50.2% in Germany. However, coal-fired power units in Jing-Jin-Ji underperform those of Germany on several flexibility parameters, including minimum output, ramp rate, and start-up time. In particular, combined heat and power (CHP) units in Jing-Jin-Ji are generally required to generate power based on the demand for heat during winter, which severely affects system flexibility. In contrast, over 50% of CHP plant capacity in Germany has carried out transformation and decoupling of heat and power. This effectively increases the flexibility of the whole system.

**On the grid side, cross-provincial and cross-regional flexible and mutually-beneficial interconnections in the Jing-Jin-Ji area have yet to be developed**. With the growing share of renewable energy, Jing-Jin-Ji is in a similar situation as Germany as the region strives to secure reliable power supply with an increasing demand for ancillary services. Interconnections with neighbouring grids including Shanxi, Henan, Shandong, and Inner Mongolia have been established with transmission capacities of over 76 GW. In terms of interconnection flexibility, Germany is ahead as it conducts real-time cross-border power exchange with nine neighbouring countries. In contrast, the inter-provincial transmission grid in Jing-Jin-Ji is currently mainly utilized as emergency support for summer and winter peak-loads. In addition, grid retrofits and extensions in Jing-Jin-Ji are organized at the provincial level, instead of responding to the overall regional need for improved system flexibility.

**On the demand side, flexibility resources are underdeveloped in both Jing-Jin-Ji and Germany**. Demand-side management in Jing-Jin-Ji and Germany has the potential to leverage gigawatt-scale flexibility resources. Various flexibility-boosting measures have been applied in industry, construction, transportation, and other sectors. However, the degree of utilization remains relatively low in both regions. In Jing-Jin-Ji, demand-side management through administrative mechanisms, such as the policy on Orderly Use of Electricity, constitute the main source of demand flexibility. In contrast, Germany relies on market mechanisms to boost flexibility.

**On energy storage, Jing-Jin-Ji lacks new energy storage technologies for commercial scale applications other than pumped-storage hydropower (PSH)**. Both Jing-Jin-Ji and Germany have great potential to utilize PSH. However, Jing-Jin-Ji has only 2.1 GW of installed PSH capacity. Other storage technologies including battery storage, compressed air energy storage and hydrogen energy storage are still in the demonstration stage with merely 32 MW installed. In comparison, Germany has installed over 1 GW capacity with battery energy storage, compressed air energy storage and Power-to-X technologies, most of which are commercial applications.

**Jing-Jin-Ji has inadequate incentives to boost flexibility**. Germany has introduced measures such as the balancing market, spot market, congestion management and internal balancing, with the aim to take full advantage of various flexibility resources. Jing-Jin-Ji has implemented Measures for Open, Fair and Impartial Power Dispatch on the supply side, Measures for the Orderly Use of Electricity on the demand side, as well as two new rules for ancillary services. However, these measures fall short of the incentives needed to boost flexibility of the power ancillary services.

## 2. QUANTITATIVE INDICATORS CAN OBJECTIVELY EVALUATE REGIONAL SYSTEM FLEXIBILITY AND THEREBY GUIDE POLICY AND INVESTMENT

To quantitatively evaluate system flexibility in the two regions, this report uses the H3E-Power System Generation Simulation jointly developed by the Energy Research Institute of the National Development and Reform Commission and North China Electric Power University. The assessment relies on several indicators, namely **probability of insufficient upward flexibility (PIUF), probability of insufficient downward flexibility (PIDF), loss of load probability (LOLP)**, the **wind curtailment rate** and the **solar curtailment rate**. Quantitative comparison shows that the capacity to utilize flexibility resources in Jing-Jin-Ji and Germany varies greatly, which results in different levels of flexibility, reliability and wind/solar curtailment rates in the two power systems.

According to 2018 operational data, Germany's power system has relatively high upward flexibility and reliability. The system has downward flexibility deficiency probability of around 8.39%. Wind and solar curtailment rates are relatively low. Upward flexibility is lower in winter than in summer and downward flexibility is lower in summer than in winter.

In Jing-Jin-Ji, the power system also has sufficient upward flexibility, and the average upward flexibility deficiency probability is lower than Germany. This ensures relatively high power supply reliability in Jing-Jin-Ji region. **However, northern Hebei as well as Tianjin have a severe shortage of downward flexibility**, PIDF stands at 19.69% in Hebei and 67.52% in Tianjin. The figure is lower in winter than in summer and lower at night than during the day. **This downward flexibility deficiency together with a high proportion of renewable capacity in northern Hebei results in a high rate of wind and solar curtailment**.

Regarding further potential for flexibility, the northern Hebei region and Germany are similar in the proportion of installed renewable energy. Given Germany's experience deploying flexibility solutions, **flexibility retrofits for coal-fired power plants in northern Hebei can significantly improve the upward and downward flexibility of the system**. The required investment per kilowatt is only higher than demand side management, but it improves system reliability whilst promoting wind and solar power consumption. **Grid interconnectivity and energy storage increase system flexibility via a different working mechanism, but both are conducive to improving the upward and downward flexibility at most relevant timescales of the power system in northern Hebei. Grid interconnectivity technologies are well established with cost-effective benefits**. As for energy storage, development of PSH is restricted due to limited site availability and high cost. Other types of energy storage technology face uncertainties in deployment at scale, with cost-efficiency as the major bottleneck. Although demand side management is cost-effective, it only has a small role to play in northern Hebei as it is limited to redeployment of flexibility sources.

## 3. SUGGESTIONS FOR IMPROVING POWER SYSTEM FLEXIBILITY IN JING-JIN-JI: PRIORITIZE COAL RETROFITS AND TRANSMISSION

To boost power system flexibility, **Jing-Jin-Ji should prioritize flexibility retrofits for coal-fired power plants and facilitate grid interconnectivity**. Construction of PSH units and energy storage power plants follow in order of priority, along with active implementation of demand-side management. Finally, the region should improve flexibility deployment within the power system. In the meantime, the region should establish a centralized electricity market that provides effective compensation for ancillary services, introduce incentive pricing for transmission and distribution in a fully open retail market, and develop an electricity capacity market.

From a sub-regional perspective, Beijing should accelerate grid interconnectivity, promote diverse energy storage technologies, and explore intelligent demand-side management. Tianjin and Hebei should shift the role of coal-fired power plants from baseload to peaking operation, reduce excess coal-fired capacity, reduce barriers to grid access, and prioritize the construction of pumped-storage. Hebei should increase its generation-grid-load-storage integration to improve flexibility across all these resources.

**To improve power system flexibility in Germany, innovative business models can enable the country to boost the use of decentralized flexibility resources on the demand side. Germany should also study and identify innovative flexibility solutions for the future renewable-based power system.**

| | Loss of Load Probability improvement (%) | Improvement on Probability of Insufficient Downward Flexibility (%) | Improvement on Probability of Insufficient Upward Flexibility (%) | Amount (GW) | Unit cost (RMB/kW) | Total cost (billion RMB) |
|---|---|---|---|---|---|---|
| Coal plant flexibility retrofit | 0.91% | 63.93% | - | 17 | 300-500 | 5.1-8.5 |
| Interconnection upgrade | 0.85% | 3.668% | - | 14 | 2000 | 28 |
| Demand side management | 0.83% | 2.36% | - | 2.3 | 200-400 | 0.46-0.92 |
| Energy Storage | 0.49% | 3.91% | - | 21 | 8000-10000 | 168-210 |

# TABLE OF CONTENTS

# 1 FOREWORD

Responding to climate change is a global imperative, and countries have begun to take action, as shown in the Nationally Determined Contributions (NDCs) submitted in response to the Paris climate agreement. Renewable energy is a major global trend, and a core component of the energy transition in many countries. In the past decade, wind and solar power have seen the fastest growth in percentage terms, and this appears likely to continue. The variability of wind and solar presents a challenge to conventional power systems based on centralized, dispatchable generation plants. The importance of flexibility has thus become increasingly important alongside reliability and cost-efficiency.

Power system flexibility is not an entirely new concept. Flexibility has always been essential to maintaining real-time balance among electricity generation and consumption; flexibility reflects the ability of a power system to respond in a timely manner to variations in electricity supply and demand. In the face of a growing proportion of renewable energy, more research on power system flexibility best practices can help ensure safe and stable system operations, with the ultimate goal of enhancing and accelerating the low-carbon energy transition.

Jing-Jin-Ji is an important economic centre in China and one of the largest regional consumers of energy, accounting for over 10% of the total energy consumption in the country. In terms of economic development, Beijing is already at the post-industrial stage, whilst Tianjin is at the late-industrialization stage, and Hebei at the middle stage of industrialization. Regarding power energy mix, Beijing mainly relies on imported electricity, though it does have some local gas-fired generation. Tianjin and southern Hebei have a high proportion of coal-fired power capacity. In northern Hebei, renewable energy accounts for more than 50% of the total energy mix, but wind curtailment is a serious and growing issue in some areas, such as Zhangjiakou.

Germany has long been Europe’s largest economy and a leading industrial powerhouse. The country proposed a renewable energy development strategy as early as the 1980s. After decades of development, installed capacity of renewable energy in Germany now accounts for 58.4% of the energy capacity, a high proportion that makes it a pioneer in renewable energy development in Europe.

With reference to the unique local conditions of Jing-Jin-Ji and successful experience of renewable energy development in Germany, this report analyses different sources for providing power system flexibility in Jing-Jin-Ji and Germany from supply, grid, demand side and energy storage. It then quantitatively compares the flexibility of the two power systems with these methods, and reviews various cost-effective technologies for boosting system flexibility. This report aims to enhance power system flexibility in Jing-Jin-Ji based on guidance from the German experience, and proposes suggestions for developing flexible energy systems in Jing-Jin-Ji considering different renewable energy development levels within the region. It also brings forward adaptive flexibility development proposals as reference for other provinces and cities in China to improve system flexibility.

# 2 DEFINITION OF AND RESOURCES FOR POWER SYSTEM FLEXIBILITY

Conventional power systems have typically relied mainly on thermal power and hydropower with dispatchable output that allows for relatively easy load-following and regulation. With the rise of wind and solar power, and increasing deployment of distributed energy resources, the proportion of variable energy sources has increased significantly. In countries such as China, electricity consumption is rising most rapidly in the commercial, service, and residential sectors, meaning that electricity load also varies more, and therefore there is a wider peak-valley system net load. This has further increased the range of system utilization and raised overall uncertainty for the power system. Coping with increasing uncertainty has become the main challenge of modern power systems. Safe and reliable system operation requires full mobilization of flexibility within generation, grid, loads, and storage to ensure the system can respond promptly to dynamic changes in supply or demand.

## 2.1 DEFINITION OF POWER SYSTEM FLEXIBILITY

In recent years, international organizations such as the International Energy Agency (IEA) and the North American Electric Reliability Corporation (NERC) have formalized definitions of system flexibility. The IEA defines power system flexibility as the ability of the power system to respond in a timely manner to variations in electricity supply and demand.[1] NERC defines power system flexibility as the ability of supply-side and demand-side resources to respond to system changes. In academic circles, extensive research on power system flexibility is also underway.[2] Lannoye et al. define flexibility as the ability of a power system to deploy its resources to respond to changes in the net load, where volatility and uncertainty arise mainly from supply and demand and equipment failures.[3] Zhao et al. define it as the ability of a system to cope with volatility and uncertainty at a reasonable cost across all timescales.[4] According to Ma et al., power system flexibility is the ability of a system to cope with volatility and uncertainty at minimal cost, and to ensure system reliability.[5]

Overall, power system flexibility refers to a system's ability to reliably manage the variability of demand and supply, thereby achieving safe and stable operations. Flexibility of a power system can be divided into upward regulating capacity and downward regulating capacity. "Upward regulating" means that additional power is provided to the system, which can be achieved by increasing output of the power generation unit or reducing the load. "Downward regulating" refers to the reduction of excess power in the system, which can be realized by reducing output of the power generation unit or increasing the load. Flexibility resources are available on the supply side, on the grid side, and on the demand side. With rapidly evolving technologies, energy storage is also becoming an important source of flexibility for power systems. In addition to the fundamental requirements of safety, reliability and economy, flexibility has become an indispensable indicator for assessing system operations against increasing variability and uncertainty.

## 2.2 CHARACTERISTICS OF SUPPLY-SIDE FLEXIBILITY RESOURCES

### 2.2.1 CONVENTIONAL HYDROPOWER

Conventional hydropower uses the energy of falling or flowing water to generate electricity. By reservoir size, hydropower stations can be divided into multi-year, annual, seasonal, weekly and daily regulation stations as well as run-of-river hydropower stations without regulation function. Hydropower plants with regulation capacity provide flexibility with short start-up/shut-down time and swift load regulation. They play the role of frequency control, peak load regulation, and backup capacity in the power system. The respective characteristics of hydropower plants with different regulation capacity are as follows.

(1) Run-of-river hydropower stations: No reservoir. The amount of water inflow determines how much electricity is generated.

(2) Hydropower stations with daily, weekly and monthly regulation capacity: Equipped with a small reservoir with regulation capacity of one day, one week or one month. All three types of hydropower stations have relatively small storage and weak load-regulating capacity. They depend on upstream water inflow to regulate system demand. For example, water is stored overnight for generation during daytime, or in the first half of the month for power generation in the second half.

(3) Hydropower stations with seasonal regulation capacity: equipped with a relatively large reservoir, which can be used for storing water during flood season and generating power at another time (for example dry season), thus helping to regulate the electricity system.

(4) Hydropower stations with annual regulation capacity optimize the allocation and regulation of natural runoff in each month of the year by depositing excess water during wet seasons into the reservoir for power generation during the dry season.

(5) Hydropower stations with multi-year regulation capacity realize optimal distribution and regulation with natural water accumulated over multiple years. Equipped with large reservoirs, the hydropower stations determine the current year's power generation and storage according to the hydrological information and actual needs of the past years, and use stored water from flood seasons in a normal or dry year to deliver dispatchable power. They are also capable of regulating natural floods, thus not only meeting power system regulation needs, but also controlling and reducing floods on large rivers.

## 2.2.2 THERMAL POWER

Thermal power plants convert chemical energy from fossil fuels into electrical energy. By fuel type, they are generally divided into coal-, gas- and oil-fired power plants. The parameters that affect flexibility of thermal power plants mainly include minimum stable output, ramp rate, and start-up time. The minimum stable output determines the capacity for adjustment of a thermal power plant, the ramp rate defines regulation capacity of the system across timescales, and the start-up time reflects the response speed of the cold standby unit to provide flexibility to the system under load increase and reduced output of renewable energy. The output characteristics of different types of thermal power plants are as follows.

**(1) Coal-fired units**

**The minimum stable output** of coal-fired units without retrofit usually reaches 50% of the rated capacity. The latest operations show that the minimum stable output of most units of 0.6 GW or less can be reduced to about 40% of the rated capacity without increasing any investment in system transformation. The addition of heat and power decoupling, low-pressure stable combustion and other technologies can further bring down the minimum stable output to 20% to 30% of the rated capacity. **The ramp rate** of coal-fired units is generally 1-2%/minute of the rated capacity, or 3-6%/minute in newer units, both of which are lower than that of gas-fired units. To improve the ramp rate, software upgrade for the control system and hardware equipment retrofit are necessary. In general, any changes in the ramp rate do not affect the average efficiency of the power plant, but inevitably cause harm to the operating life of some components. **Regarding the start-up time**, it generally depends on whether the coal-fired unit is going through a hot, warm or cold start. A hot start means starting up coal-fired units with less than 8 hours of downtime. A warm start means starting up the units after 8-48 hours of downtime, and a cold start means starting up after more than 48 hours of downtime. A hot start of common coal-fired units usually takes about 3-5 hours. The most advanced and cutting-edge units in the world currently only need 1.5 hours for this process.

**(2) Gas-fired units**

Compared with coal-fired units, a gas and steam combined-cycle unit has great advantages in terms of efficiency, environmental protection, and cost. Its outstanding start-up efficiency and peak regulation performance make it a preferred option for peak shaving. Gas-fired power plants are superior to other types of power plants in footprint, water consumption and environmental protection, leading to their deployment in load centres for power supply in situ. With the rapid development of distributed renewable energy, the advantages of gas-fired power generation are becoming more prominent; these plants help ease the pressure on grid construction and transmission, whilst improving stability of power system operations.

**(3) Oil-fired units**

Oil-fired units also have the advantages of quick start-up, peak shaving performance, high efficiency, and low emission and pollution. An oil-fired plant's peak load regulation function is widely recognized by power systems. In addition, the oil-fired unit supports the system with frequency regulation, standby, black start-up and other services. However, the high costs of power generation have limited the deployment of oil-fired power generation, and these plants have grown rare.

## 2.3 CHARACTERISTICS OF GRID-SIDE FLEXIBILITY RESOURCES

A power grid is an interconnected network for delivering electricity and is the key to power system flexibility. Well-designed construction, operation and scheduling of grids guarantee the safety and reliability of power supply, enhance integration of renewable energy into the power system, and ensure efficient allocation of power resources. Characteristics of grid-side flexibility resources are as follows.

### 2.3.1 INTERCONNECTION

Large power systems are usually divided into regional grids, which are connected by transmission lines that facilitate inter-regional power exchange. If grid A is interconnected with neighbouring grid B, grid B can be considered both a power source and a load for grid A. Electricity networks and interconnections take advantage of different power consumption demands in each region for load adjustment and reduction of reserve and installed capacity. By exchanging electricity between each other through interconnected grids, regions can effectively reduce grid stability reserves, enhance system capability against accidents, and improve the safety and security of power supply. In addition, interconnections help buffer load shocks and power fluctuations, improve quality of electricity, and integrate more wind and solar power into the networks.

### 2.3.2 FLEXIBLE POWER TRANSMISSION

The flexible alternating current transmission system (FACTS) is a new technology that has emerged in recent years. FACTS devices are high-power electronics-based technologies offering real-time controllability to swiftly adjust grid voltage, line impedance and power angle according to the needs of the system. Without causing disturbances in the system, they enhance controllability of the network, increase power system stability, and promote power transfer capability at key points in the transmission grid. This greatly reduces power loss and the generation costs, whilst significantly improving flexibility, stability and reliability of the power grid. The main functions of FACTS are 1) enabling extensive control of power flow along a specified path; 2) enabling transmission lines to be operated closer to capacity without causing disturbances in the system; 3) transmitting more power across controlled areas and reducing thermal backup of the power generation unit; 4) limiting the impact of short circuit and equipment failure and preventing power line tripping; 5) damping control of network congestion or fluctuations caused by equipment damage or overload.

### 2.3.3 MICROGRIDS

A microgrid is built on distributed generation technologies and is a modular energy system consisting of distributed energy sources, loads, energy storage devices, and a control system. It is a locally controlled system and can function both connected to the traditional grid or as an electrical island depending on the demand. Microgrids contribute to improving reliability, power quality and flexibility of power systems. When operating in the grid-connected mode, microgrids become interconnected smart loads that respond within seconds to system demand for more flexibility. In addition, they support integration and stabilization of the intermittent and volatile renewable energy into the grid with the help of energy storage devices and control systems, thus better utilizing variable renewable energy. When operating in island mode, microgrids make use of local energy storage devices and control systems to maintain stable internal voltage and frequency and to ensure supply of electricity to consumers on the grid.

## 2.4 CHARACTERISTICS OF DEMAND-SIDE FLEXIBILITY RESOURCES

As a key source of power system flexibility, demand-side management (DSM) implements various measures to guide and optimize power consumption, which reduces load variations and narrows the peak-valley difference for more effective grid utilization. It can also mobilize load-side response resources to meet flexibility needs and ensure safe and reliable operations with a high share of renewable energy. DSM can be classified into two categories for load management: incentive-based and price-based programs. Both help address the issue of power imbalances in the grid system from the demand side. From a broad perspective, DSM can be considered as a virtual power generation source that responds in the range of seconds, minutes, 10-minute, and medium to long-term time scales. It swiftly implements changes on the demand side and enhances flexibility of the power system.

### 2.4.1 INCENTIVE-BASED DSM PROGRAMS

Incentive-based DSM programs manage and regulate power consumption of specific production processes and living habits through administrative and other means, whilst promoting advanced energy-saving technologies and devices for higher end-use efficiency or change of energy behaviour. Current incentive-based DSM programs include the following: (1) Energy behaviour change: Automatic control devices including time controller and demand limiter can be used for load cycling and intermittent control to achieve peak shifting. Administrative means can encourage end users to use electricity in an orderly manner to reduce or shift load during peak times. (2) Improving end-use efficiency, such as by promoting energy-efficient refrigerators, electric water boilers, inverter air conditioners, and heat-pump water boilers, or by encouraging end-users to both replace inefficient lighting devices with high-efficiency and energy-saving products, and to use advanced control technology to further enhance energy efficiency and lighting quality. Policies can strengthen application of electric motors for regulation services to reduce the no-load ratio and achieve energy-saving operation. Finally, high-efficiency heating technologies such as far-infrared heating, microwave heating, and medium- to high-frequency induction heating are suitable for many applications.

### 2.4.2 PRICE-BASED DSM PROGRAMS

Price-based demand-side management mainly employs electricity tariffs to regulate supply and demand, depending on load variability, to stimulate and encourage end-users to change their energy usage patterns towards less consumption and more conservation. Common methods include the following: (1) Tariff structural adjustment: Common tariff designs in China and worldwide include capacity tariffs, peak-valley time-of-use tariffs, seasonal tariffs, and interruptible tariffs. Different tariffs in the energy market not only mobilize and engage grid operators in demand-side management, but also attract participation of end-users in the process. (2) DSM bidding: Electricity end-users may take energy-saving measures to reduce consumption, and trade the reductions on power exchange through tenders, auctions, and futures for economic returns. (3) Direct incentives allocate appropriate subsidies to end-users, promoters, or producers of energy-saving products with significant peak-shaving performance, to increase engagement in demand-side management activities and to create economies of scale in energy conservation. And End-user Energy-efficiency Awards can recognize outstanding energy-saving solutions to encourage more reduction in energy consumption. Low or zero interest loans can be available for the purchase of energy-efficient equipment, especially for those with high initial investment. This helps reduce the financial barriers to participating in DSM programs. Free installation or leasing of energy-saving equipment for low-income or less motivated users can be designed such that equipment costs are recovered in phases through energy-saving benefits.

## 2.5 CHARACTERISTICS OF ENERGY STORAGE AS A FLEXIBILITY RESOURCE

Energy storage technologies facilitate load shifting, improve operational stability of the power system, adjust frequency and compensate for load fluctuations. Energy storage significantly improves the utilization efficiency of renewable energy. Common energy storage technologies include battery energy storage, pumped-storage hydropower (PSH), flywheel energy storage, and compressed air energy storage. PSH transforms excess electricity during low-load times into high-value power during peak periods, which not only helps regulate and stabilize frequency, phase, current and voltage of power systems, but also functions as emergency backup. The unit is an important flexibility resource for power systems. Table 1 compares the performance of various energy storage technologies under general conditions. Batteries and flywheel energy storage have short response time but small capacity and low cost-efficiency. Compressed air energy storage offers capacity of up to 100 GWh but its response time is long. Energy storage technologies supply or store a large amount of real power for power systems. Technologies such as PSH are an important source of power system flexibility. With rapidly-evolving technologies, different energy storage methods can meet the need for flexibility across timescales.

**Table 1 Performance comparison of energy storage technologies (2018 estimates)**

| Energy storage method | Capacity (GWh) | Response time | Efficiency (%) | Investment (RMB/kWh) | Service life (yr.) |
|---|---|---|---|---|---|
| Battery Energy Storage (BES) | <0.2 | <1s | 70-90 | 800-4800 | 20-30 |
| Pumped storage hydropower | >2 | 10s-40min | 87 | 45-85 | 40 |
| Flywheel energy storage | <0.5 | <1s | 90-93 | 170-420 | 20-30 |
| Compressed air energy storage | <100 | 1-10min | 80 | 12-85 | 30 |

## 2.6 CONCLUSIONS

Research on power system flexibility is still in its infancy. Overall, power system flexibility refers to a system's ability to reliably manage the variability of demand and supply, thereby achieving safe and stable operation of the system. So far, flexibility has become another important indicator of power system performance in addition to safety, reliability and economy. Flexibility resources are available in different forms on the supply side, the grid side, the demand side, and energy storage. Their diverse characteristics support the upward and downward regulation of power systems in different ways, thus enabling the system to flexibly satisfy demand.

# 3 POWER SYSTEM FLEXIBILITY RESOURCES IN GERMANY

Located in Central Europe, the Federal Republic of Germany borders Denmark to the north, the Netherlands, Belgium, Luxembourg and France to the west, Switzerland and Austria to the south, and the Czech Republic and Poland to the east. The country covers a territorial area of 357,167 km$^2$ and a population of 82.93 million. Germany is one of Europe's four largest economies with a gross domestic product (GDP) of US$ 4.0 trillion in 2018. As early as the 1980s, Germany has proposed a renewable energy development strategy. By the end of 2018, Germany's total installed power generation capacity reached 220 GW, of which renewable energy accounted for more than 58.4%. Its total domestic power generation exceeded 595.6 TWh, of which renewable energy accounted for about 35%. Among these, the share of wind power was 17.2%, solar power 7.1% and biomass power about 8.0%.

**Figure 1 Renewable energy generation in Germany, 1990-2018**

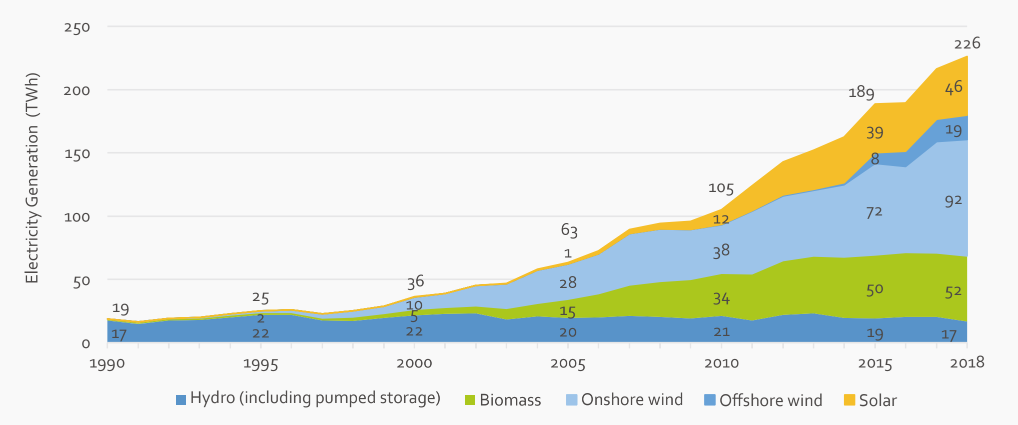



**Figure 2 Renewable energy share in power generation in Germany, 2010-2018**

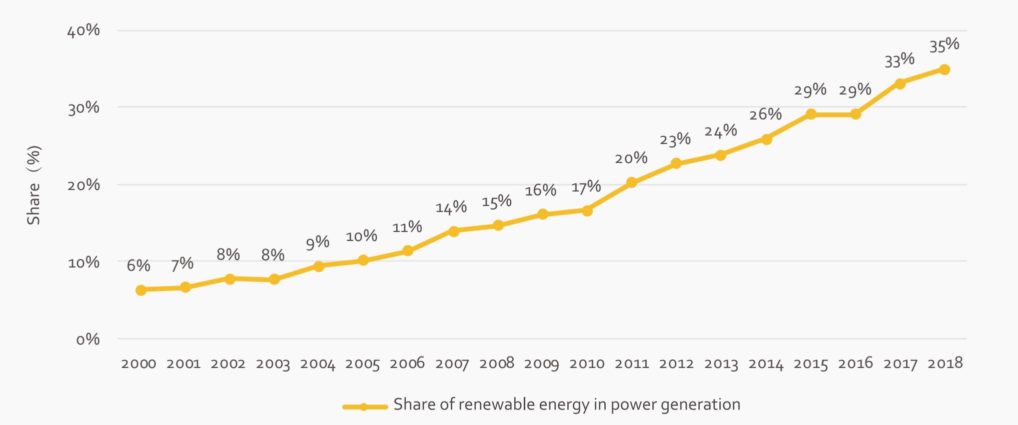



**Figure 1, Figure 2**

Source: Data for 1990 to 2017 are from the Federal Ministry for Economic Affairs and Energy (BMWi), December 2018; the 2018 data are from AG Energiebilazen e.V. (AGEB), March 2019

As biomass power generation faces cost and resource constraints, wind and solar power have become the main sources of newly-added renewable capacity in Germany. However, the significant increase in the share of wind and solar power has placed higher demands on flexibility of the German power systems. In the winter month of January 2019, for example, the net load (after deducting renewable supply) of the local power system became highly volatile despite the supply of renewable energy. Germany has made full use of different flexibility resources, such as thermal power units, trans-regional and trans-national power transmission, demand-side response, energy storage technologies and multiple power markets, to ensure safe and reliable operation of its power system whilst maintaining the curtailment rate of renewable energy within a reasonable range of 2-4%. However, the wind curtailment rate starts to increase when the share of renewable energy in power generation exceeds 30%.[6]

**Figure 3 Electricity consumption and net load which deducted renewable energy supply in the first week of 2019 in Germany**

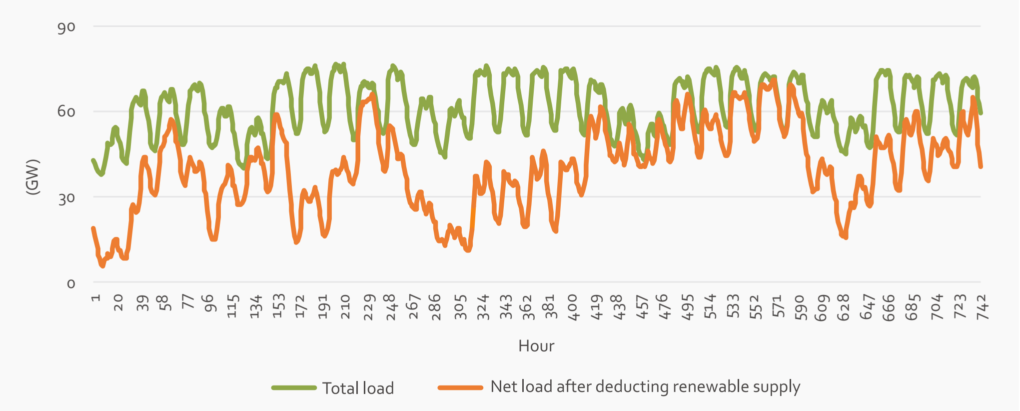



**Figure 3**
Source: Fraunhofer ISE, accessed in August 2019

**Table 2 Wind and solar curtailment rates in Germany, 2010-2016**

| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016. |
|---|---|---|---|---|---|---|---|
| Wind curtailment rate | 0.33% | 0.83% | 0.70% | 0.92% | 2.80% | 4.95% | 4.36% |
| Solar curtailment rate | - | - | - | - | - | - | 0.46% |

**Table 2**
Source: 2010-2016 data from Imperial College, 2018; Q1 2019 data are based on sources from the BNetzA, accessed in December 2019

## 3.1 SUPPLY SIDE FLEXIBILITY RESOURCES

In Germany, thermal power, nuclear power, pumped storage hydropower and biomass power generation are considered dispatchable power supply. By the end of 2018, installed capacity of dispatchable power supply in Germany exceeded 110 GW, accounting for 50.2% of the total installed capacity.[7] Specifically, thermal power units and pumped storage hydropower are the main sources of flexibility on the supply side. Pumped storage hydropower will be further covered in the subsequent chapter on energy storage.

Figure 4 Installed capacity by energy type in Germany in 2018

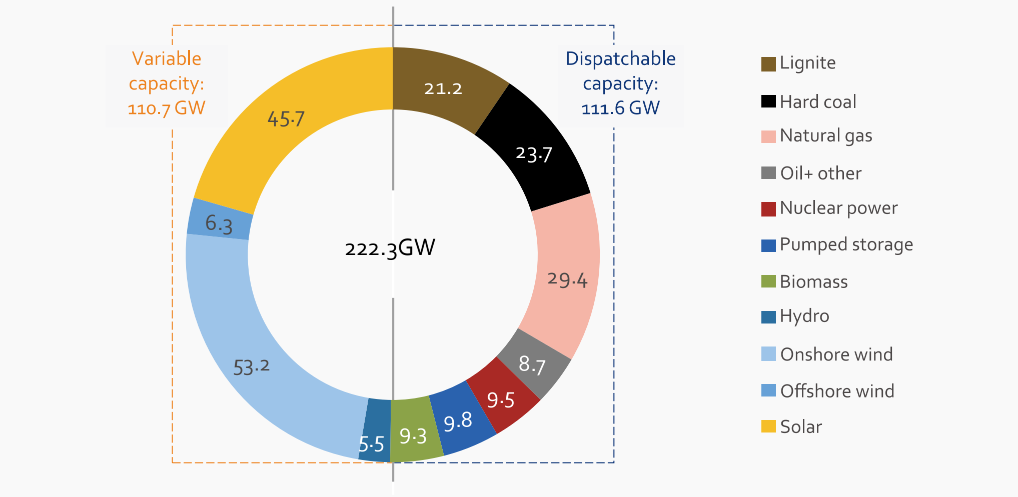



Figure 4
Source: Agora Energiewende, August 2019

### 3.1.1 THERMAL POWER UNITS

Germany's flexible thermal power units consist of four main types: hard-coal-fired units, lignite-fired units, open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT). At the end of 2018, the installed thermal power capacity in the country exceeded 83 GW, accounting for 37.3% of total capacity. Lignite-fired units were 21.2 GW, hard-coal-fired units 23.7 GW and natural gas units 29.4 GW. In 2018, Germany generated 317.3 TWh electricity with thermal power in 2018, accounting for 49.1% of the national power generation. Lignite-fired units contributed 145.5 TWh, hard-coal-fired units 83.2 TWh, and natural gas 83.4 TWh. Germany's coal power is dominated by large power generation units, which account for 56.7% of capacity. 68.1% coal-fired units are combined heat and power (CHP) units, nearly half of which have a single capacity of over 600 MW and 35% between 300 and 600 MW. Gas-fired units are mostly small-scale power generation units, of which gas CHP accounts for 59.4% of the total installed capacity. The majority have a single unit capacity of less than 300 MW.

Figure 5 Thermal power units in Germany, 2018

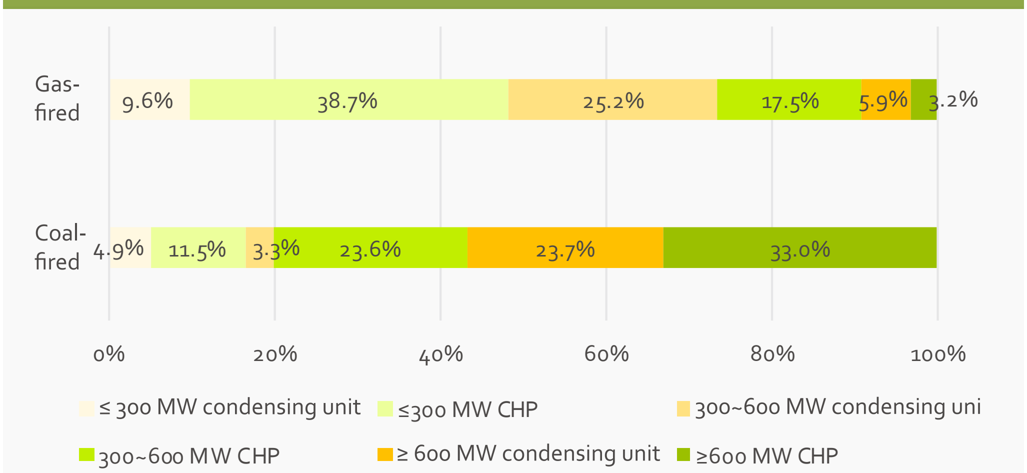



Figure 5
Source: Open Power System Data (OPSD), December 2018

### 3.1.2 ANALYSIS OF FLEXIBILITY PARAMETERS OF THERMAL POWER UNITS

As more renewable energy connects to the grid, many thermal power plants in Germany face closure due to low capacity utilization levels. Thus, providing power system flexibility becomes a new source of profit for thermal plant operators. several flexibility-boosting measures are available to operators: reducing minimum output, increasing ramp rates, shortening start-up times, and adding heat storage to CHP units. A 2017 study from Agora Energiewende found that among the four types of thermal power units, OCGTs are the most flexible whereas lignite-fired units are the least flexible.[8] The average ramp rate of regular OCGTs is 8-12% per minute, which is 4-6 times that of other units. OCGT hot and cold start times are only 5-11 minutes compared to 3-4 hours for CCGTs and 1-10 hours for coal-fired units. The minimum stable output of hard-coal-fired units is outstanding, which is as low as 25-40% of the rated capacity. The figure is about 40-60% of rated capacity for the other three types of units.

To further explore sources of flexibility on the supply side, Germany's thermal power units are undergoing technological innovation and upgrading. Lignite-fired units have the greatest potential for improvement, since the minimum stable output of the most advanced units can be reduced from 50-60% of the rated capacity to 35-50%, the ramp rate from 1-2% per minute to 2-6% per minute, the hot start time from 4-6 hours to 1.25-4 hours and the cold start time from 8-10 hours to 5-8 hours. The increased flexibility of gas-fired units mainly shows in the further reduction of the minimum output. Advanced OCGT and CCGT units already reach the same level of minimum stable output as coal-fired units. Minimum stable output of certain OCGT units is even approaching 20% of the rated capacity. As the share of natural gas continues to rise in the future, gas-fired units are expected to be the most important source of supply-side flexibility in Germany.

**Figure 6 Flexibility parameters of the 4 types of thermal power units in Germany**

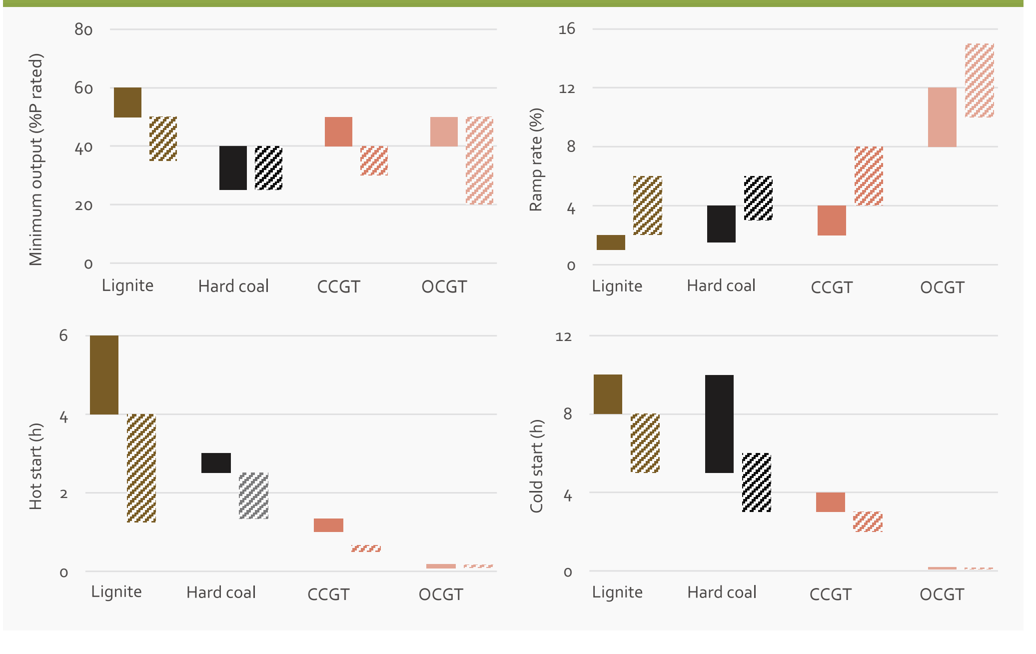



**Figure 6**

Note: The left column for each type of unit represents common technical conditions and the right represents the most advanced technical conditions.

Source: Agora Energiewende, 2017

### 3.1.3 ANALYSIS OF FLEXIBILITY OF CHP UNITS DURING HEATING SEASONS

The heating season in Germany typically runs from October through to April.[9] CHP units are set up to first meet the heating demand in winter. With the increasing share of wind and solar power, large heat storage units are used to achieve heat-power decoupling of CHP units and to increase flexibility of thermal power. For example, the Lausward Fortuna combined cycle gas turbine power plant in Düsseldorf has the world's largest hot water accumulator that can accommodate up to 36,000 m$^3$ water and can run at full load in less than 25 minutes after a hot start, providing flexibility for the grid.[10] Even if the plant is shut down for several days, it can run the whole city's heating from the huge water reservoir.

**Figure 7 Load curve and generation curve in Germany, January 2019**

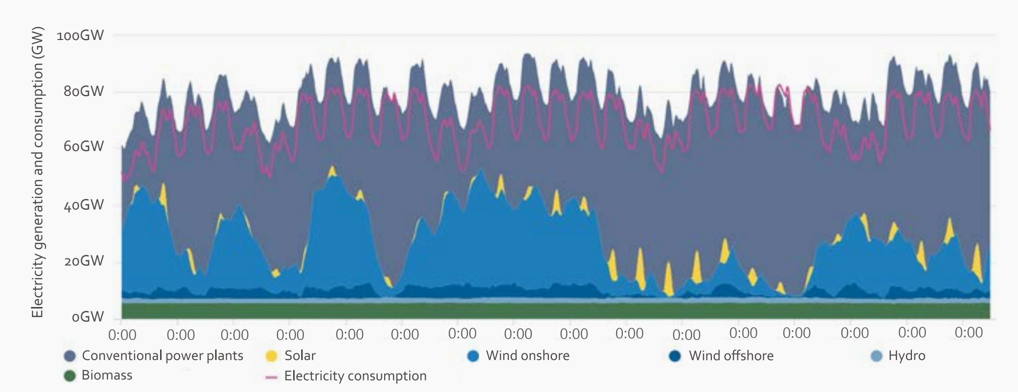



**Figure 7**
Source: Agora Energiewende, accessed in August 2019

## 3.2 GRID SIDE FLEXIBILITY RESOURCES

While Germany's share of renewable energy generation is increasing, its system average interruption duration index (SAIDI) is actually declining, and reached just 13.91 minutes in 2018.[11] To maintain stable grid operations, the cost of congestion management on the German grid has increased significantly in recent years, and was 6.7 times higher in 2018 than that in 2013.[12]

This study focuses on interconnections of large-scale power grids. Thus, this chapter will focus on flexibility enabled by cross-border power exchange.

**Figure 8 SAIDI in the German power system from 2006 to 2018 (left); cost of grid congestion in Germany from 2010 to 2018 (right)**

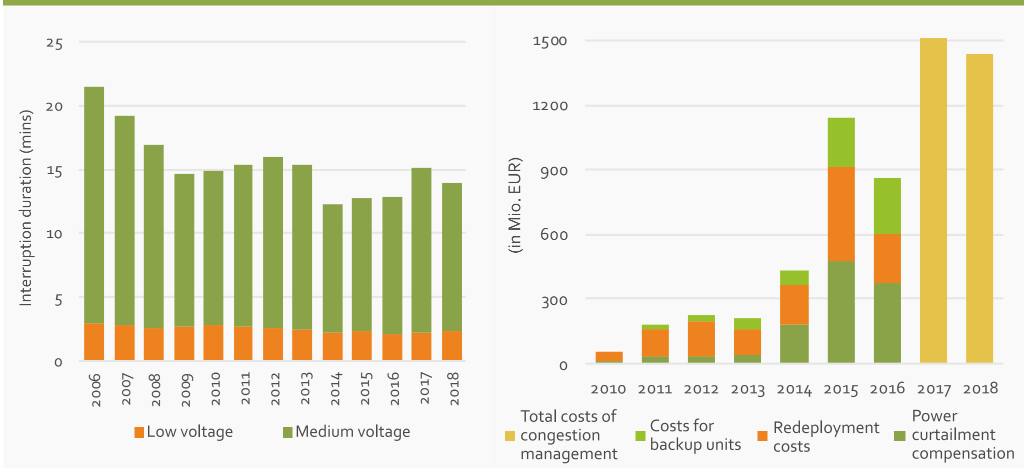



**Figure 8**
Note: Onshore wind power is primarily connected to high- or medium-voltage grids, while PV projects are primarily connected to low-voltage grids.
Source: (left) BNetzA, accessed in December 2019; (right) 2010-2016 Data from Imperial College, March 2018, 2017-2018 Data from BNetzA, August 2019

### 3.2.1 DEVELOPMENT OF CROSS-BORDER POWER GRID INTERCONNECTIONS

In Germany, the maximum voltage for electricity transmission is 220 kV or 380 kV. The total length of the main transmission grid is around 35,000 km, operated and managed by the four transmission system operators (TSOs), namely Tennet, Amprion, 50Hertz, and Transnet. Germany is a member of ENTSO-E, the European Network of Transmission System Operators, and belongs to UCTE, one of the five synchronous areas. The state connects to neighbouring grids mainly by 380-400 kV (red) and 220 kV (green) AC transmission lines, and to other synchronous grids by high-voltage DC transmission lines (pink). Germany is currently engaged in real-time cross-border power exchange with nine neighbouring countries.

**Figure 9 Five synchronous areas for European interconnected grids (left); German cross-border transmission lines (right)**

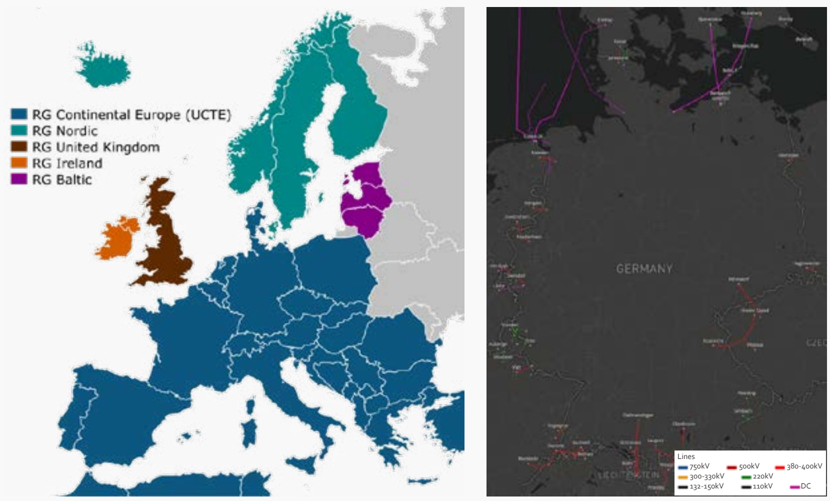



**Figure 9**
Source: (Left) Wikipedia, accessed in July 2019; ENTSO-E, January 2019

As a country with a high share of renewable energy capacity, cross-border power transmission plays an important role in renewable energy consumption in Germany. For example, when there is large amount of excessive electricity generated by renewable energy in Germany, Austria and Luxembourg may benefit from low energy prices by purchasing the excessive German electricity from the electricity market. Cross-border power exchange also provides a safe and stable operation for the German power system in the case of unexpected events. For example, during the solar eclipse on 20 March 2015, Germany imported 169% more electricity from Denmark between 9 and 10 a.m., shifting from electricity exports to imports from Sweden, and receiving an additional 423 MW of power from Switzerland.[13]

**Figure 10 Germany's conventional energy generation and net exports of electricity, March 20, 2015 (left); electricity imports and exports (right)**

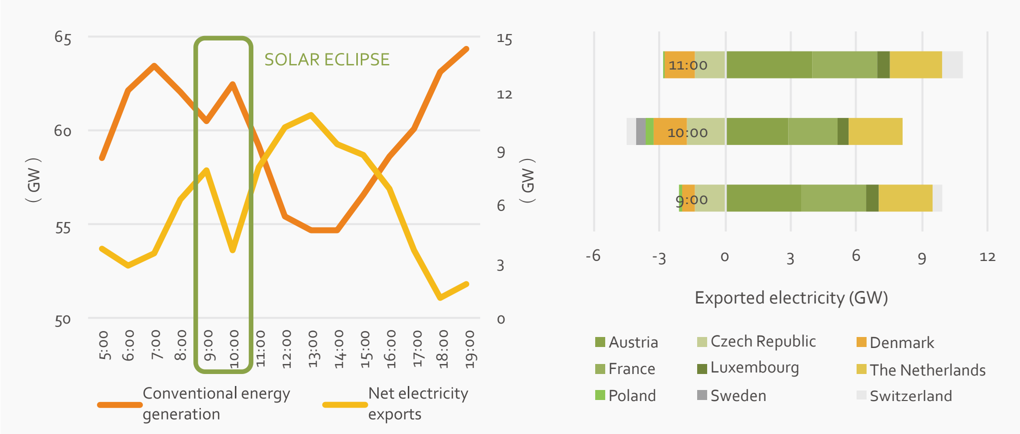



Figure 10
Source: Agora Energiewende, accessed in July 2019

### 3.2.2 MEASURES FOR IMPROVING GRID FLEXIBILITY

To improve grid flexibility and prevent congestion, Germany has developed its grid using the GORE principle, which place grid optimisation prior to grid reinforcement prior to grid expansion.[14] Grid optimization measures include remote control of renewable energy power plants and real-time generation data tracking systems. Grid reinforcement includes temperature monitoring equipment for transmission lines and use of phase-shifting transformers. Grid expansion policies focus on reducing cost and improving public acceptance.[15]

## 3.3 DEMAND SIDE FLEXIBILITY RESOURCES

Germany's resources for demand-side flexibility come mainly from industry, the tertiary sector and private households. Price-based demand-side management is the main form of such flexibility. In 2014, the German Aerospace Centre (DLR) assessed the potential for load reduction demand response in Germany at 13.8 GW, or about 17% of the highest load in the country. The potential for load enhancement demand response was estimated at 32.3 GW, or about 40% of the highest load.[16] From the perspective of cost-efficiency, the fixed costs of demand-side response of German industries is between Euro 0.2-8/kW with variable costs not higher than Euro 0.5/kW, which is only a tenth of the cost of a power plant flexibility retrofit. However, only aluminium companies in the industrial sector are currently engaged in the process to scale up demand-side flexibility.[17]

**Table 3 Theoretical potential of various demand-side response resources in Germany**

| Unit (GW) | Total | Industry | Tertiary sector | Private households |
|---|---|---|---|---|
| Load reduction | 13.8 | 3.5 | 3.8 | 6.4 |
| Load enhancement | 32.3 | 0.7 | 4.2 | 27.4 |

Table 3
Note: Load reduction demand-side response potential is the demand-side average load that can be interrupted or delayed for a minimum duration of 1h; load enhancement demand-side response potential is the demand-side average load that can be brought forward for a minimum duration of 1h.
Source: German Aerospace Centre (DLR), 2014

### 3.3.1 FLEXIBILITY RESOURCES FROM INDUSTRY

Industrial users provide demand response through quickly ramping up or slowing down production activities, or changing production times. According to studies by Deutsche Energie-Agentur (dena), all industrial sectors in Germany such as metallurgy, chemicals, rubber and plastics industries offer varying degrees of demand-side flexibility.[18] Large and energy-intensive enterprises can implement flexibility independently, whilst small energy-using enterprises contribute through virtual power plants (VPP). The Research Centre for Energy Economics (FfE) estimates that Germany has 9 GW industrial load available for demand-side response of less than 5 minutes during interruptions, and 2.5 GW load for providing flexibility for more than 1 hour continuously.[19] Among them, chemical and metallurgical enterprises have greater potentials in demand response. For example, Trimet is Germany's largest aluminium producer and smelter and the most advanced industrial flexibility provider. It has the capacity to regulate load of 80 to 600 MW per second and provide primary and secondary control reserves and interruptible loads to the electricity system.[20]

**Figure 11 Technical potential for industrial demand-side response in Germany**

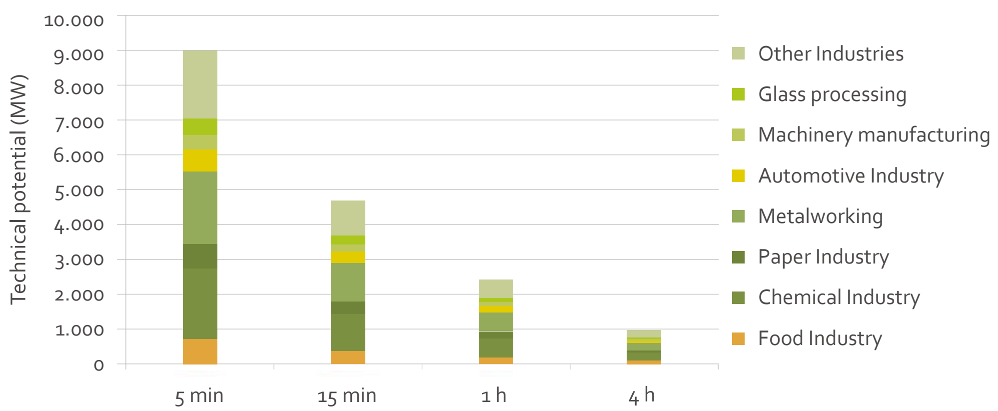



Figure 11
Source: The Research Centre for Energy Economics (FfE), 2011

### 3.3.2 FLEXIBILITY RESOURCES FOR THE TERTIARY SECTOR

According to a 2014 assessment by DLR, the theoretical potential for load reduction and load enhancement demand response in Germany's tertiary sector exceeded 4 GW, of which nearly half is from commercial ventilation.[21] Fraunhofer ISI interviewed 1,000 companies in the service sector and identified significant flexibility potential in buildings such as hotels, office buildings and restaurants.[22] They may participate in the spot market or balance market as secondary control reserve and minute reserve via the VPP model. The service sector currently is not able to fully unleash its flexibility potentials due to the lack of effective incentives.

### 3.3.3 ELECTRIC VEHICLES AS FLEXIBILITY RESOURCE

The number of electric vehicles (EVs) in Germany reached 180,000 in 2018[23] with 7,900 AC charging piles and more than 1,400 DC charging piles.[24] Electric vehicles are a potential source of flexibility: Vehicle-to-Grid technology (V2G) is in the pilot phase in some regions. Next Kraftwerke, a German VPP integrator and Jedlix, a Dutch smart charging platform operator, plan to work together on a pilot project to provide secondary control reserve for EV batteries from 2019.[25] The project will provide positive or negative frequency control services to the German power system.[26]

**Figure 12 Projected cumulative number of new electric passenger cars in Germany**

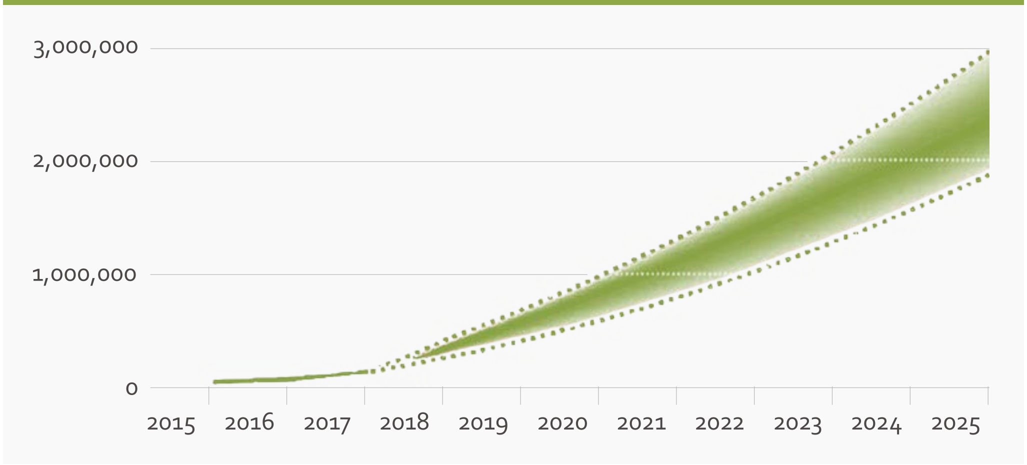



**Figure 12**

Source: The National Platform for Electric Mobility (NPE), May 2018

## 3.4 ENERGY STORAGE FLEXIBILITY RESOURCES

Energy storage facilities in Germany mainly include pumped-storage hydropower, battery energy storage, compressed air energy storage (CAES), and Power-to-X (PtX). As of 2018, the installed capacity of energy storage in Germany has reached nearly 7.9 GW, providing fast and short-term flexibility to the power system. Specifically, pumped storage has still the largest installed capacity and is the most economical option in Germany. With the development of technology and cost reduction, batteries as storage also start to be commercially deployed on a large scale with diverse technologies and business models. CAES has the advantage of high flexibility and stable operation, but is limited by stringent construction conditions. Currently there is only one commercial project in Germany. Power-to-X technology remains in the small-scale pilot stage and is expected to achieve large-scale commercial operation after 2020.

**Table 4 Installed capacity of different energy storage technologies in Germany, 2018**

| | Total | Pumped storage hydropower | Commercial batteries as storage | Household batteries as storage | Compressed air energy storage | Power-to-X |
|---|---|---|---|---|---|---|
| Installation (MW) | 7,897 | 6,800 | 370 | 380 | 321 | 26 |
| Proportion | - | 86.10% | 4.70% | 4.80% | 4.10% | 0.30% |

Table 4
Source: Pumped-storage hydropower data are from International Hydropower Association, May 2019; commercial batteries as storage data are from GTAI, accessed in August 2019; household batteries as storage data are estimates from Clean Energy Wire, October 2018; compressed air energy storage data are from GIZ, January 2019; Power-to-X data are from TÜV, March 2019

### 3.4.1 PUMPED STORAGE HYDROPOWER

Germany has been constructing PSH plants since the late 1950s. As of year-end 2018, its installed capacity of pumped storage reached 6.8 GW, mostly located in central and southern Germany.[27] Approximately 3 GW PSH plants in neighbouring Luxembourg, Switzerland and Austria are under management of German grid as well.[28] Germany's PSH plants typically have a minimum stable output of about 30% of rated capacity and can ramp to maximum capacity in 75 to 100 seconds. They provide primary, secondary and minute reserves for the balancing market. For example, Goldisthal, Germany's largest pumped storage power plant, located in Thuringia, has an installed capacity of 1.06 GW.[29] It purchases inexpensive surplus electricity from lignite-fired power plants during off-peak hours for storage and contributes to peak shaving when demand hits. Its single-unit operating capacity can be increased from a minimum of 40 MW to 265 MW at full capacity in a matter of seconds.

### 3.4.2 BATTERIES AS STORAGE

With the decline in battery costs, batteries as energy storage are developing rapidly in recent years. In 2018, the installed capacity of battery energy storage in Germany reached about 700 MW, of which 52.9% are commercial projects and 47.1% are household projects.[30] At present, batteries as storage provide primary control reserve, secondary control reserve, balancing grid supply and demand and providing reactive power compensation for the German power system.[31] The installed capacity of commercial storage batteries for primary control reserve is about 371 MW and most are Li-ion batteries.

**Figure 13 New and total installed capacity of commercial energy storage batteries, 2012-2018 (left); locations of battery energy storage projects as primary control reserve, 2018 (right)**

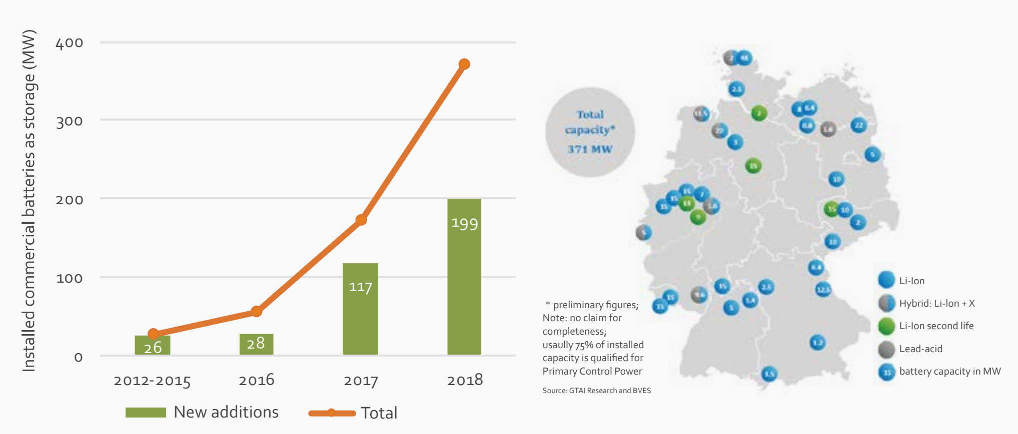



**Figure 13**
Source: (left) GTAI and Inspiratia, March 2019; (right) GTAI and the German Energy Storage Association (BVES), accessed in August 2019

About 100,000 households in Germany have their home energy storage system connected to the grid. Sonnen, a German battery manufacturer is preparing to engage several thousand PV+battery storage users in the primary control reserve service.[32] According to the arrangement, each household will be able to use the energy storage system independently, or in the event of fluctuations in the power system, add it to a virtual battery with a capacity of 1 MW as primary control reserve.

**Figure 14 Number of household batteries as storage systems, 2013-2018**

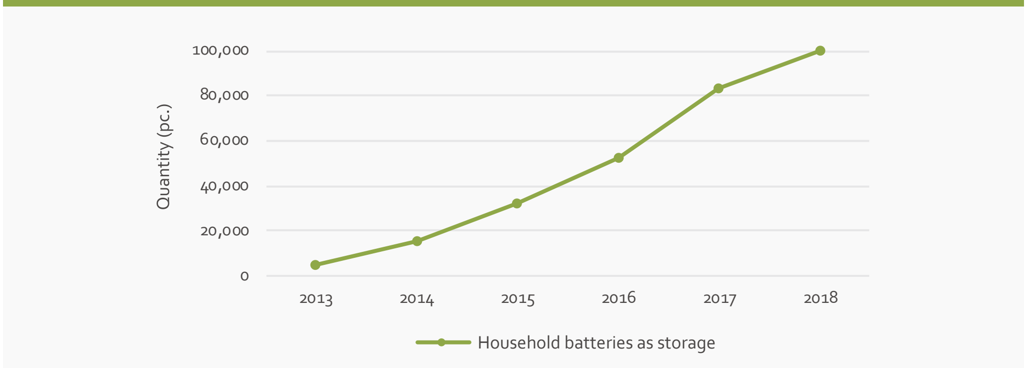



**Figure 14**
Note: Data for 2018 are as of August 2018.
Source: German Solar Association, August 2018

### 3.4.3 COMPRESSED AIR ENERGY STORAGE

Compressed air energy storage (CAES) has been commercially available since the 1970s. It offers the advantages of short start-up time, stable start-ups and fast ramp rate. In Germany, CAES usually provides minute reserve, peak shaving and quick compensation for wind and solar power in the grid. At present, Germany has the largest and longest running CAES project in the world,[33] with a total installed capacity of 321 MW and a continuous power supply for 3 hours at rated power.[34] The project's start-up time is 10-12 minutes, and cold start time can reach 5 minutes in an emergency.[35] The ramp rate is about 30% of rated capacity per minute, more than double that of the most flexible CCGT (8-12%/minute).[36] Start-up stability is as high as 99%.[37]

### 3.4.4 POWER-TO-X

Currently, Germany's Power-to-X (PtX) projects are mainly Power-to-Hydrogen (PtH2) and Power-to-Methane ($PtCH_4$). As of the end of 2018, the total installed capacity of PtX projects larger than 50 $kW_{el}$ in operation in Germany amounted to 26 MW,[38] of which approximately 17.5 MW were $PtH_2$ projects and 8.5 MW were $PtCH_4$ projects. The German PtX projects provide certain flexibility in the power system by using surplus renewable energy in the system to produce hydrogen and methane. Although PtX projects currently in operation are all research-oriented or pilot projects which are far from being profitable, they have, to some extent, contributed to the consumption of surplus wind power in northern Germany.[39]

**Figure 15 Installed capacity of PtX projects in 2014, 2018 and 2022 (up); locations of PtX projects in Germany as of March 2019 (down)**

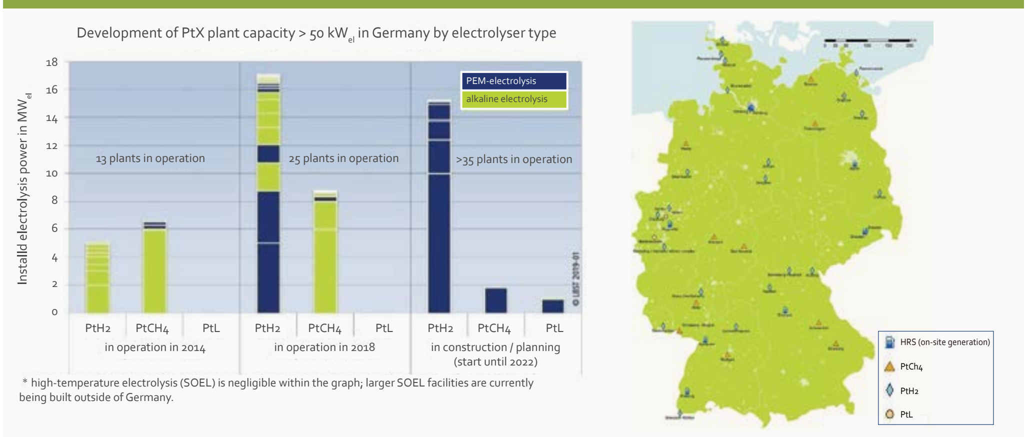



Figure 15
Source: TÜV, March 2019

## 3.5 FLEXIBILITY MARKET MECHANISMS

Various flexibility resources in Germany may participate in the flexibility market through measures such as the balancing market, spot market, congestion management and internal balancing. More details on market mechanisms are available in another GIZ report, Incentivizing Flexibility: The Role of the Power Market in Germany.[40] This chapter provides a brief overview of the balancing market for a better understanding of the characteristics of various flexibility resources.

Depending on the flexibility demand, German transmission system operators determine the flexibility resources for utilization by means of an auction.[41] The primary control reserve usually makes an automatic response to small fluctuations in system frequency. Secondary control reserve is used for unpredictable incidents with great fluctuations. The minute reserve plays a role in large or prolonged power outage incidents, such as a forced shutdown of nuclear power plants. For primary and secondary control reserves which require fast response speed, thermal power units, PSH plants, large industrial producers, and small amounts of battery storage are typically engaged. Minute reserve accommodates more flexible sources, such as CAES and small power users integrated through virtual power plants.

**Table 5 Products and attributes of the German balancing market**

| | Primary control reserve (PCR) | Secondary control reserve (SCR) | Minute reserve (MR) |
|---|---|---|---|
| Tender period | Weekly | Daily | Daily |
| Time of tender | Usually Tuesdays of the previous week | Start of tender: 7 days before day of provision | Start of tender: 7 days before day of provision |
| | | End of tender: Day before provision, 8am | End of tender: Day before provision, 10am |
| Product time slice | Entire week | 4-hour time slice | 4-hour time slice |
| Product differentiation | One offer for positive and negative PCR | One offer for positive or negative SCR | One offer for positive or negative MR |
| Response time | Within 30 seconds | Within 5 minutes | Within 15 minutes |
| Minimum offer | 1 MW | 5 MW | 5 MW |
| | | Minimum 1 MW under certain conditions | Minimum 1 MW under certain conditions |
| Offer pooling | Possible within the same control area | Possible within the same control area | Possible within the same control area |

**Table 5**
Source: German Energy Agency dena, December 2018

## 3.6 CONCLUSIONS

Germany makes full use of a variety of flexibility resources on the supply side, the grid side, the demand side, and energy storage to support flexible operation of its power system. On the supply side, gas turbines and coal-fired units provide fundamental security for power system flexibility. Cross-border interconnections on the grid side play an important role in maintaining stability of the power system and promoting renewable energy consumption. The largest industrial users, the tertiary sector, and electric vehicles on the demand side have the potential to respond with effective means of regulation for market balance. Pumped storage hydropower, battery storage and other storage technologies provide diverse options for the flexible operation of power system. Various types of flexibility resources further support the balancing market to provide primary control reserve, secondary control reserve and minute reserve.

# 4 JING-JIN-JI POWER SYSTEM FLEXIBILITY RESOURCES

Jing-Jin-Ji is one of the economically largest and most dynamic regions in northern China. In the past 20 years or so, Jing-Jin-Ji's population has continued to grow from 90.39 million in 2000 to 112.70 million in 2018. Total GDP has increased by 760% from RMB 990.70 billion in 2000 to RMB 8,514 billion in 2018. Jing-Jin-Ji is also an important regional energy consumption centre in China. Energy consumption has long been dominated by the use of coal, and energy efficiency is relatively low. This is one of the major reasons for the high concentration of air pollutants in this region. As of end 2018, Jing-Jin-Ji's total installed capacity exceeded 100 GW of which renewable energy accounted for 30.2%: hydropower installed capacity was 2.81 GW, thermal power installed capacity 69.41 GW, wind power installed capacity 14.62 GW, and solar power installed capacity 14.02 GW. In 2018, Jing-Jin-Ji's total electricity generation reached 390.60 TWh, and renewable energy electricity accounted for approximately 11.7% of the total electricity: wind power electricity 7.5%, and solar power electricity 3.5 %.

**Figure 16 GDP (RMB100 million) distribution among 13 cities in Jing-Jin-Ji in 2018**

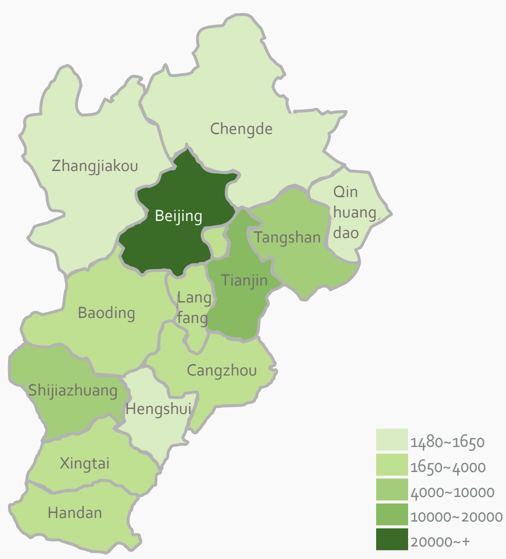



Figure 16
Source: China Statistical Yearbook

**Figure 17 Proportion of renewable energy electricity generation, 2010-2018**

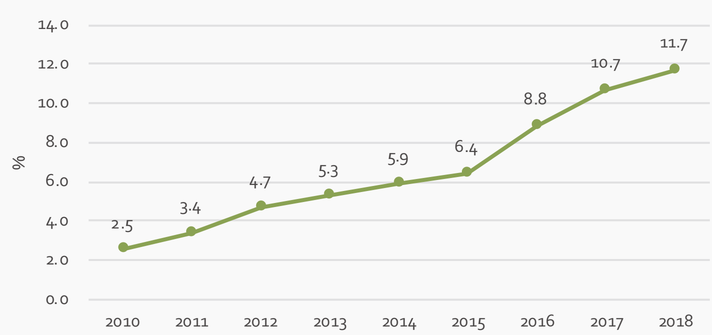



Figure 17
Source: Power Industry Statistics Compilation 2010-2018

At present, renewable energy enjoys good development prospects in Jing-Jin-Ji. Beijing and Tianjin are mainly focused on distributed photovoltaic power generation, while Hebei sees rapid growth in both wind power and photovoltaic power generation. However, Jing-Jin-Ji's renewable energy electricity is still far below the national average, both in terms of installed capacity and electricity generated. At the same time, wind curtailment and solar curtailment are frequently seen in some sub-regions, such as Zhangjiakou, that have a higher percentage of renewable energy, with a record high wind curtailment rate exceeding 20%. Insufficient system flexibility is the main constraint on the development of renewable energy. In addition, as cities in Jing-Jin-Ji successively enter a post-industrial stage, the proportion of industrial load has declined significantly, while the proportion of commercial and residential loads has climbed up rapidly, leading to an increasing peak-valley difference of the power grid, and a decreasing degree of utilization, which means higher requirements for the regulation capability of the power system.

## 4.1 SUPPLY SIDE FLEXIBILITY RESOURCES

In Jing-Jin-Ji, thermal power, pumped storage hydropower, and biomass power generation are considered controllable power supply. As of the end of 2018, the installed capacity of dispatchable power supply in Jing-Jin-Ji exceeded 75 GW, accounting for 72.5% of the total installed capacity. Among these, hydropower occupies a relatively small share in Jing-Jin-Ji. In addition to PSH plants, hydropower also includes agricultural irrigation and water transfer power plants of a certain scale, but with limited regulation capacity. Coal power and gas power are the main regulating power supply in Jing-Jin-Ji.

**Figure 18 Installed capacity by energy type in Jing-Jin-Ji in 2018**

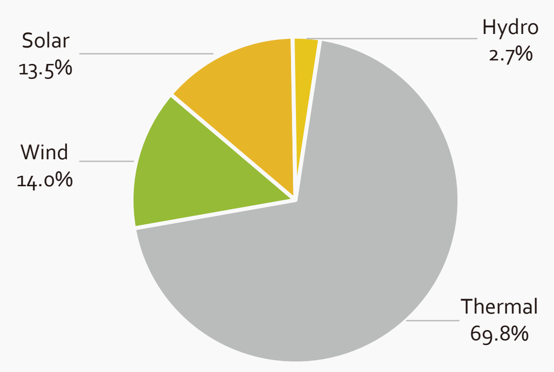



**Figure 18**

Source: Power Industry Statistics Compilation 2018

### 4.1.1 THERMAL POWER RESOURCES

As of the end of 2018, the total installed capacity of thermal power in Jing-Jin-Ji reached 72.63 GW. Among them, the installed capacity of coal-fired units was 55.79 GW, accounting for 76.8% of the total installed capacity of thermal power; gas-fired units 13.05 GW, accounting for 18.0% of the total installed capacity of thermal power; oil-fired units 0.22 GW, accounting for 0.3% of the total installed capacity of thermal power; waste heat and pressure units 2.48 GW, accounting for 3.4% of the total installed capacity of thermal power; and biomass units 0.47 GW, accounting for 0.5% of the total installed capacity of thermal power. By region, the total installed capacity of thermal power in Beijing was 11.19 GW, dominated by gas-fired units with a share of more than 88%. The total installed capacity of thermal power in Tianjin was 15.29 GW, dominated by coal-fired units with a share of 77.6%, and supplemented by gas-fired units claiming 3.17 GW. The total installed capacity of thermal power in Hebei was 46.16 GW, also dominated by coal-fired units with an overwhelming share of more than 93%, and supplemented by a certain number of self-provided power plant waste heat and pressure units. To ensure winter heating, the CHP units take up a high proportion in Jing-Jin-Ji's installed thermal power capacity which is approximately 19 GW. Moreover, waste heat and pressure self-provided power plants basically do not participate in system regulation. All these factors affect the flexibility of thermal power. We estimate that the regulation capacity of thermal power in Jing-Jin-Ji is about 30 GW.

**Table 6 Installed capacity of thermal power in Jing-Jin-Ji as of 2018**

| Unit type | Beijing | Tianjin | Hebei |
|---|---|---|---|
| Coal-fired unit (MW) | 845 | 11,868 | 43,079 |
| Gas-fired unit (MW) | 9,849 | 3,167 | 30 |
| Oil-fired unit (MW) | 219 | 0 | 0 |
| Waste heat and pressure unit (MW) | 8 | 148 | 2,321 |
| Biomass (MW) | 0 | 0 | 471 |

Table 6
Source: China Electricity Council

### 4.1.2 ANALYSIS OF FLEXIBILITY PARAMETERS OF THERMAL POWER UNITS

Jing-Jin-Ji is dominated by coal-fired power units. Due to policies that shut down small units, introducing large units, and restricted smaller plants, most coal-fired units currently operating in the region are relatively new with a capacity above 300 MW and a minimum stable output usually set to 50% of the rated capacity. However, the most recent experience of operation in some areas shows that the minimum stable output of most units of 600 MW and below can reach up to 40% of the rated capacity without increasing any investment in transformation. The ramp rate of coal-fired units in Jing-Jin-Ji is generally 1-2%/minute of the rated capacity, and the ramp rate of some new units can reach 3-6%/minute, but it is still lower than that of gas-fired units. Start-up time is another important flexibility parameter for coal-fired units. In Jing-Jin-Ji, hot start of coal-fired units generally takes 3 to 5 hours, and cold start time is 72 hours.

Table 7 Jing-Jin-Ji improves flexibility parameters of conventional coal-fired units

| Unit type | Flexibility parameter | Currently | International advanced level |
|---|---|---|---|
| Conventional coal power unit | Start and stop time (h) | 72 | 36 |
| | Minimum output (%) | 50 | 20 |
| | Ramp rate (%/h) | 60 | 60 |
| CHP unit | Start and stop time (h) | 72 | 36 |
| | Minimum output (%) | 80-90 | 40 |
| | Ramp rate (%/h) | 30 | 60 |
| Self-provided unit | Start and stop time (h) | - | - |
| | Minimum output (%) | 100 | 50 |
| | Ramp rate (%/h) | - | - |

Table 7
Source: Energy Research Institute of National Development and Reform Commission

### 4.1.3 ANALYSIS OF HEATING SEASON FLEXIBILITY OF CHP UNITS

Winter heating in Jing-Jin-Ji is usually available from November each year through March of the following year. To ensure winter heating needs, CHP units in Jing-Jin-Ji generally operate according to the principle of generating power based on the demand for heat in winter, which makes power generation volume depend on the heat load, thus leading to dramatically reduced regulation capability and increasing the difficulty of load shifting for the grid.

Figure 19 Jing-Jin-Ji power generation curve in January 2019

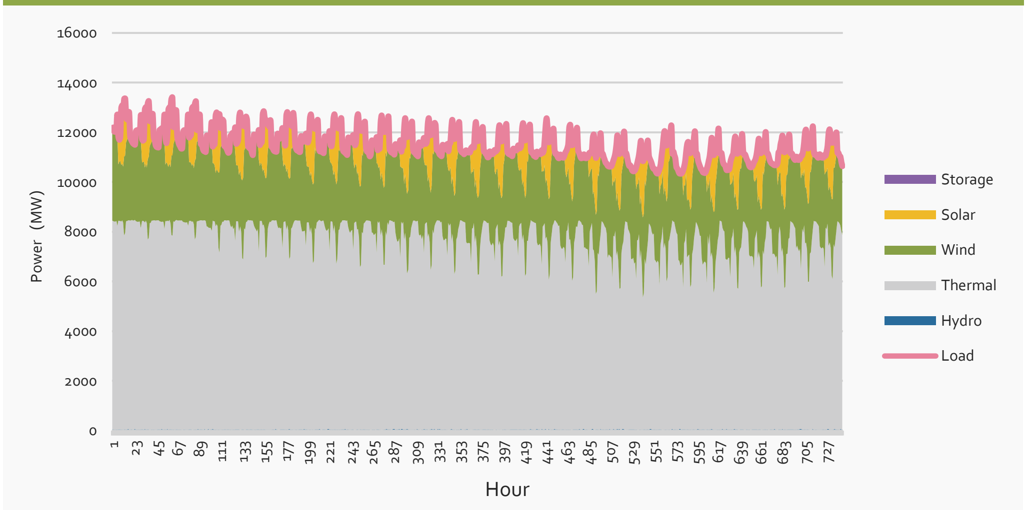



Figure 19
Source: Energy Research Institute of National Development and Reform Commission

## 4.2 GRID SIDE FLEXIBILITY RESOURCES

With the continuous development of power grids, the power supply reliability rates of Beijing and Tianjin power grids exceeded 99.9% in 2017, with an average power outage time of 6.19 hours in Beijing and 6.00 hours in Tianjin, ranking top across the whole country. The power supply reliability rates of North Hebei and Hebei power grids were 99.80% and 99.81%, respectively, at national average with an average power outage time of 16.79 hours in North Hebei and 17.09 hours in Hebei. This suggests a gap from internationally grid reliability standards. To achieve the rapid growth of renewable energy generation and consumption, the region's compensation costs for power ancillary services such as frequency regulation and peak shaving are increasing. In 2018, the region paid RMB 840 million, of which frequency regulation took up 60.2%, peak shaving 36.5%, standby 0.3%, and voltage regulation 2.4%.

### 4.2.1 CONSTRUCTION OF POWER GRIDS IN THE REGION

Jing-Jin-Ji has a reliable power grid, which is a foundation for regional electricity flexibility and interconnection. As of the end of 2018, the length of transmission lines of 220 kV and above in Jing-Jin-Ji reached 48,584 km, of which Beijing accounted for 4,967 km, Tianjin 5,023 km, and Hebei 38,594 km. The capacity of 220 kV and above transformers in Jing-Jin-Ji was approximately 378.59 million kVA, of which Beijing accounted for 81.14 million kVA, Tianjin 58.76 million kVA, and Hebei 238.69 million kVA.

Table 8 Length of transmission lines in Jing-Jin-Ji as of 2018

| Region | 1000 kV (km) | ±800 kV (km) | ±660 kV (km) | 500 kV (km) | 220 kV (km) |
|---|---|---|---|---|---|
| Beijing | | | | 1905 | 3062 |
| Tianjin | 579 | 392 | | 1076 | 2976 |
| Hebei | 1839 | 1044 | 200 | 12417 | 23094 |

Table 8

Source: Power Industry Statistics Compilation 2018

Table 9 Transformer capacity in Jing-Jin-Ji as of 2018

| Region | 1000 kV ('0000 kVA) | 500 kV ('0000 kVA) | 220 kV ('0000 kVA) |
|---|---|---|---|
| Beijing | | 3450 | 4663 |
| Tianjin | 600 | 1725 | 3551 |
| Hebei | 1800 | 9355 | 12714 |

Table 9

Source: Power Industry Statistics Compilation 2018

Jing-Jin-Ji is also promoting the application of flexible transmission in power grids. Zhangjiakou will build the world's first ±500 kV four-terminal flexible DC power grid with a power flow capacity of 3 GW. Flexible DC enhances the support of reactive voltage through independent control of active and reactive powers, which can significantly improve the safety of Zhangjiakou's large-scale renewable energy grid connection. Because there is no synchronization stability problem, unstable renewable energy can be collected at multiple points to form a stable and controllable power supply and solve the problem of transmitting renewable energy. In addition, it will make full use of the complementary characteristics of large-scale wind and solar energy in the region, combined with the flexible peak shaving offered by PSH to ensure effective consumption of renewable energy.

### 4.2.2 CROSS-REGIONAL POWER GRID CONSTRUCTION

Jing-Jin-Ji has established 15 ultra-high voltage and extra-high voltage power transmission corridors connecting its neighbouring provinces, namely, Shanxi, Henan, Shandong, and Inner Mongolia, with a total power exchange capacity of 76 GW, as shown in Table 10. However, the cross-provincial and cross-regional power exchange is relatively inadequate in Jing-Jin-Ji. Flexible dispatching of power grids usually plays an emergency support role during peak load periods such as at the summer peak and the winter peak. For example, during the summer peak in 2018, Jing-Jin-Ji relied on North China Power Grid to carry out 179 inter-provincial and inter-regional contact line support operations, with a maximum support capacity of nearly 9 GW for Hebei and Shandong.

**Table 10 Interconnection between Jing-Jin-Ji and neighbouring provinces**

| Region | Voltage level (kV) | Start point | End point | Number (lines) | Distance (km) |
|---|---|---|---|---|---|
| Shanxi | 500 | Datong | Fangshan | 3 | 245 |
| | 1000 | Beiyue | Baoding | 2 | 175 |
| | 500 | Shener | Baoding | 2 | 240 |
| | 500 | Jinjie (2), Fugu (1) | Shijiazhuang | 3 | 361 |
| | 500 | Guishan | Shijiazhuang | 2 | 68 |
| | 500 | Guishan | Yuanshi | 2 | 79 |
| | 500 | Lucheng | Xin'an | 2 | 134 |
| Henan | 500 | Huan'an | Xin'an | 1 | 67 |
| Shandong | 500 | Liaocheng | Xin'an | 2 | 116 |
| | 500 | Binzhou | Huanghua | 2 | 124 |
| | 1000 | Beiyue | Ordos | 2 | 337 |
| Inner Mongolia | 500 | Tuoketuo | Anding | 4 | 483 |
| | 500 | Daihai | Wanquan | 4 | 194 |
| | 500 | Hanhai | Guyuan | 2 | 200 |
| | 500 | Shangdu | Chengde | 3 | 240 |

**Table 10**
Source: Energy Research Institute of National Development and Reform Commission

### 4.2.3 MEASURES FOR IMPROVING POWER GRID FLEXIBILITY

To improve power grid flexibility and prevent grid congestion, Jing-Jin-Ji improves, repowers and expands power grids on a provincial basis. The development of cross-provincial and cross-regional transmission lines is completed by the grid company in collaboration with relevant provinces and cities. Similar to Germany, Jing-Jin-Ji power grid must meet the needs of power consumption, peak load, load distribution, and load structure. To accomplish these goals and improve flexibility, grid companies begin by prioritizing operational adjustments, enhancements or up-ratings of the existing transmission assets, and finally transmission grid expansion. Operational changes include changes to the allocation of functional components of the power grid. Typically, Jing-Jin-Ji will first guarantee the stable and safe operation of the power grid itself, second it will satisfy the electricity quality requirements of users, and third economically optimize system operations. As for power grid transformation or expansion, grid companies conduct planning based on monitoring historic load growth and power quality, newly forecast demand and identified grid failures, and then coordinate investments in equipment manpower, land and other elements to implement the construction plan, and finally inspect, accept and commission the enhancement or expansion project to ensure reliable operation.

## 4.3 DEMAND SIDE FLEXIBILITY RESOURCES

Jing-Jin-Ji is one of China's most important load centres. Hebei and Tianjin accommodate large industrial loads. Also, the mega-cities of Beijing, Tianjin, Shijiazhuang and Baoding have tremendous commercial and residential electricity demand. All these create basic conditions for Jing-Jin-Ji to develop a power demand side management. As of the end of 2018, Jing-Jin-Ji recorded a total power consumption exceeding 566.90 TWh, of which 7.8 TWh was consumed by the primary sector; 340.2 TWh by the secondary sector; 132.7 TWh by the tertiary sector; 50.3 TWh by urban residents; and 37.9 TWh by rural residents. With the economic development, electricity demand structure in Jing-Jin-Ji has also undergone constant changes.[42] The proportion of the secondary sector has continued to decrease, while the proportions of the tertiary sector and residential electricity consumption have risen significantly. In 2018, the proportions of primary, secondary, tertiary, and residential electricity consumption in Jing-Jin-Ji were 1.6%, 59.2%, 39.7%, and 26.5%, respectively. Compared with 2012, the proportion of the primary sector decreased by 0.6%, the secondary sector decreased by 14.7%; while the tertiary sector increased by 28.2%, and residential consumption increased by 14.1%.[43]

However, due to technical and policy constraints, current demand side management in Jing-Jin-Ji is mainly characterized by administrative promotion of "orderly use of electricity." Demand side management in this region is still evaluated against the two 0.3% rules: the electricity savings and annual demand side management are at least 0.3% of electricity sales and 0.3% of maximum electrical load in the region in the previous year. This 0.3% indicates that demand has a limited role in the power system. Given international experience and the current situation of power demand side management in China, the implementation of power demand side management toward different industries could provide a maximum load shedding of more than 14 GW and an interruptible load of more than 1.7 GW in Jing-Jin-Ji. Electricity demand side management will become an important flexibility resource for Jing-Jin-Ji in the future.

**Figure 20 Power consumption of the primary, secondary and tertiary industries**

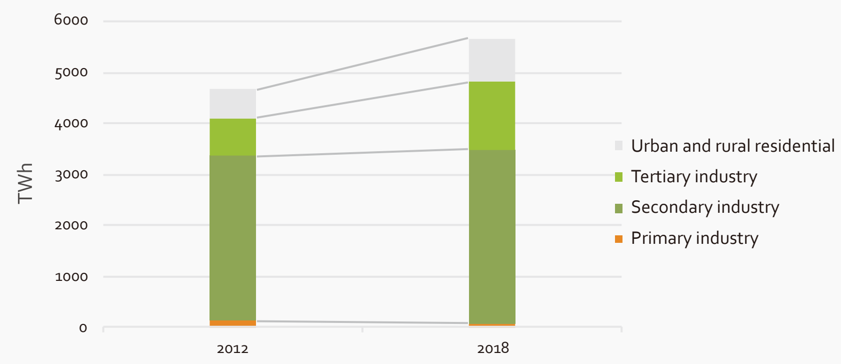



**Figure 20**
Source: Power Industry Statistics Compilation 2018

## 4.3.1 FLEXIBILITY RESOURCES FOR INDUSTRY

Jing-Jin-Ji is the first region in China to involve industrial users in demand response practices. As early as 2012, a series of incentive policies were developed for the research and promotion of demand response technology, the development and procurement of demand response equipment, as well as subsidies for pilot cities and pilot companies. Beijing and Tangshan became the first batch of pilot cities for demand response, where thousands of companies explored and implemented demand response. At present, a technical system supported by load management technology, energy efficiency management technology and automatic demand response technology has been put in place.

The industrial flexibility resources in Jing-Jin-Ji mainly include two types, namely, transferable load and reducible load. Currently, the demand side management of industrial load is still at an exploration and demonstration stage. As for transferable load, (1) steel companies in the region can reduce the peak-valley difference by adjusting the production time to shift the electricity load during daytime peak period to night-time low period. For example, ancillary production departments such as machine repairs may refrain from using electricity during peak hours. (2) Machinery manufacturers in the region have strong transferable load capacity, and therefore huge potential for peak shifting production. For example, some production equipment with high energy consumption, such as electric arc furnaces, heat treatment furnaces, electric welding equipment, and large-scale machine tools can be transferred to regular or valley periods for electricity consumption. (3) Chemical enterprises in the region present distinct peak-valley characteristics. The electricity load of a certain peak period can be reduced by advancing or postponing some production times.

As for reducible load, (1) most steel companies in the region have a certain percentage of interruptible production equipment. For example, electrical equipment in the steel rolling production process is open to a reduction or even suspension of electricity consumption, with a load reduction potential of 10%. (2) Machinery manufacturers in the region may reduce electricity consumption on some production equipment such as electric arc furnaces, and appropriately interrupt electricity consumption for some electric equipment such as intermediate frequency furnaces, which offers large potential of load reduction. (3) Chemical enterprises in the region usually adopt a three-shift continuous production, so their load reduction potential mainly depends on the electricity consumption of ancillary production departments and management departments.

### 4.3.2 FLEXIBILITY RESOURCES FOR BUILDINGS AND TRANSPORTATION

Benefiting from policy support and reduced battery costs, electric vehicles are being integrated into Jing-Jin-Ji's coordinated development. As of the end of 2018, the number of electric vehicles in Jing-Jin-Ji exceeded 310,000, and more than 64,000 public charging piles had been built. It is predicted that the number of electric vehicles in Jing-Jin-Ji will exceed 30 million by 2030. State Grid Corporation of China is now building out an electric vehicle charging network as an important part of the ubiquitous power Internet of Things (UPIoT), and exploring the application of Vehicle-to-Grid (V2G) technology in Jing-Jin-Ji to use the mobile energy storage characteristics of electric vehicles and achieve benign interaction between electric vehicles and the power grid; in addition, during power grid failure, the grid will take advantage of electric vehicles as a mobile power bank to guarantee power supply.

**Figure 21 Development prospects of electric vehicles in Jing-Jin-Ji**

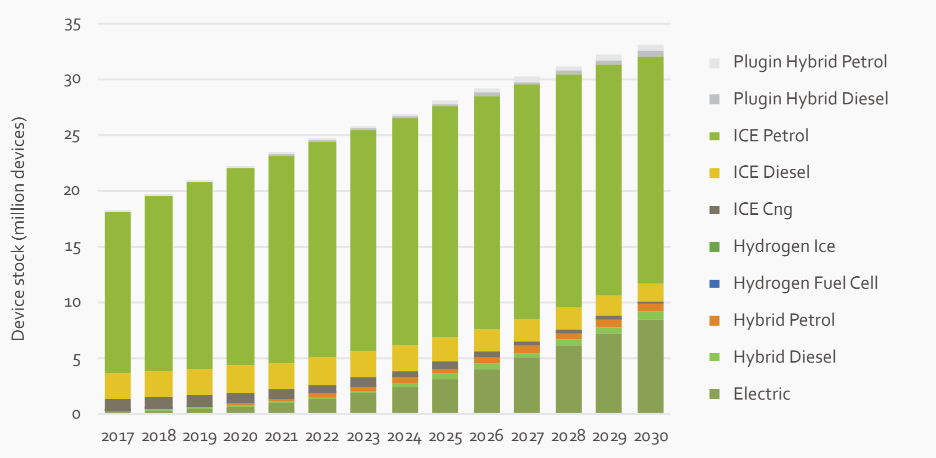



Figure 21
Source: China Renewable Energy Outlook 2019

With the application of automatic control technology and building management systems, the demand response in the field of construction is also developing rapidly. Large buildings such as Beijing Daxing Airport and China Zun CITIC Tower have built ice storage projects to achieve daytime air-conditioning and night-time ice storage. With the changes in Jing-Jin-Ji's industrial structure, the proportion of commercial and residential electricity consumption continues to rise, so does the air-conditioning load. For example, the proportion of air-conditioning load in summer in Beijing has exceeded 40% of the maximum load. Air-conditioning load will be an important demand side flexibility resource in Jing-Jin-Ji.[44]

## 4.4 ENERGY STORAGE FLEXIBILITY RESOURCES

Energy storage facilities in Jing-Jin-Ji mainly include pumped storage hydropower, battery energy storage, compressed air energy storage, and Power-to-Hydrogen (P2H). Among them, the installed capacity of pumped storage hydropower is 2.1 GW, while other types of energy storage are mainly concentrated in demonstration projects, claiming about 32 MW.

### 4.4.1 PUMPED STORAGE HYDROPOWER RESOURCES

As of the end of 2018, the total installed capacity of hydropower in Jing-Jin-Ji was about 2.81 GW, of which, 0.71 GW was from small hydropower, mostly belonging to irrigation, water transfer and other supporting construction. The remaining 2.1 GW was from PSH plants, including 800 MW Shisanling Power Plant, 10 MW Zhanghewan Power Plant, 2.7 MW Panjiakou Power Plant, 0.2MW Miyun Power Plant, and 0.1 MW Gangnan Power Plant. The 13th Five-Year Plan for Hydropower Development has identified Shangyi Pumped Storage Hydropower Plant as a national key project for PSH plants under the 13th Five-Year Plan, with an installed capacity of 1.2 GW. Considering the pumped storage hydropower projects in operation and under planning, such as Fengning, Funing, and Yixian, the total installed capacity of PSH plants in Jing-Jin-Ji is expected to reach 9.3 GW by 2030 (see Table 11). There will be no further large-scale additions due to site resource constraints.

**Table 11 Construction of pumped storage hydropower in Jing-Jin-Ji**

| | Project | Location | Year of first operation | Total installed capacity (MW) | Number of units | Capacity per unit (MW) | Annual electricity generation (GWh) |
|---|---|---|---|---|---|---|---|
| In operation | Zhanghewan | Hebei Xingjing | 2009 | 1000 | 4 | 250 | 1675 |
| | Shisanling | Beijing Changping | 1995-1997 | 800 | 4 | 200 | 1200 |
| | Panjiakou | Hebei Qianxi | 1993 | 270 | 3 | 90 | 200 |
| | Miyun | Beijing Miyun | 1973-1975 | 22 | 2 | 11 | |
| | Gangnan | Hebei Pingshan | 1968 | 11 | 1 | 11 | |
| Planned | Fengning Phase I completed Phase II 2023 | Hebei Fengning | Not in operation | 3600 | 12 | 3 | 3424 |
| | Funing (2030) | Hebei Funing | Not in operation | 1200 | 4 | 3 | |
| | Shangyi (2020) | Hebei Shangyi | Not in operation | 1200 | 4 | 3 | |
| | Yixian (2023) | Hebei Yixian | Not in operation | 1200 | 4 | 3 | |

Table 11
Source: Power Industry Statistics Compilation 2018

### 4.4.2 OTHER TYPES OF ENERGY STORAGE RESOURCES

Battery energy storage, compressed air energy storage and P2H have developed rapidly in Jing-Jin-Ji. However, these technologies are still concentrated on demonstration projects. As of the end of 2018, Jing-Jin-Ji had completed about 32 MW of various types of energy storage (excluding PSH), mainly distributed in the North Hebei Power Grid. Among them, Zhangjiakou has completed the world's first new energy power station with virtual synchronous generator function and a 3 MW electric vehicle battery cascade energy storage demonstration project. The 3,000 $m^2$ solar energy seasonal heat storage demonstration project at Zhuolu Fanshan Huangdicheng has also been put into commission. The 200 MW wind-power-to-hydrogen project is currently under construction in Guyuan. Compressed air energy storage, as well as wind-solar-heat multi-energy hybrid storage and transportation, and a number of other relevant projects have also been demonstrated in China. Except for pumped storage hydropower, other energy storage technologies are not yet fully mature or are not yet cost-competitive. However, the cost reduction trend of battery energy storage shows a faster decline in cost and, due to the current expansion of electric vehicle industry scale in China, the production cost of battery energy storage is expected to be less than RMB 1,000/kWh, close to the cost of pumped storage.

**Table 12 Comparison of battery energy storage technology performance**

| Energy storage method | Investment cost (RMB/kWh) | Electronic control system (RMB/kW) | Annual O&M cost percentage (%) | Energy conversion efficiency (%) | Life cycle (times) |
|---|---|---|---|---|---|
| Lithium-ion batteries | 2000 | 650 | 3% | 90% | 2000 |
| Vanadium batteries | 4225 | 1300 | 3% | 85% | 13000 |
| Sodium-sulfur batteries | 2600 | 1300 | 4% | 80% | 4500 |
| Lead carbon batteries | 1300 | 650 | 3% | 85% | 1000 |
| Cascade of electric vehicle batteries | 780 | 650 | 3% | 90% | 500 |

Table 12
Source: China Renewable Energy Outlook 2019

## 4.5 SUPPORTING POLICIES AND MECHANISMS

Jing-Jin-Ji's existing dispatch plans and arrangements are still characterized by administrative planning, both on the supply side and demand sides. Various dispatch entities have inadequate incentives to proactively engage in system balancing and adjustment. On the supply side, under the current dispatch model (which follows the principle of impartial, reasonable and consultative dispatch, aims to ensure the utilization hours of power generation units and implement the approved annual electricity generation plan) makes owners of existing power generation units reluctant to provide the system with reserve services, peak shaving services and other active services. Some power generation units with high energy efficiency and strong regulation ability are disadvantaged in the dispatch process, which in turn lowers their general willingness to improve energy efficiency and regulation ability. From the perspective of demand side, the Measures for the Orderly Use of Electricity stipulate that in case of power supply-demand tensions, the dispatch center will directly adopt mandatory measures such as peak avoidance, power limiting, and power outages to reduce load and regain balance between power generation and consumption. At present, there is no reasonable economic compensation mechanism in place for users that are subject to forcible electricity limitation or even power outages, thus preventing the effective utilization of the potential of demand-side resources.

The current feed-in tariff mechanism in Jing-Jin-Ji generally uses a benchmarking approach by province and by generation type, which means the feed-in tariff of the same power source in the same province is fixed for a certain period of time. Since this price level is not determined by market competition, it doesn't reflect the supply-demand situation of the power system at different times of the day or year nor does it reflect the current scarcity of reserve resources. Prices also do not guide investment in generation and load flexibility to achieve the optimal allocation of system flexibility resources.

In 2006, to strengthen the management of ancillary services for grid-connected power plants, and improve electricity quality and safe and stable operation, China formulated the Regulations on the Management of Grid-Connection of Power Plants[45] and the Interim Measures for the Management of Ancillary services of Grid-Connected Power Plants,[46] requiring the electric regulatory authority of each of the six subordinate regions (East China, Central China, North China, Northeast, Northwest, and South China) to formulate for their own region a set of Power Plant Management Rules and Power Plant Ancillary Services Rules. With the implementation of these two rules in Jing-Jin-Ji, power generation companies which undertake more ancillary services can receive a certain amount of compensation, while those undertaking less or no ancillary services have to pay ancillary service fees. This to some extent helps increase the enthusiasm of power generation companies to provide ancillary services, so that the system can obtain more flexibility resources. However, the current ancillary service mechanism still has certain deficiencies: (1) the compensation level is insufficient to encourage stakeholders to participate in the system peak shaving; (2) the cost allocation and recovery mechanism of ancillary services needs to be improved; (3) compensation for non-rotating reserves is weak.

## 4.6 CONCLUSIONS

Jing-Jin-Ji's flexibility resources are broadly distributed on the supply side, power grid side, demand side, and energy storage. Thermal power units and pumped storage hydropower are the main sources of power system flexibility in Jing-Jin-Ji. The flexible connectivity of power grids and flexible transmission have played an important supporting role during peak load periods. Demand side management has started early, providing more adjustment means for the balance of power systems in Jing-Jin-Ji. Various types of energy storage and P2H flexibility services are still in a demonstration stage. The Power Plant Management Rules and Power Plant Ancillary Services Rules have to some extent promoted the effective utilization of system flexibility resources in Jing-Jin-Ji. However, it is also notable that various types of flexibility resources in Jing-Jin-Ji need further development, and most aspects of flexibility currently lack incentives, which hinders both utilization of existing flexibility resources and investment in medium- and long-term flexibility resources to ensure sufficient system flexibility.

# 5 QUANTITATIVE COMPARISON OF POWER SYSTEM OPERATIONAL FLEXIBILITY BETWEEN CHINA AND GERMANY

## 5.1 QUANTITATIVE ASSESSMENT METHOD OF GENERATION SIMULATION AND SYSTEM FLEXIBILITY

To analyze power system operational flexibility and quantitatively compare flexibility in Jing-Jin-Ji and Germany, the analysis in this report uses the H3E-Power System Generation Simulation Model, using five system assessment indicators:

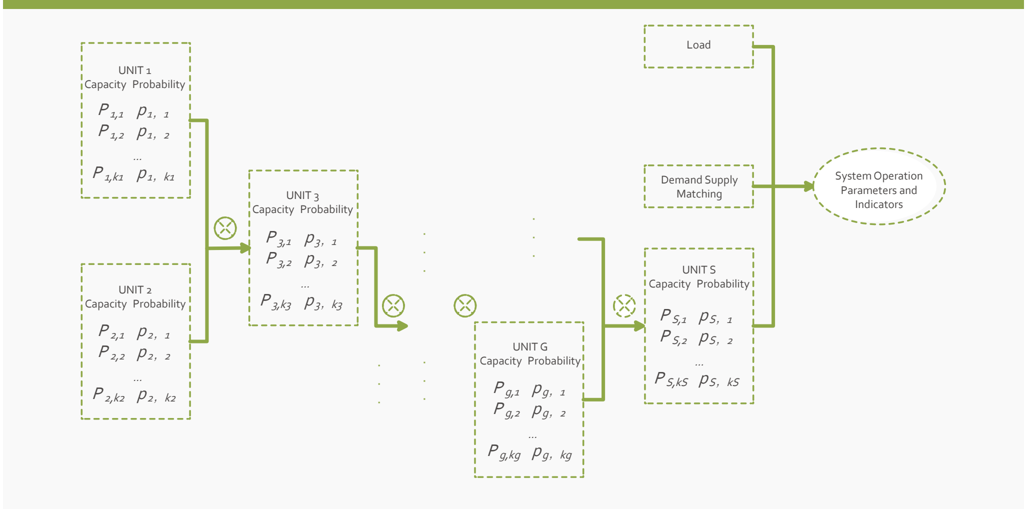
- probability of insufficient upward flexibility (PIUF),
- probability of insufficient downward flexibility (PIDF),
- loss of load probability (LOLP),
- the wind curtailment rate,
- and the solar curtailment rate.

### 5.1.1 H3E-POWER SYSTEM GENERATION SIMULATION METHOD

The H3E-Power System Generation Simulation, jointly developed by the Energy Research Institute of the National Development and Reform Commission and North China Electric Power University, is an important part of the Hummingbird Electricity Economics Engine model system. The H3E-Power System Generation Simulation is a probabilistic random generation simulation, which discretizes the power generation capacity of various types of generator units to obtain a probability distribution of the capacity. Then the joint probability distribution of the total capacity of all units is obtained via combination operation based on the generation capacity of various units to estimate a series of indicators including the expected power generation of each unit and the flexibility and reliability of the operation of the system through supply and demand matching simulation, as shown in Figure 22. Compared to traditional methods for power generation simulation, this approach has the following advantages:

1. It comprehensively accounts for uncertainty of each element of generation, grid, load, and storage within the power system by establishing a multi-state uncertainty model for each element to more accurately study the system's ability to address uncertainties.
2. It quantifies the probabilities of indicators at each point of 8760 time series using a dynamic simulation of time sequences to identify moments with weak indicators.
3. It more accurately reflects the nature of flexibility.

**Figure 22 Schematic diagram of the H3E-Power System Generation Simulation Method**

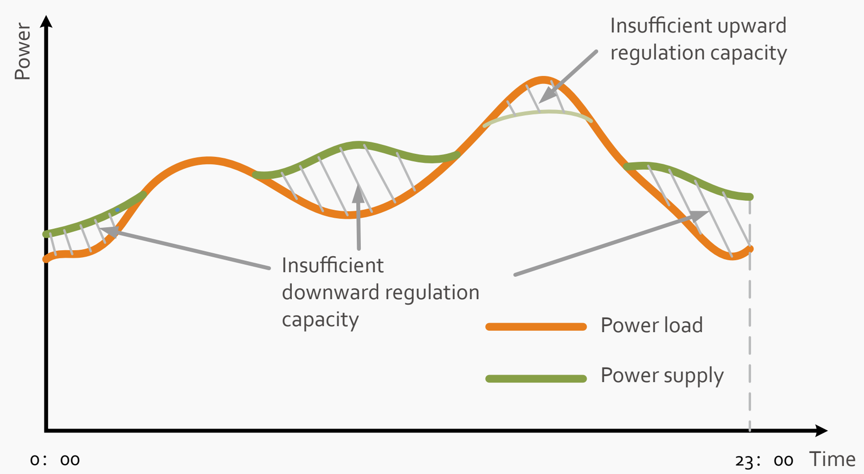


### 5.1.2 FLEXIBILITY AND OTHER OPERATION EVALUATION INDICATORS

Power system flexibility refers to the ability of the system to cope with uncertainty while meeting certain economic and reliability preconditions. This ability manifests itself primarily when uncertainties cause the system's power supply to fall below demand, in which case the system can increase output through upward adjustment, thereby reducing load shedding and meeting demand as soon as possible; when uncertainties cause the system's power supply to exceed demand, in which case the system can decrease output through downward adjustment, thereby reducing curtailment and restoring the supply-demand balance as soon as possible. In accordance with the current definition of flexibility and the requirements for reliable operation of the system, the report proposes five indicators, namely, probability of insufficient upward flexibility (PIUF), probability of insufficient downward flexibility (PIDF), loss of load probability (LOLP), wind curtailment rate and solar curtailment rate, to study the overall flexibility of the power system.

Among the above indicators, PIUF refers to the probability that the output cannot be increased through flexible upward adjustment to avoid load shedding, which indicates the system's ability to follow the increase of load. PIDF refers to the probability that the output cannot be decreased through flexible downward adjustment to avoid curtailment, which indicates the system's ability to follow the decrease of load. LOLP refers to the probability that the power generation capacity of the system cannot meet the load, which reflects the reliability of the system's power supply. The wind curtailment rate and the solar curtailment rate refer to the proportion of wind curtailment power and solar curtailment power to the total wind power generation and solar power generation respectively, which can reflect the system's ability to absorb wind and solar power. Current research has found that the probability of insufficient upward flexibility focuses more on the system's ramping ability, and has a great impact on the loss of load probability of the system. The probability of insufficient downward flexibility focuses more on the ability of the system to reduce the output of conventional units, and insufficient downward flexibility is a major cause of wind and solar curtailment, especially with the increased share of renewable energy installations.[47]

**Figure 23 PIUF and PIDF principles**



### 5.1.3 RESEARCH BOUNDARY CONDITIONS

The simulation for this report is based on 2018 generation and transmission capacity in Jing-Jin-Ji and Germany; the simulation primarily considers the external interconnection lines and ignores transmission constraints within the region. The simulation uses a full year 8760-hour load curve. Northern Hebei experiences a higher probability of insufficient flexibility, LOLP, wind curtailment, and solar curtailment than other parts of Jing-Jin-Ji, and its portion of renewable energy installations and power demand is similar to Germany. For this reason, the report's analysis of policies to improve power system flexibility focuses on this region to evaluate thermal power flexibility retrofits, flexible grid interconnections improvement, increased demand response, as well as energy storage development. This analysis uses current levels of flexibility resources and technologies in Germany, and compares the economic differences of various measures to improve flexibility. Different scenario settings for Germany and Jing-Jin-Ji are shown in Table 13.

**Table 13 Scenario settings in Germany and northern Hebei for the potential of system flexibility improvement**

| | Scenario setting |
|---|---|
| Baseline scenario Germany | Actual 2018 Germany |
| Baseline scenario Jing-Jin-Ji | Actual 2018 Jing-Jin-Ji |
| Northern Hebei thermal power flexibility retrofit scenario | Minimum stable output of condensing units reduced to 30% of the rated capacity. Minimum stable output of CHP units reduced to 40% of the rated capacity in winter. |
| Northern Hebei flexible grid interconnections improvement scenario | Interconnection between northern Hebei and surrounding areas enables flexible dispatch of surplus capacity |
| Northern Hebei demand response release scenario | Demand response results reach an international advanced level capable of achieving 5% peak load transfer and 5% peak load regulation |
| Northern Hebei energy storage development scenario | Energy storage in northern Hebei to reach 2.1 GW, 1/9 of wind & solar installed capacity, based on Germany's ratio of energy storage to wind & solar installation |

## 5.2 QUANTIFICATION OF GERMAN POWER SYSTEM FLEXIBILITY

**Based on this modelling, Germany's power system has relatively high upward flexibility and reliability, 8.39% downward flexibility deficiency probability and a low wind/solar curtailment rate.** Since the share of installed capacity of wind and solar power in Germany has reached 47.3%, huge amounts of wind and solar power has shrunk the output of conventional thermal power units, which usually run at a relatively low output level as a result, allowing the system more room for upward adjustment. In addition, the thermal power generator units in Germany have a strong ramp up ability, resulting in a low PIUF of less than 0.001%. The low PIUF also guarantees the reliability of Germany's power system, where the risk of load shedding caused by insufficient power supply can be reduced by a rapid increase in output. In Germany, LOLP is about 0.11%, corresponding to mere 9.64 hours of annual loss of load time expectation. On the other hand, conventional units operating at lower output levels have caused Germany's ability to reduce its output downwards to avoid wind/solar curtailment to be limited, which results in PIDF as high as 8.39%, and a wind curtailment and solar curtailment of 4.01% and 1.49% respectively in Germany. Germany's PIUF, PIDF, LOLP, wind curtailment rate and solar curtailment rate are shown in Table 14.

Table 14 Main flexibility indicators in Germany 2018

| LOLP (%) | PIUF (%) | PIDF (%) | Wind curtailment rate (%) | Solar curtailment rate (%) |
|---|---|---|---|---|
| 0.11 | $6.11\times10^{-5}$ | 8.39 | 4.01 | 1.49 |

In Germany, the power system's PIUF in winter is higher than in summer, while its PIDF in winter is lower than in summer. Taking the typical maximum load day in summer and in winter in 2018 as an example, due to the large share of CHP units of more than 50%, the room for thermal power adjustment in Germany is smaller in winter than in summer, resulting in a lower upward flexibility and a higher rate of insufficient power supply. The higher loss of load probability mostly occurs during morning and evening peaks. Due to the large load demand in winter, which increases the output level of conventional thermal power units, the downward flexibility deficiency probability of the German system in winter is also lower than that in summer. However, it must be noted that due to the rapid rise of wind and solar power generation at 6 a.m., which has a great impact on the flexibility of the system, resulting in a higher downward flexibility deficiency probability than other time periods. Germany's LOLP and PIDF changes over time in summer and winter are shown in Figure 24-25.

Figure 24 Typical day LOLP in Germany

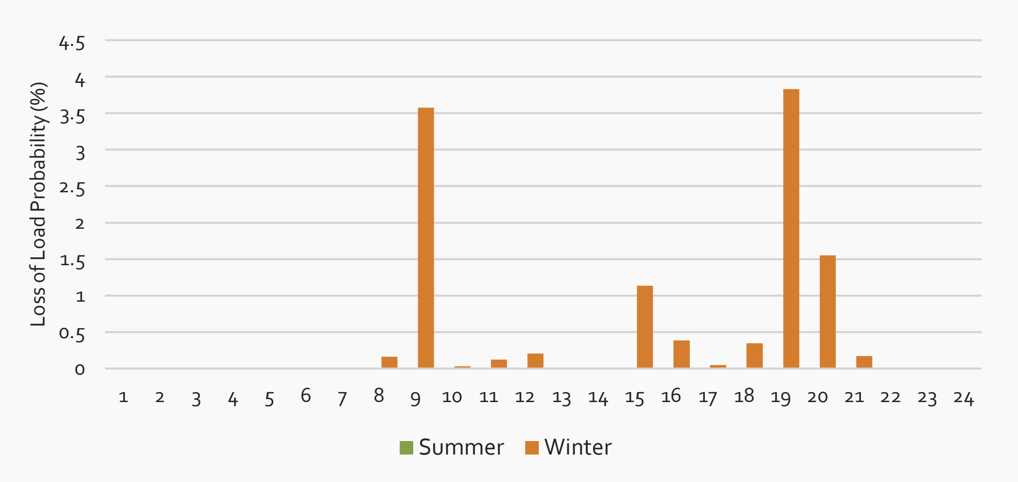



**Figure 24**

Note: Some data in the figure are not shown in the diagram because the value is too small.

Figure 25 Typical day PIDF in Germany

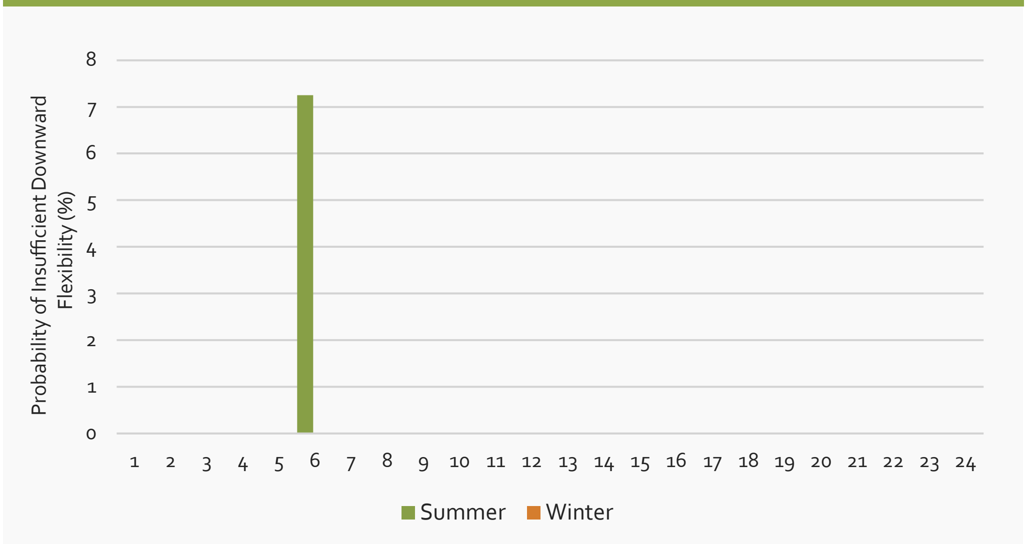



**Figure 25**

Note: Some data in the figure are not shown in the diagram because the value is too small.

## 5.3 QUANTITATIVE EVALUATION OF POWER SYSTEM FLEXIBILITY IN JING-JIN-JI

**Among all the areas in the Jing-Jin-Ji region, Beijing has the highest power system flexibility and reliability, and the lowest wind and solar curtailment, followed by grids in Tianjin and southern Hebei, while northern Hebei has the lowest power supply flexibility and reliability and serious wind and solar curtailment effects.**

The installed capacity of natural gas units in Beijing accounts for 86.86% of the thermal power installed capacity and 77.30% of the total installed capacity. The system has strong regulation ability. In addition, the installed capacity of wind power and photovoltaic power generation accounts for only 3.39%. The demand for flexibility is low. Therefore, the power system in Beijing has much lower probabilities of insufficient upward and downward flexibility than other areas of Jing-Jin-Ji, with a high level of power supply reliability.

Although Tianjin's thermal power units account for 89.90% of the total installed capacity, of which natural gas makes up over 20% to guarantee higher reliability, its relatively low load level and the fact that its 1.8 GW wind and solar capacity and 4 GW electricity import capability result in a sufficient upward flexibility of its power system but a high PIDF of 19.69% in Tianjin. But it must also be noted that as the proportion of renewable energy installed capacity such as wind and solar is only at 10%, the lack of downward flexibility has not led to severe curtailment of renewable energy in the area.

The proportion of installed thermal power in the southern Hebei grid is as high as 74.39%, with a significant share of CHP, which results in a limited regulation capacity for the system. However, with the installed capacity of wind/solar power of less than 25%, the demand for flexibility is not high. Therefore, the PIUF and LOLP of southern Hebei's power system are both relatively low. Its PIDF is about 4.64% and wind and solar curtailment rates are also low.

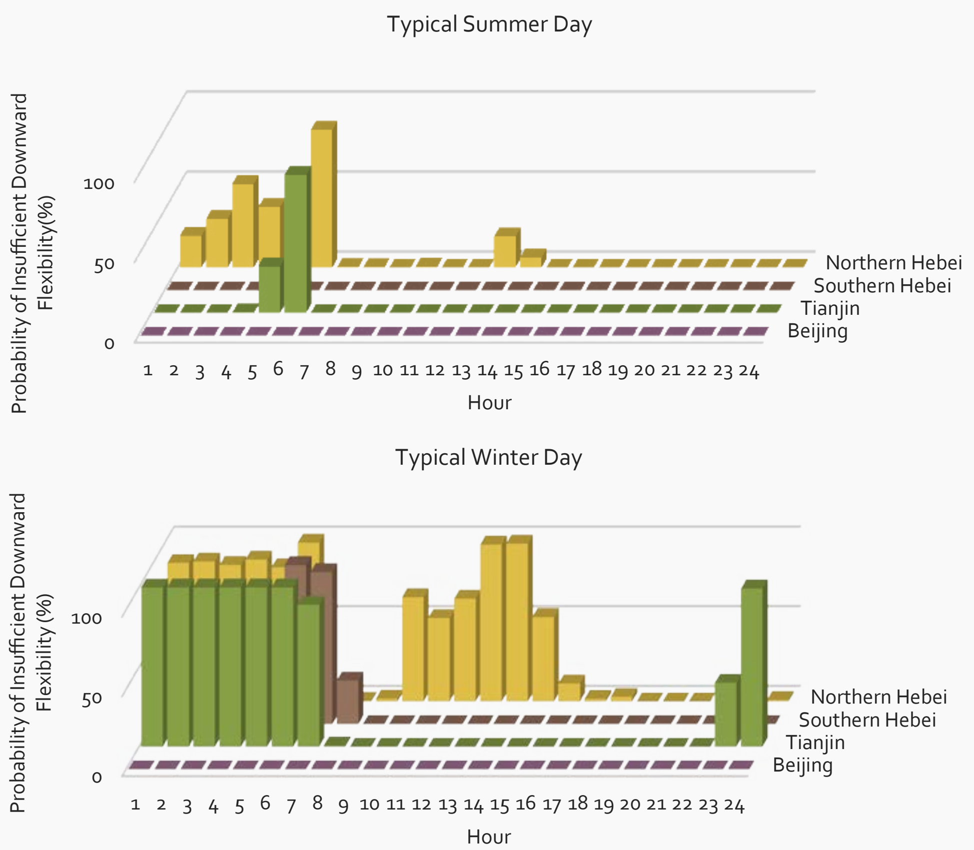
In northern Hebei, the installed capacity of renewable energies, i.e. wind and solar power generation, exceeds 51%, and there is a lack of power supply units capable of flexible regulation such as PSH and natural gas power generation. This combination of excessive wind/solar installation and inadequate flexibility resources have caused a comparatively insufficient flexibility in this region, making the PIUF in northern Hebei higher than other areas of Jing-Jin-Ji, impacting the area's power supply reliability to a considerable extent. With a high PIDF of 67.52%, its wind and solar curtailment rates also reach 6.79% and 4.19% respectively. Jing-Jin-Ji's PIUF, PIDF, LOLP, wind curtailment rate and solar curtailment rate are shown in Table 15.

**Table 15 Main flexibility indicators in Jing-Jin-Ji in 2018**

| | LOLP | PIUF | PIDF | Wind curtailment rate (%) | Solar curtailment rate (%) |
|---|---|---|---|---|---|
| Beijing | $3.33\times10^{-5}$ | $1.75\times10^{-11}$ | 0.0000 | 0.00 | 0.00 |
| Tianjin | $9.76\times10^{-5}$ | $2.04\times10^{-15}$ | 0.1969 | 0.28 | 0.00 |
| Southern Hebei | 0.0001 | $8.46\times10^{-23}$ | 0.0464 | 0.06 | 0.00 |
| Northern Hebei | 0.0091 | $4.22\times10^{-9}$ | 0.6752 | 6.79 | 4.19 |

In Jing-Jin-Ji, the power system's upward flexibility and downward flexibility in winter are both lower than in summer. Taking the typical maximum load day in summer and in winter in 2018 as an example, due to the demand for heating in winter, CHP units are run with the principle of generating power based on the demand for heat, therefore the room for thermal power adjustment in winter in Jing-Jin-Ji is significantly lower than in summer, resulting in higher PIUF and LOLP in winter. The time periods with insufficient flexibility and loss of load are mostly during evening peaks in winter, and morning peaks in summer. Meanwhile, this study has found that northern Hebei has more time periods with high LOLP than other areas. Due to the influence of heating needs and increased wind power output in winter, the PIDF of the power system in Jing-Jin-Ji in winter is generally higher than in summer. Among the different areas, because of the rapid increase in wind and photovoltaic output, Beijing's PIDF reaches its maximum at 6:00, while the southern Hebei grid reaches its maximum between 6:00-8:00; likewise, due to the fluctuation of wind power and photovoltaic output, Tianjin's downward flexibility reaches its peak between 5:00-6:00 in summer and between 1:00-7:00 and 23:00-midnight in winter. Because the share of wind and solar power is much higher than other areas, and due to the lack of adequate support of flexible power supply, northern Hebei's power system has more periods with high PIDF than other areas. The maximum PIDF values are during 1:00-6:00 and 13:00-14:00 in summer and 1:00-7:00 and 10:00-16:00 in winter. The PIDF changes over time on a typical day in summer and winter in different areas of Jing-Jin-Ji are shown in Figure 26.

**Figure 26 Typical day PIDF in Jing-Jin-Ji**



## 5.4 QUANTITATIVE COMPARISON OF POWER SYSTEM FLEXIBILITY BETWEEN CHINA AND GERMANY

**As the preceding chapters have shown, despite similarities in the types of flexibility resources for power system in Jing-Jin-Ji and Germany, significant differences remain in terms of the ability to flexibly dispatch such resources. Jing-Jin-Ji coal plants have immense untapped potential for flexibility. The region has yet to exploit inter-provincial grid interconnections. And unlike Germany, the region has not fully developed demand-side flexibility resources. In addition, the demand side should promote commercial application of new types of energy storage and new policy incentives.** Jing-Jin-Ji and Germany are both rich in flexibility resources on the power supply side, grid side, demand side, and energy storage aspect. Compared to Germany, although the proportion of generator units that are involved in flexibility regulation on the supply side in Jing-Jin-Ji is 72.5%, the flexibility of coal power units is not fully tapped. On the grid side, inter-provincial transmission links with the adjacent provinces of Shanxi, Henan, and Shandong focuses mainly on emergency support, and the 11 transmission corridors do not engage in flexible, real-time electricity exchange.

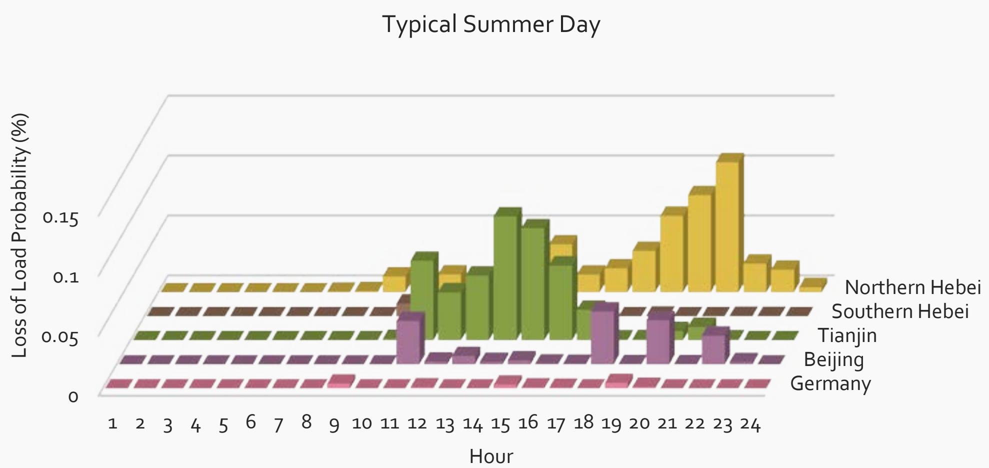
On the demand side, although there is huge potential, present administrative-based management cannot effectively realise its full flexibility capacity. In terms of energy storage, the region has 2.1 GW of conventional pumped storage, with the potential for 9.3 GW of future PSH. Battery energy storage, compressed air energy storage, and P2H programs are currently at demonstration stage. The Power Plant Management Rules and Power Plant Ancillary Services Rules implemented in Jing-Jin-Ji provide compensation for businesses that provide ancillary services. However, the region still lacks effective ancillary services markets or other mechanisms for incentivizing flexibility.

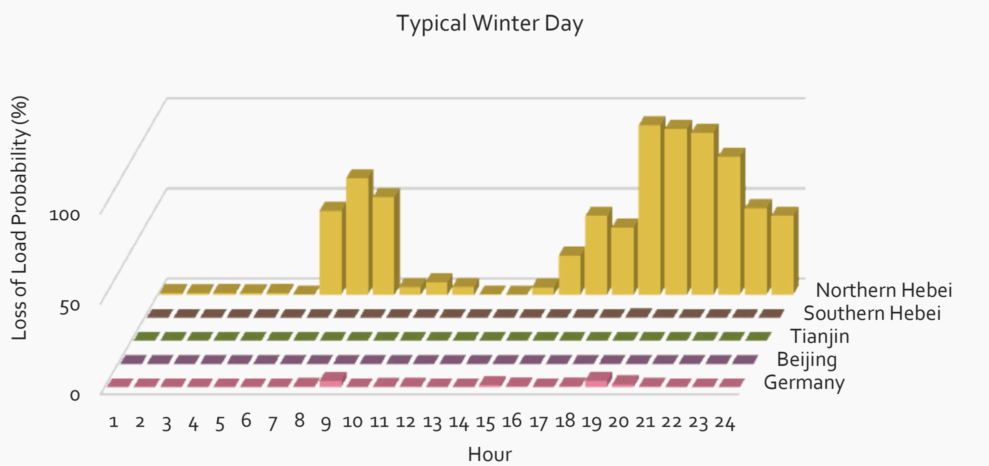
**Table 16 Comparison of flexibility resources between China and Germany**

| Flexibility resources | Germany | Jing-Jin-Ji |
|---|---|---|
| Supply side | Installed capacity of dispatchable power supply above 110 GW, accounting for 50.2% of the total installed capacity. | Installed capacity of dispatchable power supply exceeded 75 GW, accounting for 72.5% of the total installed capacity. |
| Grid side | Real-time cross-border power exchange with 9 neighbouring countries. | 11 ultra-high voltage and extra-high voltage power transmission lines connecting its neighbouring provinces, i.e., Shanxi, Henan and Shandong, primarily for emergency support. |
| Demand side | Flexibility resources such as industry, tertiary sector, and electric vehicles provide the system with level primary reserve, secondary reserve, minute reserve and interruptible load | Demand side management is still assessed using the two 3‰ criteria. |
| Energy storage | Nearly 7.9 GW of installed capacity of energy storage, including 6.8 GW of PSH, over 1 GW from battery energy storage, compressed air and P2X, in addition to 3 GW of PSH resources managed abroad. | 2.1 GW PSH installation currently; about 32 MW of battery & compressed air energy storage and P2H installation. |
| Supporting policies and mechanisms | Various flexibility services, including primary reserve, secondary reserve, and minute reserve, are provided through spot market, interruptible load and balancing market. | Compensation for businesses providing ancillary services through the implementation of the Two Rules. |

**From the perspective of overall operational flexibility of the power system, compared with Germany, the upward flexibility of the power system in the Jing-Jin-Ji region is equally sufficient, with low upward flexibility deficiency probabilities in all areas, while the LOLP of the northern Hebei grid is considerably higher than in other areas.** Throughout the full year cycle, the PIUF of the grids in Beijing, Tianjin, southern Hebei and northern Hebei are all less than 0.001%, which is lower than Germany's 0.006%. In the typical day, PIUF on typical summer day in Germany is significantly higher than that of all areas of Jing-Jin-Ji, while PIUF on typical winter day in northern Hebei is significantly higher than that of Germany and other parts of the Jing-Jin-Ji region; high PIUF has also resulted in a higher LOLP in northern Hebei, at 0.91%, than other areas. In addition to the morning peak period, Germany and northern Hebei also have a high LOLP at some time periods during evening peaks.

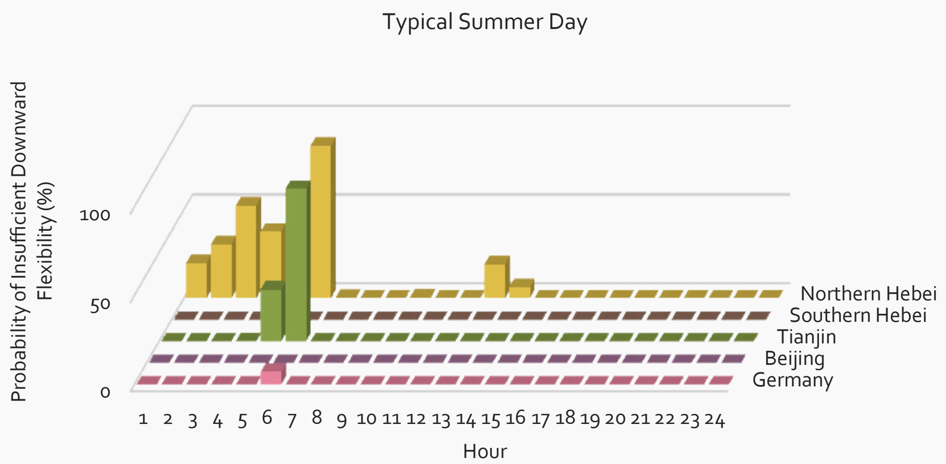
Figure 27 Comparison of typical day LOLP between Jing-Jin-Ji and Germany

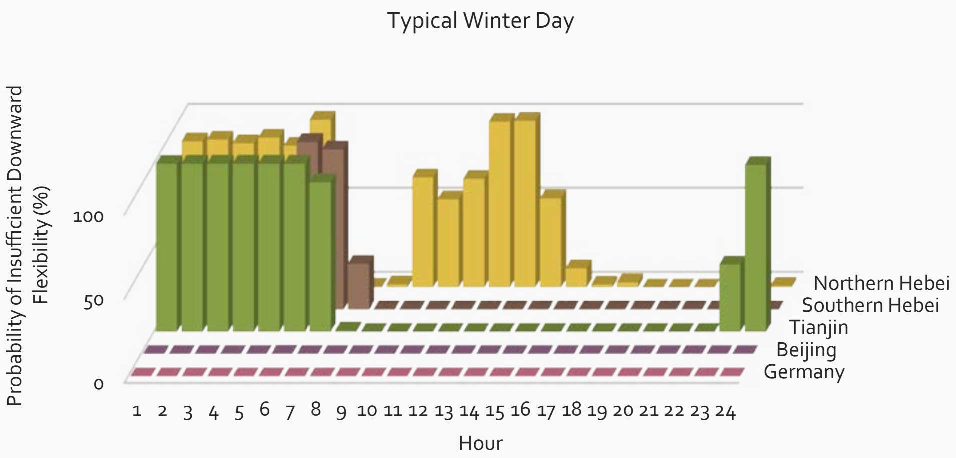



**In comparison with Germany, northern Hebei and Tianjin operate with an insufficient downward flexibility, which is lower in winter than in summer and lower at night than during daytime; the grid in northern Hebei has high wind and solar curtailment rates.** Throughout the whole year, Beijing has the lowest PIDF, followed by the southern Hebei grid. Germany's PIDF is at about 8.39%, ranking third, while Tianjin and northern Hebei have severely insufficient downward flexibility, at 19.69% and 67.52% respectively. On the typical day, Tianjin's time periods with insufficient downward flexibility in summer and winter are concentrated from 1:00-6:00, with maximum probability of insufficiency close to 100%. Downward flexibility insufficiency in northern Hebei during summer and winter mostly happens from 1:00-6:00 and 10:00-16:00 during the day, with maximum probability of insufficiency close to 100% as well. In comparison, Germany's downward flexibility insufficiency mostly occurs in the morning. In terms of wind and solar curtailment, severely inadequate downward flexibility causes high North Hebei wind and solar curtailment rates of 6.79% and 4.19%, respectively. However, it must be noted that due to the low share of renewable energy installations of wind and solar power, insufficient downward flexibility in Tianjin has not caused severe wind and solar curtailment.

**Figure 28 Comparison of typical day PIDF between Jing-Jin-Ji and Germany**




## 5.5 POTENTIAL OF SYSTEM FLEXIBILITY IMPROVEMENT AND HORIZONTAL COMPARISON

It can be derived from previous analysis that the probability of insufficient flexibility, LOLP, wind curtailment rate and solar curtailment rate in northern Hebei are much higher than those in other parts of Jing-Jin-Ji, and share similarities with Germany. Therefore, the report will further analyse the impact on northern Hebei's power system flexibility of various flexibility related measures and their differences in terms of cost effectiveness based on the current levels of flexibility resources and technologies in Germany. LOLP, probability of flexibility and wind and solar curtailment rates under different scenarios are shown in Table 17.

**Table 17 LOLP, probability of flexibility and wind and solar curtailment rates under different scenarios in Germany and northern Hebei**

| | PIUF (%) | PIDF (%) | LOLP (%) | Wind curtailment rate (%) | Solar curtailment rate (%) |
|---|---|---|---|---|---|
| Baseline scenario northern Hebei | $4.22\times10^{-7}$ | 67.52 | 0.91 | 6.79 | 4.19 |
| Northern Hebei thermal power flexibility retrofit scenario | $3.26\times10^{-13}$ | 3.59 | $1.16\times10^{-5}$ | 0.75 | 0.06 |
| Northern Hebei flexible grid interconnections improvement scenario | $5.53\times10^{-8}$ | 63.84 | 0.06 | 1.00 | 0.32 |
| Northern Hebei demand response release scenario | $4.83\times10^{-11}$ | 65.16 | 0.08 | 3.30 | 1.87 |
| Northern Hebei large-scale energy storage development scenario | $1.20\times10^{-6}$ | 63.61 | 0.42 | 0.97 | 0.17 |

### 5.5.1 THERMAL POWER FLEXIBILITY RETROFIT

**Thermal power flexibility retrofit has the most significant effect on improving the flexibility and power supply reliability for northern Hebei power system.** As shown in Table 17, the upward flexibility of the northern Hebei power system has improved through thermal power flexibility retrofit, which will also bring significant boost to the power supply reliability for the area. Retrofit of 17 GW in coal capacity in the region would lead to improvement of LOLP from 0.91% to less than 0.001%. Downward flexibility of the power system would also improve, with PIDF reduced from 67.52% to 3.59%, a decrease of more than 65 percentage points. This would effectively solve the problem of wind and solar curtailment for the Jing-Jin-Ji region, reducing wind curtailment to just 0.75% and solar curtailment to just 0.06%. On a typical day, as upward flexibility improves, LOLP in summer and winter in northern Hebei will be greatly reduced, with the highest daily probability reduced significantly from 93.98% before retrofit to 0.01% after retrofit. Thermal power flexibility retrofit will also dramatically improve the power system's downward flexibility during summer and winter for northern Hebei, by lowering the typical day maximum insufficiency rate from 85.96% to less than 0.001% in summer and from 99.80% to less than 0.001% in winter.

**Figure 29 LOLP changes before and after thermal power flexibility retrofit in northern Hebei**

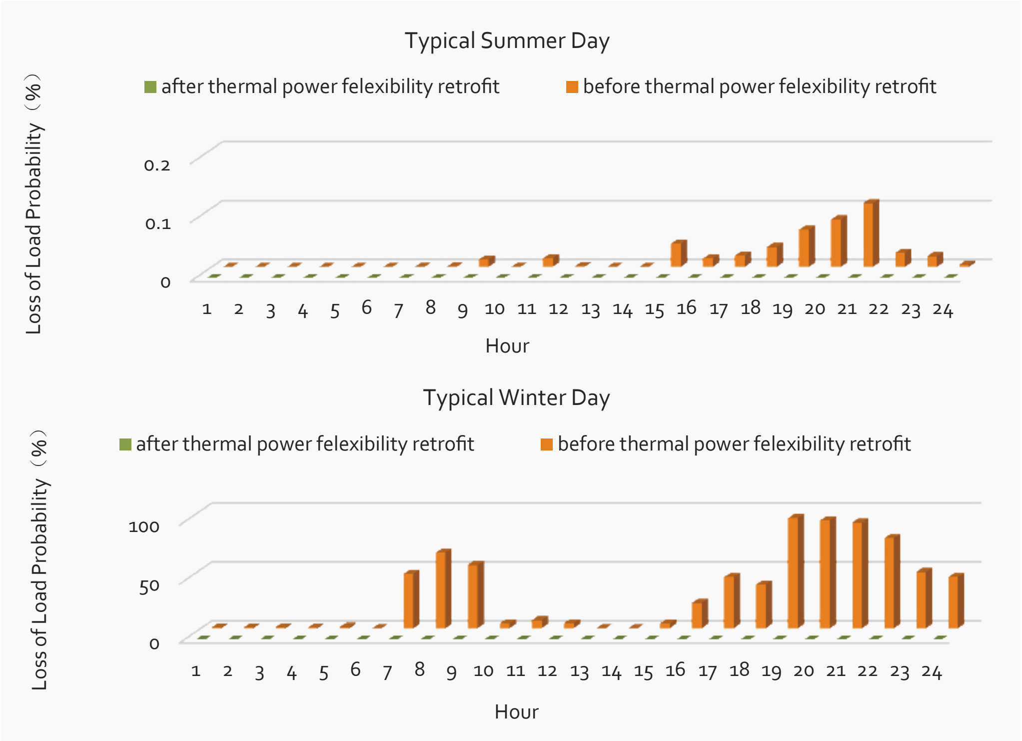
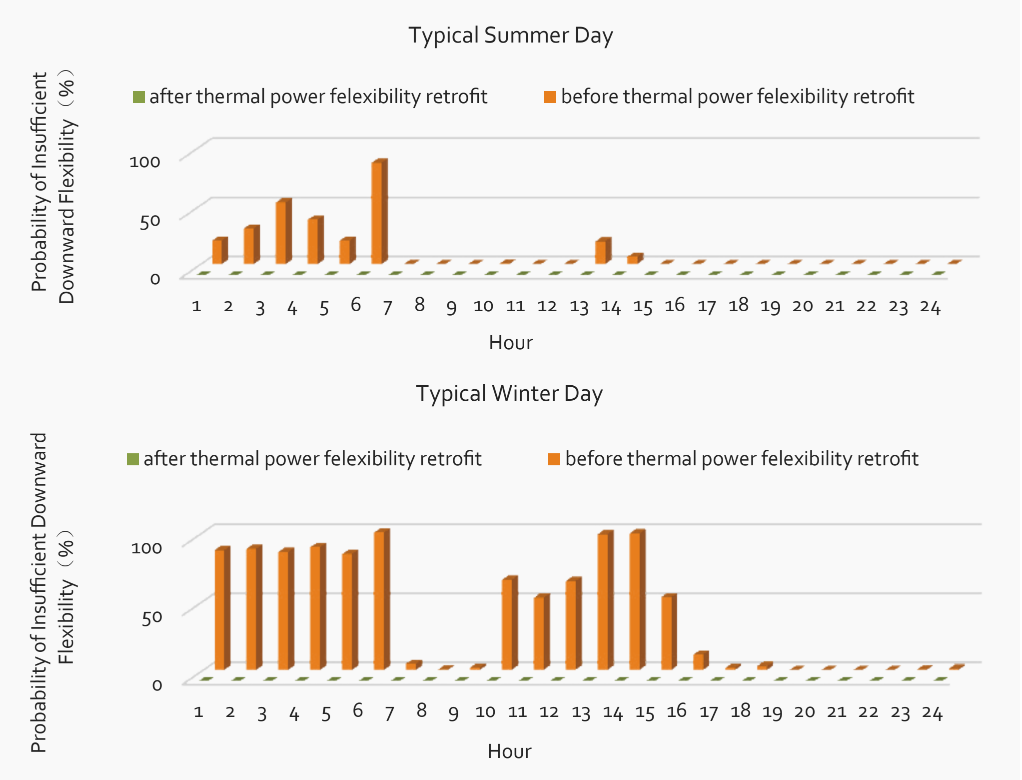



**Figure 30 PIDF changes before and after thermal power flexibility retrofit in northern Hebei**



### 5.5.2 FLEXIBLE GRID INTERCONNECTION IMPROVEMENT

**Interconnection with external power transmission corridors can increase the flexibility of the power system and improve its reliability to a certain extent, thus effectively reducing wind and solar curtailment.** As shown in Table 17, release of interconnection with external transmission corridors will also result in the improvement of the power system's upward flexibility, and the power supply reliability for the area to some extent. A 14 GW improvement in grid interconnection transfer capacity would lead to a reduction of LOLP from 0.91% to 0.06%; downward flexibility of the power system will also be moderately enhanced, with PIDF reduced from 67.52% to 63.84%, enabling a reduction of wind and solar curtailment rates in the area to 1.00% and 0.32% respectively. On a typical day, with the improvement of upward flexibility, LOLP will be improved in most periods of summer and winter in northern Hebei, especially in winter, but it must also be noted that LOLP increases over certain periods of summer. For example, LOLP goes up at 16:00 and 22:00 in the afternoon on a typical summer day, which is mainly due to the change of the energy storage working state from discharging idle, resulting in a certain increase in LOLP during these periods. Interconnection will also improve downward flexibility in most of the summer and winter periods in northern Hebei. Meanwhile, PIDF in certain periods will also rise due to changes in the of energy storage status.

**Figure 31 LOLP changes before and after grid interconnection retrofit of the northern Hebei grid**

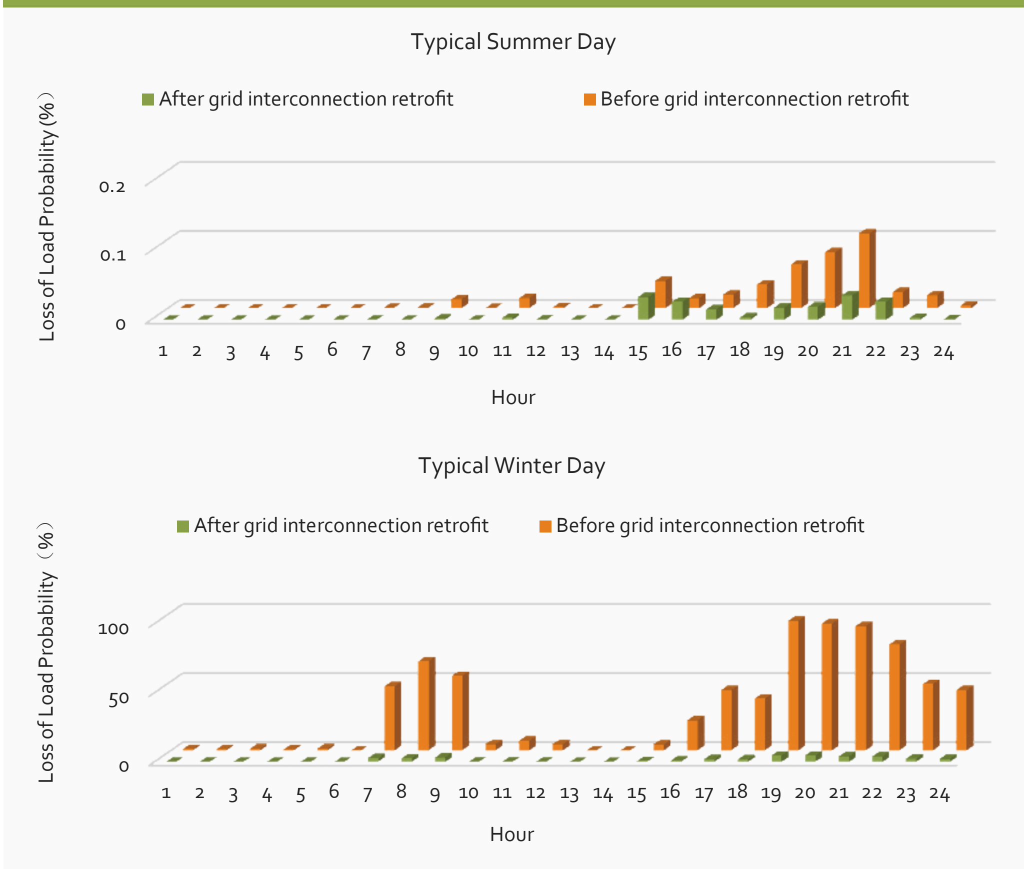
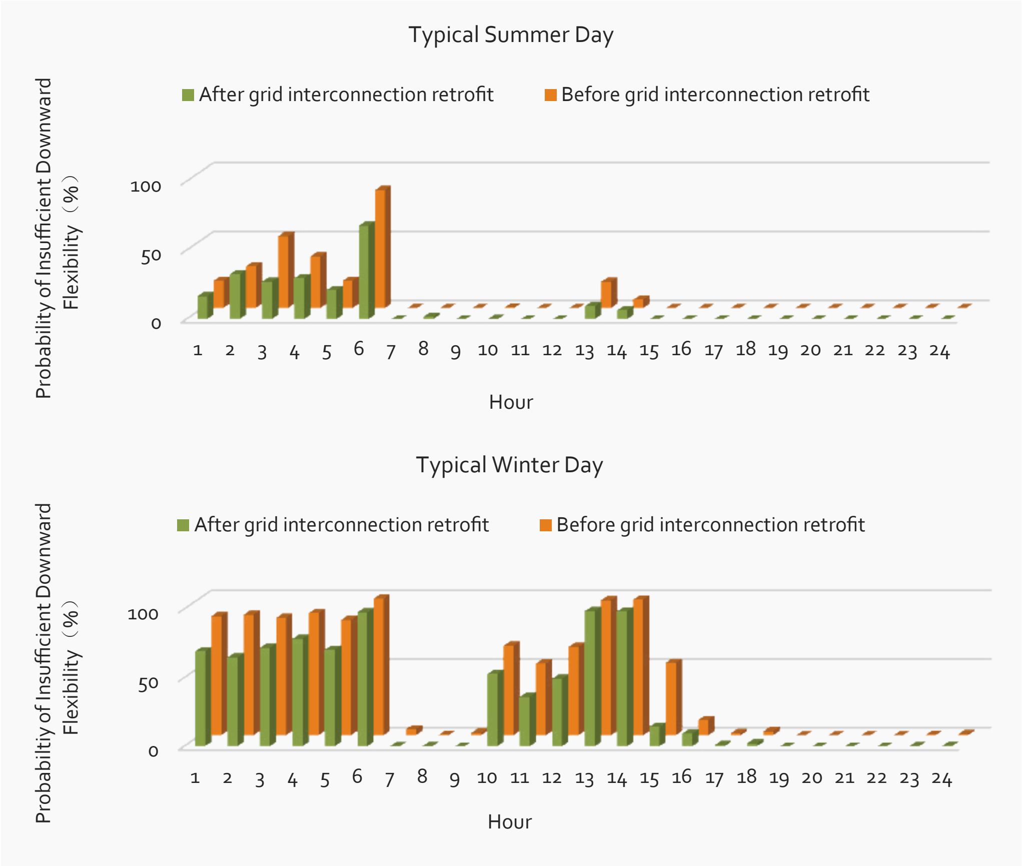


**Figure 32 PIDF changes before and after grid interconnection retrofit of the northern Hebei grid**




### 5.5.3 POWER DEMAND RESPONSE RELEASE

**The release of demand response can also increase the flexibility of the system and improve the reliability of power supply to a certain extent, but has very limited effect on the reduction of wind and solar curtailment** As shown in Table 17, demand response will also bring about the improvement in power system's upward flexibility, and the power supply reliability for the area to some extent. A 2.3 GW improvement on demand response will reduce the LOLP from 0.91% to 0.08%; downward flexibility of the power system will also be moderately enhanced, though limited, with PIDF reduced to 65.16%, still bringing down the wind and solar curtailment rates in the area. On a typical day, the upward flexibility improvement will also help reduce LOLP for all time periods in summer and winter in northern Hebei. For instance, the maximum LOLP on a typical day in winter is reduced from 93.98% to 16.18%. Different from other flexibility measures, demand response is more about promoting the re-allocation of the downward flexibility of the system, to increase the system's downward flexibility at night while improving downward flexibility during the day as well.

The re-allocation of downward flexibility brought about by demand response is mainly due to load shifting that lowers power demand during the day and increases the load at night, which increases the downward flexibility of the system at night and decreases downward flexibility during the day. The insufficient downward flexibility has also shifted from night to daytime. Particularly, due to the clear peak load counter-regulation characteristics of the wind power in Jing-Jin-Ji, with huge wind power output during the night, the re-allocation of flexibility from demand response facilitates the consumption of wind power for the region.

**Figure 33 LOLP changes before and after implementation of demand response in northern Hebei**

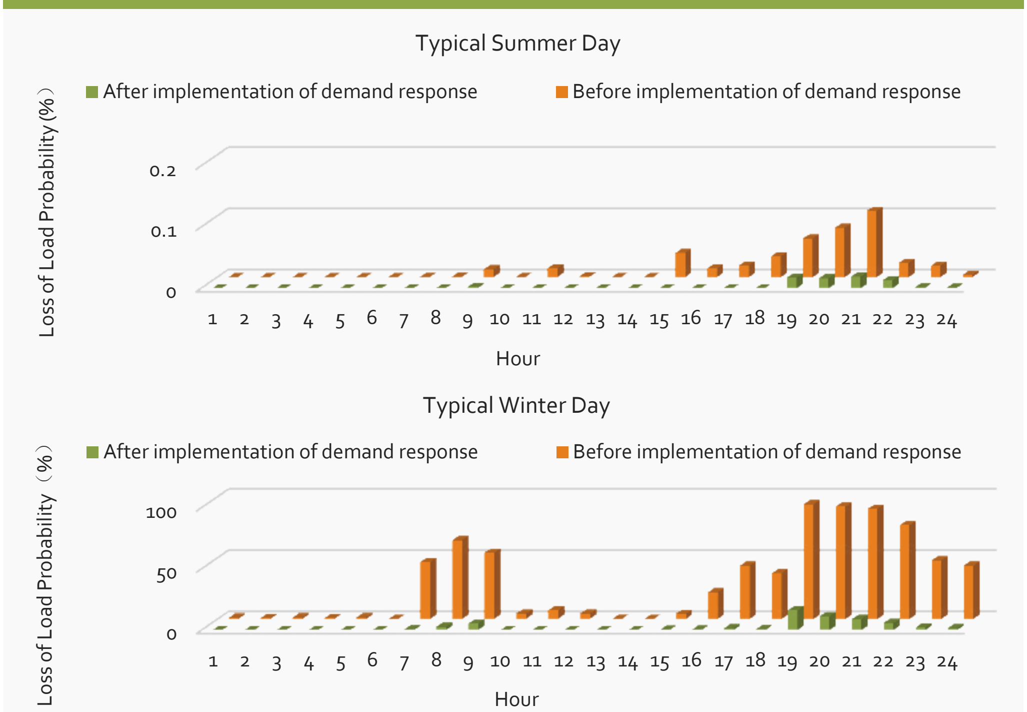
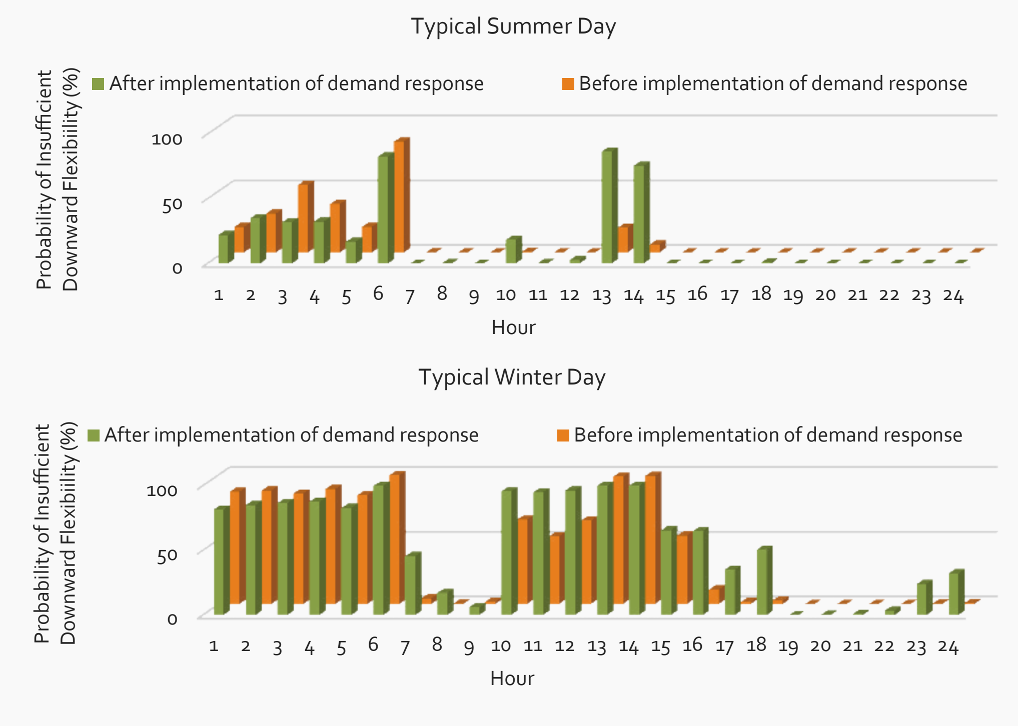


**Figure 34 PIDF changes before and after implementation of demand response in northern Hebei**




### 5.5.4 LARGE-SCALE ENERGY STORAGE

**Large-scale development of energy storage can also increase the flexibility of the system and improve the reliability of power supply to a certain extent, thus effectively reducing wind and solar curtailment in the area.** As shown in Table 17, large-scale development of energy storage results in a similar impact as interconnection with external power transmission corridors, which will result in improvement of the power system's upward flexibility and power supply reliability in the area for some extent. An increase of 21 GW of energy storage capacity will reduce the LOLP from 0.91% to 0.42%. Adding storage would moderately improve downward flexibility of the power system, reducing PIDF from 67.52% to 63.61%, which is second only to the effect of thermal power flexibility retrofit, bringing down the wind and solar curtailment rates in the area to 0.97% and 0.17%. On a typical day, the expansion of the scale of energy storage can effectively reduce LOLP in all time periods, especially in morning and evening peak hours. Paradoxically, this could also increase the risk of loss of load during charging periods, resulting in a higher LOLP during some charging periods. Energy storage development can also reduce PIDF in most time periods in summer and winter in northern Hebei to a certain extent, but has limited improvement effect for periods with higher probability of shortage such as 6:00 am and 13:00-14:00, thus there's still a high risk of wind and solar curtailment.

**Figure 35 LOLP changes before and after energy storage capacity increase in northern Hebei**

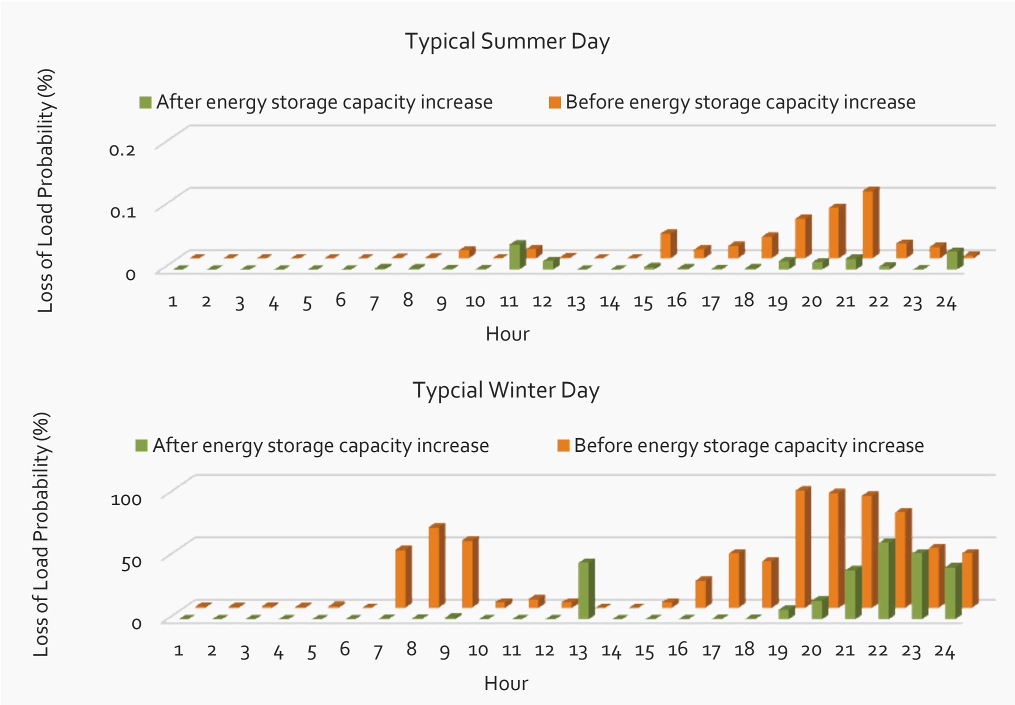
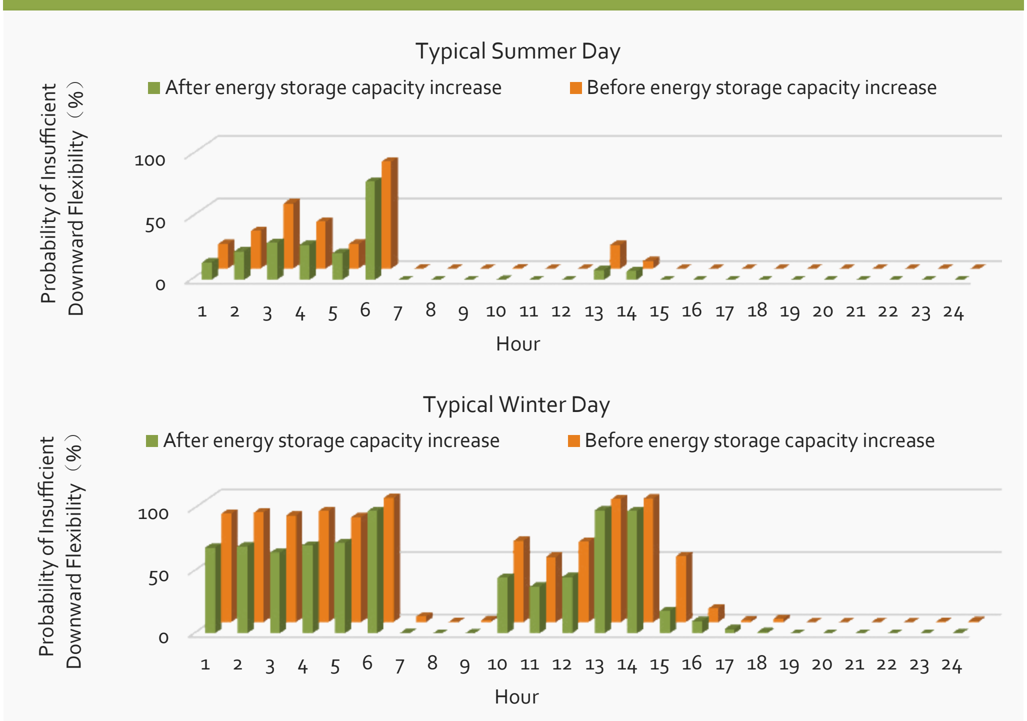



**Figure 36 PIDF changes before and after energy storage capacity increase in northern Hebei**



### 5.5.5 HORIZONTAL COMPARISON OF ECONOMY BETWEEN DIFFERENT FLEXIBILITY IMPROVEMENT TECHNOLOGIES

Based on international experience and China's energy system status, the retrofit investment per kW for lowering the minimum stable output of the 300 MW and 600 MW condensing units in Jing-Jin-Ji to 30% is at about RMB 125/kW.[48] The investment cost for improving ramp rate of coal-fired units will depend on the specific project, but is roughly RMB 50/kW, most of which represents equipment replacement rather than software upgrades. For large power plants with 300-600 MW capacity, heat-power decoupling will need thermal energy storage tanks of 20,000-70,000 $m^3$, which typically cost around RMB 40-80 million. Combining of all retrofit measures—including minimum stable output, ramp rate, start-up time, and heat-power decoupling—results in a cost of RMB 300-500/kW for retrofitting a 300-600 MW coal plant.

The economic efficiency of PSH plants depends on factors such as topography and geology, prices of basic building materials, equipment prices, and construction supervision methods. Including labour and materials, the current investment cost of PSH plants in the Jing-Jin-Ji region is approximately RMB 5,000/kW.

Grid interconnection is technically more mature and doesn't require major retrofit of existing lines. However, some upgrades of dispatch management system is necessary as well. We estimate the investment costs for the grid improvement at RMB 2,000/kW taking into account the addition of new lines.

Due to the complexity of loads in each sector, the technical maturity of DSM is currently low—particularly in Jing-Jin-Ji, but also in China as a whole. Investments is needed in demand side load control methods, management platform development, and the incentive mechanism. Accounting for costs for marketing, smart load-management equipment and a management software platforms, we estimate the investment cost at RMB 200-400/kW, but this estimate has high uncertainty.

Apart from pumped storage hydropower, other storage types are limited by their low technical maturity, and have high investment cost. According to 2018 data, the cost of other types of storage is around RMB 8,000-10,000/kW, exceeding that of all other flexibility resources.

Overall, coal power flexibility retrofit can greatly improve the system's upward and downward flexibility. In addition, with an investment per kW only slightly higher than that of power demand side management, it can improve the system's reliability and further facilitate the consumption of solar and wind power as well. Therefore, for northern Hebei, coal power flexibility retrofit is the preferred measure for the improvement of power system flexibility. Grid interconnections and energy storage increase system flexibility are based on different operating mechanisms, but both are conducive to improving the upward and downward flexibility at most relevant timescales of the power system in northern Hebei. Grid interconnection technologies are well established with cost-effective benefits. As for energy storage, the development of pumped storage hydropower is restricted due to limited site availability and extensive investment.

Other types of energy storage technology face uncertainties in large-scale deployment, and cost-effectiveness is the largest bottleneck. Therefore, in terms of overall cost effectiveness, improvements in grid interconnections and energy storage development rank behind flexibility retrofits for coal-fired power plants for flexibility increase of power systems in northern Hebei. Although the development of power demand side management has a strong economic effect, it is more of a re-allocation of flexibility rather than resulting in the improvement of flexibility for northern Hebei. Therefore, the demand response measures rank third in terms of improving power system flexibility for northern Hebei.

Table 18 Cost-effectiveness evaluation table

| | Loss of Load Probability improvement (%) | Improvement on Probability of Insufficient Downward Flexibility (%) | Improvement on Probability of Insufficient Upward Flexibility (%) | Amount (GW) | Unit cost (RMB/ kW) | Total cost (billion RMB) |
|---|---|---|---|---|---|---|
| Coal plant flexibility retrofit | 0.91% | 63.93% | - | 17 | 300-500 | 5.1-8.5 |
| Interconnection upgrade | 0.85% | 3.668% | - | 14 | 2000 | 28 |
| Demand side management | 0.83% | 2.36% | - | 2.3 | 200-400 | 0.46-0.92 |
| Energy Storage | 0.49% | 3.91% | - | 21 | 8000-10000 | 168-210 |

## 5.6 CONCLUSIONS

Jing-Jin-Ji and Germany have little difference in the upward flexibility of power systems. However, upward flexibility usually affects the power supply reliability of the system, and the small difference will result in a higher probability of insufficient power supply. However, compared to Germany, the downward flexibility in parts of Jing-Jin-Ji is obviously inadequate, especially in areas with high proportion of renewable energy power generation installed capacity. The lack of downward flexibility has caused serious wind and solar curtailment. From the perspective of cost effectiveness, flexibility retrofits for coal-fired power plants have the most significant effect on increasing the flexibility of the system, followed by improvement in flexible grid interconnection and energy storage, while the power demand response measure focuses more on the re-allocation of flexibility.

# 6 SUMMARY AND SUGGESTIONS FOR POWER SYSTEM FLEXIBILITY IN CHINA AND GERMANY

## 6.1 COMPARATIVE SUMMARY OF POWER SYSTEM FLEXIBILITY IN CHINA AND GERMANY

In terms of flexibility resources for power systems, Jing-Jin-Ji and Germany are both rich in flexibility resources on the power supply side, grid side, demand side, and energy storage solutions. Compared to Germany, the supply side of Jing-Jin-Ji has only limited types of generator units involved in flexibility regulation. Moreover, there is room for the increase of the minimum stable output, ramp rate and start-up time of the generator units. On the grid side, power transmission crossing provinces and regions focuses more on emergency support, without flexible real time exchange. On the demand side, although there is huge potential, the administration-centred management model cannot effectively utilize its flexibility capacity. In terms of battery energy storage, conventional PSH has a large operative scale, while battery energy storage, compressed air energy storage, and P2H programs are currently at demonstration stage. The Power Plant Management Rules and Power Plant Ancillary Services Rules implemented in Jing-Jin-Ji are providing certain amount of compensation for businesses responsible for ancillary services. However, there is still a lack of effective market and mechanisms to stimulate further potential for flexibility.

**Table 19 Comparison of flexibility resources between China and Germany**

| Flexibility resources | Germany | Jing-Jin-Ji |
|---|---|---|
| Supply side | In addition to thermal power and PSH, nuclear power is also considered a controllable power source. The minimum stable output of the lignite-fired units with the least flexibility can also be reduced to 30-50%. The ramp rate reaches 2-6%/minute. The time of hot start and cold start reaches 1.25-4 hours and 5-8 hours respectively. | Thermal power and PSH are the main flexibility resources. The minimum output of coal-fired power units is usually set at 50-90%, the ramp rate is 0.5-1%/minute, and the start-up time is at a relatively conservative level. The CHP units operate in accordance with the principle of generating power based on the demand for heat during winter. |
| Grid side | Real-time cross-border power exchange with 9 neighbouring countries; developing its grid using the GORE principle, which places grid optimization prior to grid reinforcement prior to grid expansion. | 11 ultra-high voltage and extra-high voltage power transmission lines connecting its neighbouring provinces, i.e., Shanxi, Henan and Shandong, primarily for emergency support; optimizing, rebuilding and expanding power grids on a provincial basis. |
| Demand side | Huge potential for "load reduction" and "load enhancement" demand response. At present, it is mainly industrial users who participate in the flexibility service. | Huge potential for maximum load shedding and interruptible load; mainly characterized by administrative demand-side management such as orderly use of electricity. |

| Flexibility resources | Germany | Jing-Jin-Ji |
|---|---|---|
| Energy storage | 6.8 GW of PSH and 3 GW of PSH resources managed abroad; Battery energy storage, compressed air, and Power-to-X have all achieved rapid development. | 2.1 GW PSH installation currently; battery energy storage, compressed air energy storage and P2H programs are small in scale and at demonstration stage. |
| Supporting policies and mechanisms | Various flexibility services, including primary reserve, secondary reserve, and minute reserve, are provided through spot market, interruptible load and balancing market. | Compensation for businesses providing ancillary services through the implementation of the Two Rules. |

From the perspective of overall operational flexibility of the power system, Jing-Jin-Ji and Germany have little difference in the upward flexibility of power systems. However, upward flexibility usually affects the power supply reliability of the system, and a small difference will result in a high probability of insufficient power supply. Compared to Germany, the downward flexibility in parts of Jing-Jin-Ji is inadequate, especially in northern Hebei, with its high proportion of variable renewable energy installed capacity. The lack of downward flexibility has caused wind and solar curtailment in the region. In the future, the proportion of installed wind and solar renewable energy in Jing-Jin-Ji will continue to increase. To ensure the continuous improvement of power supply reliability, the upward flexibility of power systems in Jing-Jin-Ji must be maintained at the current level, or even improved from the current level. Meanwhile, the downward flexibility of power systems in Jing-Jin-Ji must be greatly improved to ensure the consumption of renewable energy and the development of a growing proportion of renewable energy. From the perspective of economic feasibility of the technology, flexibility retrofits for coal-fired power plants have the most significant effect on releasing the flexibility of the system, followed by improvement in flexible grid interconnection and energy storage, while the power demand response measure focuses more on the re-allocation of flexibility.

**Table 20 Comparison of power system operational flexibility between China and Germany**

| Flexibility indicators | Germany | Jing-Jin-Ji |
|---|---|---|
| Upward flexibility | Germany's power system has relatively high upward flexibility and reliability. The PIUF is higher in winter than in summer. | Jing-Jin-Ji's power system also has sufficient upward flexibility. The PIUF is lower in winter than in summer. |
| Downward flexibility | The PIDF is 8.39%. The wind curtailment rate and the solar curtailment rate are within a reasonable range. The PIDF is higher in summer than in winter. | Northern Hebei and Tianjin have seriously insufficient downward flexibility. A growing proportion of renewable energy installed capacity has resulted in high wind curtailment rate and solar curtailment rate in northern Hebei. The downward flexibility is lower in winter than in summer and lower at night than during daytime. |

**Table 21 Comparison of contributions from various flexibility initiatives**

| Indicators | Upward flexibility | Downward flexibility | Reliability | Wind and solar curtailment | Economy |
|---|---|---|---|---|---|
| Thermal power flexibility retrofit | ☆☆☆ | ☆☆☆ | ☆☆☆ | ☆☆☆ | ☆☆ |
| Flexible grid interconnections improvement | ☆☆ | ☆☆ | ☆☆ | ☆☆ | ☆☆ |
| Power demand response release | ☆ | ☆ | ☆ | ☆ | ☆☆☆ |
| Large-scale energy storage development | ☆☆ | ☆☆ | ☆☆ | ☆☆ | ☆ |

## 6.2 SUGGESTIONS FOR JING-JIN-JI

### (1) JING-JIN-JI SHOULD PRIORITIZE FLEXIBILITY RETROFITS FOR COAL-FIRED POWER PLANTS AND FACILITATE GRID INTERCONNECTIONS. CONSTRUCTION OF PSH PLANTS AND ENERGY STORAGE POWER PLANTS SHOULD FOLLOW, WITH ACTIVE IMPLEMENTATION OF DEMAND-SIDE MANAGEMENT. FINALLY, OPTIMAL FLEXIBILITY DEPLOYMENT WITHIN THE POWER SYSTEM CAN BE ACHIEVED.

The primary task of Jing-Jin-Ji in improving the flexibility of coal-fired units should be promoting the flexibility retrofits of coal-fired units and improving the flexibility of the power transmission corridors connecting different provinces. Doing so will improve both the flexibility of the power system and the reliability of power supply, thereby allowing more room for the utilization of renewable energy in Jing-Jin-Ji. Secondly, the preliminary work for the construction of PSH plants in Shangyi, Yixian and Funing of Hebei Province should be accelerated to ensure completion on schedule. The energy storage industry should be encouraged by reducing the uncertainty of investment returns. The region should continue to develop pilot renewable energy projects featuring diverse energy storage technologies and applications to accumulate experience. We suggest to focus on the most technologically mature and economical forms energy storage. The region should also strictly monitor energy efficiency of electrical equipment, improve standards, and develop energy-saving design specifications. Public energy conservation campaigns should raise public awareness around saving electricity. The region should establish a government-initiated demand-side management system implemented by power grid companies, and with full participation by a wide variety of stakeholders. Finally, according to the characteristics of various flexibility resources in Jing-Jin-Ji, the region should also promote the coordination and allocation of different flexibility resources while improving system flexibility.

### (2) BEIJING SHOULD ACCELERATE GRID INTERCONNECTIONS, PROMOTE DIVERSIFIED USE OF ENERGY STORAGE TECHNOLOGIES, AND EXPLORE INTELLIGENT DEMAND-SIDE MANAGEMENT.

Areas like Beijing that mainly rely on imported electricity should deploy advanced technologies such as big data, cloud computing, and smart grids to establish a central forecasting system on the grid side as well as improve the flexibility of interconnections among inter-provincial and inter-regional power grids, thus allow for greater clean energy consumption. These areas should carry out pilot distributed energy storage projects on the demand side and explore new energy storage business models. Beijing should also promote the bidirectional interaction between electric vehicles and smart grids in terms of both energy (vehicle-to-grid or V2G) and information, and utilize EVs in V2G modes for grid regulation services. Demonstration projects for intelligent demand response and user interaction such as smart residential compounds and smart industrial parks are also needed.

### (3) TIANJIN AND HEBEI SHOULD SHIFT COAL-FIRED POWER PLANTS TO PEAKING PLANTS, REDUCE EXCESS COAL POWER CAPACITY, REMOVE BARRIERS TO AN OPEN AND FLEXIBLE GRID, AND PRIORITIZE THE CONSTRUCTION OF PSH PLANTS.

As target areas for elimination of excess coal power capacity, Tianjin and Beijing should strictly limit the transformation of condensing coal-fired power units to heating or CHP and thereby ensure the system can flexibly meet peak loads. Flexibility retrofits of local coal-fired units should be promoted in line with international standards. High-efficiency thermal energy storage devices should be added to CHP units to increase the downward flexibility in winter. Coal power should gradually shift from baseload operations to flexibility services. The region should make full use of flexible loads and different variable renewable energy generating electricity at different times in different areas of Jing-Jin-Ji to balance system supply and demand across provinces. The region should establish a unified grid regulation mechanism and reserve sharing system. The region should also develop PSH plants and better coordinate environmental protection efforts so as to scientifically evaluate the environmental impact of PSH projects and the effectiveness of environmental protection measures.

### (4) NORTHERN HEBEI SHOULD FULLY UTILISE AND OPTIMALLY ALLOCATE FLEXIBILITY RESOURCES FROM THE GENERATION SIDE, GRID SIDE, LOAD SIDE, AND STORAGE RESOURCES.

Having taken the lead to achieve a high proportion of renewable energy installed capacity, Northern Hebei needs to further promote the flexibility retrofits of local thermal power units and to improve the interconnection capacity of existing transmission lines. Northern Hebei should consider increasing trans-provincial power transmission lines to promote the balanced consumption of local renewable energy. In addition, the region should carry out further pilot projects of large-capacity energy storage in Chongli County and Zhangbei County, which are rich in renewable energy, and to explore methods of commercial energy storage to support the large-scale development of energy storage. To address the increasing proportion of renewable energy on the grid, the region should formulate a plan for optimizing generation, grid, loads, and storage for optimal coordination and allocation of flexibility resources.

### (5) THE REGION SHOULD ESTABLISH A CENTRAL ELECTRICITY TRADING MARKET WITH A SOUND COMPENSATION MECHANISM FOR ANCILLARY SERVICES, INTRODUCE INCENTIVE-BASED RETAIL POWER PRICES IN A FULLY OPEN ELECTRICITY MARKET, AND TO DEVELOP A CAPACITY MARKET.

Jing-Jin-Ji should gradually establish day-ahead and intraday wholesale electricity markets and implement a balance mechanism to implement central market trading of electric energy by 2030. The region should also improve compensation for ancillary services. This will entail transitioning from the initial market design, which features compensation of costs plus a reasonable return, to a competitive ancillary service market where beneficiaries assume responsibility, and ancillary services prices and consumption adjust accordingly. The region should also establish power transmission and distribution pricing based on the peak-load liability, using a location-marginal price model. The demand side should be guided to perform load shifting for suitable electricity loads. The electricity market should be gradually liberalized, the scope of market access should be further expanded, and all power generation companies should be allowed to enter the competitive electricity market to achieve full competition in the retail electricity business. It is necessary to explore ways to establish a capacity market. Market changes should be revised and coordinated in a timely manner to ensure the adequacy of power system capacity.

## 6.3 SUGGESTIONS FOR GERMANY

### (1) GERMANY SHOULD EMPLOY INNOVATIVE BUSINESS MODELS TO MORE EFFICIENTLY USE DECENTRALIZED RESOURCES ON THE DEMAND SIDE.

In view of the potential for deploying distributed flexibility resources on the demand side, it is essential to study the characteristics of the centralized response of different users. The application of innovative models such as energy management aggregators, P2P transactions, and community ownership models should be expanded to enable the full utilization of flexibility resources on the demand side. Priority should be given to industry and commercial distributed flexibility resources, and residential users' participation in demand response should gradually increase in the long run. Germany should improve trading mechanisms that encourage greater flexibility on the demand side. Efforts should be made to establish a model driven by price and other factors for centralized control of flexibility resources on the demand side.

### (2) GERMANY SHOULD STUDY AND IDENTIFY INNOVATIVE FLEXIBILITY SOLUTIONS FOR FUTURE RENEWABLE-BASED POWER SYSTEM.

In view of the large-scale phase-out of coal power and nuclear power in the future, Germany should develop flexibility solutions such as battery energy storage and demand response to replace traditional energy sources. Germany should accelerate technology development and deployment and boost capital investment to encourage innovation and new sources of flexibility to enter the market at scale. Germany should prioritize economically affordable solutions for flexibility resources for power systems in the renewable-based era.

# REFERENCES


1 Hugo Chandler, "Harnessing Variable Renewables: A Guide to the Balancing Challenge, " International Energy Agency, at https://doi.org/10.1787/9789264111394-en.

2 "Accommodating high levels of variable generation," North America Electric Reliability Corporation, April 2009, at https://www.yumpu.com/en/document/view/24977261/accommodating-high-levels-of-variable-generation-nerc.

3 E. Lannoye, D. Flynn and M. O'Malley, "Evaluation of Power System Flexibility," IEEE Transactions on Power Systems, vol. 27, no. 2, pp. 922-931, May 2012, at https://ieeexplore.ieee.org/document/6125228.

4 T. Zheng, J. Zhao, F. Zhao, and E. Litvinov, "Operational flexibility and system dispatch," in Proc. IEEE Power Energy Soc. Gen. Meeting, San Diego, CA, USA, 2012, pp. 1-3.

5 J. Ma, V. Silva, R. Belhomme, D. S. Kirschen, and L. F. Ochoa, "Evaluating and planning flexibility in sustainable power systems," IEEE Trans. Sustain. Energy, vol. 4, no. 1, pp. 200-209, Jan. 2013.

6 Michael Joos, Iain Staffell, "Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany," Renewable and Sustainable Energy Reviews, April 2018, at https://www.sciencedirect.com/science/article/pii/S1364032118300091.

7 Philipp Litz, Dr. Patrick Graichen, Frank Peter, "The German Coal Commission, A Roadmap for a Just Transition from Coal to Renewables," Agora Energiewende, July 2019, at https://www.agora-energiewende.de/fileadmin2/Projekte/2019/Kohlekommission_Ergebnisse/168_Kohlekommission_EN.pdf.

8 F. Ess, F. Peter, F. Klummp, "Flexibility in thermal power plants with a focus on existing coal-fired power plants," Agora Energiewende, June 2017, at https://www.agora-energiewende.de/en/publications/flexibility-in-thermal-power-plants/.

9 "Energy statistics - cooling and heating degree days," Eurostat, 10 July 2019, at https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.html.

10 "Extremely Competitive CHP Concepts: Reference CHP CCGT Plant Lausward," AZG, accessed on 12 November 2020 at: https://azg-consulting.com/en/CHP/; Lee Buchsbaum, "2016 Plant of the Year," Power Magazine, 2 August 2016, at https://www.powermag.com/long-form-stories/2016-POWER-Plant-of-the-Year-Award/.

11 Sören Amelang, Jakob Schlandt, "Germany's electricity grid stable amid energy transition," Clean Energy Wire, 12 November 2018, at https://www.cleanenergywire.org/factsheets/germanys-electricity-grid-stable-amidenergy-transition.

12 Michael Joos, Iain Staffell, "Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany," Renewable and Sustainable Energy Reviews, April 2018, at https://www.sciencedirect.com/science/article/pii/S1364032118300091.

13 "Agora Meter—Import and Export," Agora Energiewende, accessed 27 August 2019, at https://www.agora-energiewende.de/en/service/recent-electricity data/chart/power_import_export/19.03.2015/20.03.2015/.

14 Stephanie Ropenus, Philipp Godron, Markus Steigenberger, "A word on grids – how electricity grids can help integrate variable renewable energy," Agora Energiewende, February 2019, at https://www.agora-energiewende.de/fileadmin2/Projekte/2018/A_word_on/A-Word-On-Grid_agora-energiewende_WEB.pdf.

15 Kerstine Appunn, "Energiewende hinges on unblocking the power grid," Clean Energy Wire, 10 April 2018, at https://www.cleanenergywire.org/dossiers/energy-transition-and-germanys-power-grid.

16 Hans Christian Gils, "Assessment of the theoretical demand response potential in Europe," Energy, 1 March 2014, at https://www.sciencedirect.com/science/article/abs/pii/S0360544214001534.

17 Jan Stede, "Demand Response in Germany: Technical Potential, Benefits and Regulatory Challenges," May 2016, at https://www.diw.de/sixcms/detail.php?id=diw_01.c.532829.de.

18 Lukas Vogel, Carolin Schenuit, Liu Jian, "Industrial Demand Side Flexibility in China," Dena, December 2019, at https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/190830_Industrial_Demand_Side_Flexibility_report_final_dena.pdf.

19 "Demand Response in Industry - Status and Potential in Germany," The Research Centre for Energy Economics, 24 February 2011, at https://www.ffe.de/publikationen/pressemeldungen/354-demand-response-in-der-industrie-status-und-potenziale-in-deutschland.

20 Heribert Hauck, "Aluminium Smelters as Service Provider for Transmission System Operators," Power system flexibility in China and Germany roundtable seminar, 30 October 2019.

21 Hans Christian Gils, "Assessment of the theoretical demand response potential in Europe," Energy, 1 March 2014, at https://www.sciencedirect.com/science/article/abs/pii/S0360544214001534

22 Katharina Wohlfarth, "Demand response in the service sector – setting course for energy flexibility and efficiency," June 2017, at http://publica.fraunhofer.de/dokumente/N-452713.html

23 "为达到 100 万销量目标，德国再续扶持政策，" Reuters, 22 February 2020, at https://chejiahao.autohome.com.cn/info/3372136/.

24 Simon Huo, "Vive La e-Volution!" Markets Germany, issue 2 2018, at https://www.gtai.de/resource/blob/77784/27d0460be46ea3ed14426bc7cb3a64d0/markets-germany-18-02-vive-la-e-volution-data.pdf.

25 "Next Kraftwerke and Jedlix launch initiative to use electric car batteries for grid stability," Next Kraftwerke, 10 September 2018, at https://www.next-kraftwerke.com/news/nextkraftwerke-jedlix-launch-initiative-to-use-electriccar-batteries-for-grid-stability.

26 "Progress Report 2018 – Market ramp-up phase," German National Platform for Electric Mobility, May 2018, at http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/Publikationen/NPE_Progress_Report_2018.pdf

27 Wolf-Peter Schill, Jochen Diekmann, Alexander Zerrahn, "Power Storage: An Important Option for the German Energy Transition," DIW Economic Bulletin, October 2015, at https://www.econstor.eu/handle/10419/108856.

28 Wolf-Peter Schill, Jochen Diekmann, Alexander Zerrahn, "Power Storage: An Important Option for the German Energy Transition," DIW Economic Bulletin, October 2015, at https://www.econstor.eu/handle/10419/108856.

29 "Goldisthal Pumped – Storage Plant: More than Power Production," Hydro Review, 3 January 2007, at https://www.hydroreview.com/2007/03/01/goldisthal-pumped-storage-plant-more-than-power-production/#gref.

30 "Energy Storage," German Trade & Invest, accessed 16 August 2019, at https://www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Energy/energy-storage.html#1184180; Sören Amelang, "Electricity storage is next feat for Germany' s energy transition," Clean Energy Wire, 10 October 2018, at https://www.cleanenergywire.org/dossiers/energystorage-and-energiewende.

31 Andy Colthorpe, "Japanese sodium-sulfur and lithium batteries used in German grid demonstrator project," Energy Storage News, 2 November 2018, at https://www.energy-storage.news/news/japanese-sodium-sulfur-and-lithium-batteriesused-in-german-grid-demonstrat; Andy Colthorpe, "RedT's vanadium flow energy storage to be deployed on grand scale in Germany," Energy Storage News, 26 July 2018, at https://www.energy-storage.news/news/redts-vanadium-flow-energy-storageto-be-deployed-on-grand-scale-in-germany.

32 Sandra Enkhardt, "Sonnen to provide primary balancing power to German grid from networked home storage," PV magazine, 5 December 2018, at https://www.pv-magazine.com/2018/12/05/sonnen-to-provide-primarybalancing-power-to-german-grid-from-networkedhome-storage/.

33 Fritz Crotogino, "Huntorf CAES: More than 20 Years of Successful Operation," E. On, 15-18 April 2001, at http://www.fze.uni-saarland.de/AKE_Archiv/AKE2003H/AKE2003H_Vortraege/AKE2003H03c_Crotogino_ea_HuntorfCAES_CompressedAirEnergyStorage.pdf.

34 Wang Bo, Sebastian Bauer, "Compressed air energy storage in porous formations: a feasibility and deliverability study," Petroleum Geoscience 23(3), 27 April 2017, at https://pubs.geoscienceworld. org/pg/article/23/3/306/519394/compressed-airenergy-storage-in-porous-formations.

35 Lee Layton, "Compressed Air Energy Storage," PDH Center, 2012, at https://pdhonline.com/courses/e365/e365content.pdf.

36 Lee Layton, "Compressed Air Energy Storage," PDH Center, 2012, at https://pdhonline.com/courses/e365/e365content.pdf.

37 Samir Succar, Robert H. Williams, "Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power," Princeton University, 8 April 2008, at https://acee.princeton.edu/wp-content/uploads/2016/10/SuccarWilliams_PEI_CAES_2008April8.pdf.

38 "Power-to-Gas Plants in First Commercial Applications," TÜV, 19 March 2019, at https://www.globenewswire.com/newsrelease/2019/03/19/1757426/0/en/Power-to-Gas-Plants-in-First-Commercial-Applications.html.

39 Julian Wettengel, "Power-to-gas: Fix for all problems or simply too expensive?" Clean Energy Wire, 20 June 2018 at https://www.cleanenergywire.org/factsheets/power-gas-fix-allproblems-or-simply-too-expensive.

40 "Incentivizing Flexibility: The Role of the Power Market in Germany," GIZ, October 2019, at https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2019.10_Flex_Studie/EN_Final_giz_Study_Flexibility_2019_Web_1029.pdf.

41 Carolin Schenuit, Lukas Vogel, "Making money with smart electricity consumption Demand Side Management (DSM): Introduction and practical experiences in Germany," Dena, December 2018, at https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/181219_DSM_in_Germany_EN_final.pdf.

42 "电力工业统计资料编汇 [China power industry yearbook of 2018]," China Electricity Council, August 2019.

43 "电力工业统计资料编汇 [China power industry yearbook of 2018]," China Electricity Council, August 2019.

44 "北京市空调负荷运行规律及调控建议 ," Beijing Municipal Commission of Development and Reform, 2014.

45 "关于印发《发电厂并网运行管理规定》的通知 , 电监市场〔2006〕42 号 ," State Electricity Regulatory Commission, 3 November 2006, at http://zfxxgk.nea.gov.cn/auto79/201306/t20130628_1618.htm.

46 "关于印发《并网发电厂辅助服务管理暂行办法》的通知 , 电监市场〔2006〕43 号 ," State Electricity Regulatory Commission, 7 November 2006, at http://jsb.nea.gov.cn/news/2010-5/201059100025.htm.

47 Zheyu Guo et al., "Power system flexibility quantitative evaluation based on improved universal generating function method: A case study of Zhangjiakou," Energy, 2019, at https://www.sciencedirect.com/science/article/abs/pii/S0360544220310707.

48 "China Renewable Energy Outlook 2019," China National Renewable Energy Centre, National Development and Reform Commission Energy Research Institute, March 2020, at http://boostre.cnrec.org.cn/index.php/2020/03/30/china-renewable-energy-outlook-2019-2/?lang=en.

## Energy Research Institute of the National Development and Reform Commission (ERI of NDRC)

The Energy Research Institute of the National Development and Reform Commission (ERI of NDRC) established in 1980. It is a research institute affiliated to the National Development and Reform Commission and directly managed by Institution of Macroeconomic Research of the National Development and Reform Commission. ERI is a research institute which comprehensively research on China's energy issue. ERI's main research aims are formulation of energy development strategies, plans and policies for China as well as providing consultancy and theoretical support for energy regulations and energy standards. Through soft science research, research topics covers the production, distribution and consumption of energy, with a focus on energy related economics, efficiency and environment topics as well as development of renewable energy. ERI has cooperated with various international organizations, includes United Nations Development Program (UNDP), United Nations Environment Program (UNEP), Word Bank, Asian Development Bank, Global Environment Fund, World Wild Fund, International Energy Agency (IEA) and International Atomic Energy Agency (IAEA). ERI also collaborated with governments, research institutes, universities and consulting companies from EU, USA, Japan, Australia, Canada, Demark, Norway, Republic of Korea, Thailand, India and etc.

## North China Electric Power University (NCEPU)

North China Electric Power University was founded in 1958. It is a national Project 211 and Project 985 key university under the Ministry of Education that specialises in polytechnic disciplines The university has one key discipline of the national "Double World-classes" construction (Energy and Power Science and Engineering), two national key disciplines (Power System and Automation, and Thermal Power Engineering), 25 provincial key disciplines. NCEPU now has about 3,000 faculty members and over 20,000 full-time undergraduate students and near 10,000 post-graduate students. The university has cultivated highly competent talents for the country's energy and power industry and promoted scientific and technological progress in this field. The university possesses well-structured, high-quality teaching staff, including 2 members of Chinese Academy of Engineering.

## Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

As a non-profit, federally owned enterprise, the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH is active in over 130 countries worldwide, implementing international cooperation projects and measures in the field of sustainable development. With about 40 years of experience implementing projects in the People's Republic of China, GIZ provides policy advice on various topics and sectors relating to China's reform process, including: environmental protection, sustainable economic development (especially renewable energies and energy efficiency), sustainable urban development, sustainable transport development, vocational training, law, product safety and consumer protection. The German Energy Transition Expertise for China Project, which is funded and commissioned by the German Federal Ministry for Economic Affairs and Energy (BMWi), supports the sustainable development of the Chinese energy sector by transferring knowledge and experiences of German energy transition (Energiewende) experts to its partner in China: the China National Renewable Energy Centre (CNREC), a leading Chinese think tank for advising the National Energy Administration (NEA) on formulating renewable energy policies and energy transition process.

**Energy Research Institute of the National Development and Reform Commission**

14-15 floors, Building B, Guohong Building, No. Jia11, Muxidi Bei Li,
Xicheng District, Beijing, China 100038
T +86-(0)10-6390 8491
F +86-(0)10-6390 8469
W http://www.eri.org.cn

**Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH**

1-15-1 Tayuan Diplomatic Office Building, No.14, Liangmahe Nanlu,
Chaoyang District, Beijing, China
T +86-(0)10-8527 5589
F +86-(0)10-8527 5591