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Power System Flexibility and Virtual Power Plant (VPP) in Shanxi Province

Sino-German Energy Partnership

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Foreword

To peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 as pledged by President Xi Jinping,[1] China is accelerating the transformation of its energy structure and increasing the share of renewable energy. China will boost its total installed capacity of wind and solar power to more than 1,200 gigawatt (GW) by 2030, forming an energy system with considerable shares of renewable energy. With high shares of renewable energy on the grid, an increasing level of electric energy consumption, extensive power electronics applications and local access to large-scale distributed energy resources, the balancing, regulating and support capacity of the power system will all face huge challenges. Improving power system flexibility is an important way to realise clean and low-carbon development in the energy sector.

Power system flexibility is defined as the capability of a power system to reliably manage the variability and uncertainty of demand and supply across all relevant timescales. Flexible resources are available through many process, including the supply side, the grid side, the demand side, and energy storage etc.. At present, the flexible resources of China's power system are mainly on the supply side, as flexibility potentials on the grid and demand side have not yet been effectively explored.[2] Virtual power plants (VPP) provide an important way to comprehensively utilise flexible resources of the power system and support the power system transition from current structure into an electricity system with high shares of variable renewables along with hydropower and nuclear.

Shanxi Province is an energy, chemical and heavy industry base in China, and a pilot province for the comprehensive reform of China's energy transition. To achieve the goal of a green and low-carbon energy transition, the province accelerates the development of the new type of power system with renewable energy as the mainstay, increases the use of renewable energy, deepens the market-based reform of the power sector, improves its power system flexibility, and promotes the implementation of virtual power plants.

This report presents an overview of China's energy and power system development and transition, with a focus on the potential of enhancing power system flexibility on the supply side, grid side and demand side on a macro level. Taking VPP of Shanxi Province as the main study and practice object, the report analyses the current status and models of VPP under the framework of socio-economic development and power system. The authors provide a summary of the province's five advantages to develop VPP: policy environment, mechanism, demand, technology and market-based developments. Challenges that Shanxi faces in VPP development in the areas of infrastructure, information technology, operational mechanisms, incentive programs and public communication are also stated in the report. As conclusion, the report suggests that Shanxi should draw on international experience, strengthen its market designs and related mechanisms, improve necessary hardware facilities and information technology, and ensure safe and secure operation as it further develops VPP in the future.

Background - Sino-German Energy Partnership: Power system flexibility

Power system flexibility has been one of the key topics of Sino-German Energy Partnership under the framework of the Sino-German Working Group on Energy directed by the German Federal Ministry for Economic Affairs and Energy (BMWi) and the National Energy Administration (NEA). Over the years, GIZ has been working with Chinese and German partners to review the experiences and best practices of power system flexibility in Germany, and use them as reference for China to develop an energy system with a high share of renewable energy. Also, Sino-German bilateral cooperation has been actively broadened and deepened and many workshops, seminars, and joint policy studies have been implemented. With the framework of Sino-German Energy Partnership and Sino-German Energy Transition Project, Reports has been published including Flexibility Technologies and Measures in the German Power System, Incentivizing Flexibility: The Role of the Power Market in Germany, A Quantitative Comparative Study of Power System Flexibility between Jing-Jin-Ji and Germany, Flexibility Toolbox for Coal-fired Power Plants and Business Models of Virtual Power Plants (VPPs) in Germany.

As an important energy base and a pilot province for comprehensive energy transition and reform in China, Shanxi Province plays a key role in building a new type of power system with renewable energy as the mainstay and accelerating energy transition through the development of a flexible power system and virtual power plants. The report reviews the current power system and VPP development in Shanxi, highlights its advantages and challenges of developing VPP, and proposes suggestions for future VPP development in the province. Other regions in China can benefit from drawing on the experiences and ideas of VPP development in Shanxi. As a next step, GIZ plans to place its focus on the regional scale, with contribution from the project outputs. According to the characteristics of regional economic development and power systems, GIZ will further promote collaborative and practical demonstration between China and Germany in the field of power system flexibility and virtual power plants, so as to steadily contribute to building a new type of power system in China with renewable energy as the main source, and to support China in achieving its “dual carbon” goal.

1. Power System Flexibility in China

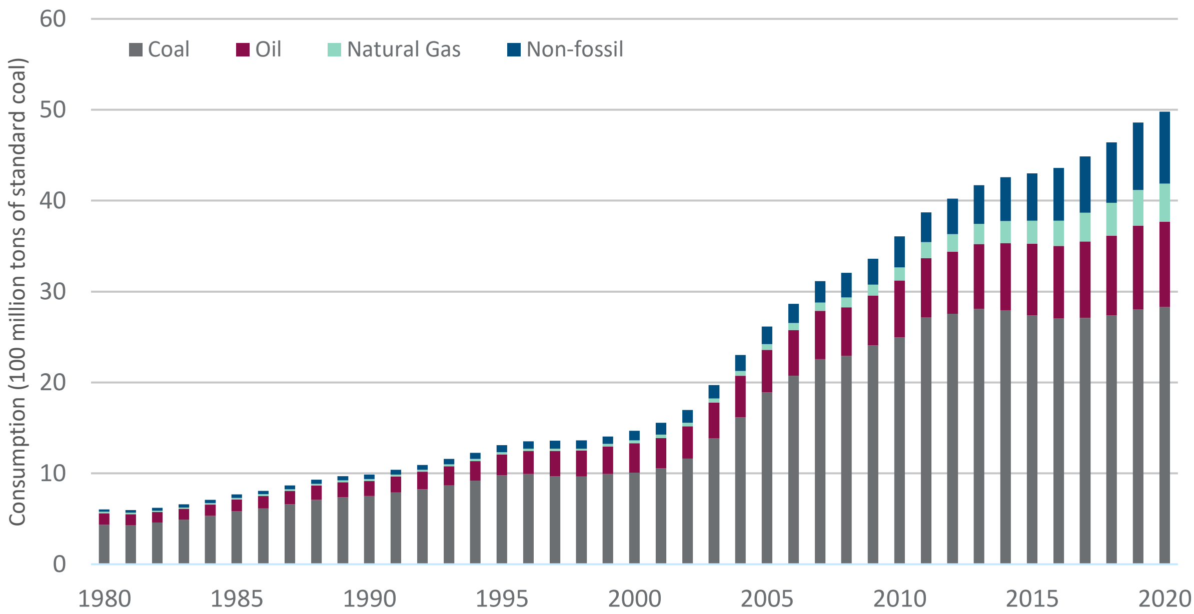
1.1 The status quo of energy and power development in China

Changes in China’s energy system have driven the optimisation of the energy production and consumption structure in recent years. The results are significant improvements in energy efficiency, energy supply for industry and households as well as increased energy security. These changes have significantly added to the high-quality development of the Chinese economy and society.[5]

According to the 2021 statistics of the NEA, China produced 4.07 billion tons of raw coal, 199 million tons of crude oil, and 205.26 billion cubic meters of natural gas. Total installed power generation capacity reached 2,380 GW in 2021. All county-level administrative districts have been connected to large-scale power grids, ensuring secure energy supply for ongoing socio-economic development and people's livelihood.

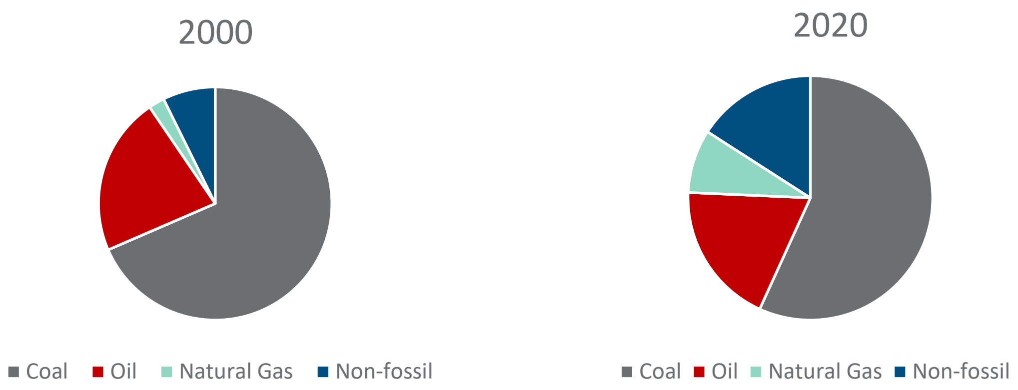
Through continuous and transformative energy reforms, China has gradually built the world's largest energy supply system. While coal is the dominant source, the use of electricity expanded greatly, and comprehensive growth took place for oil, natural gas and renewable energy sources (compare Figure 1).[6] Through the promotion of several policy measures for structural reform of the supply side and prioritising non-fossil energy, China continues to rapidly develop non-fossil energy sources and increases their share in the energy mix. At the same time, the energy consumption growth rate in the country is slowing down significantly and the energy mix is being further diversified optimised with more non-fossil energy.[7] In 2020, total primary energy consumption stood at 4.98 billion tons of coal equivalent (tce), including 56.8% raw coal, 18.9% crude oil, 8.4% natural gas and 15.9% non-fossil energy (compare Figure 2), while the total primary energy production was 4.2 billion tce.

Figure 1: National Energy Consumption, 1980-2020



Source: China Statistical Abstract 20221

Figure 2: Share of Energy Consumption by Source in 2000 and 2020

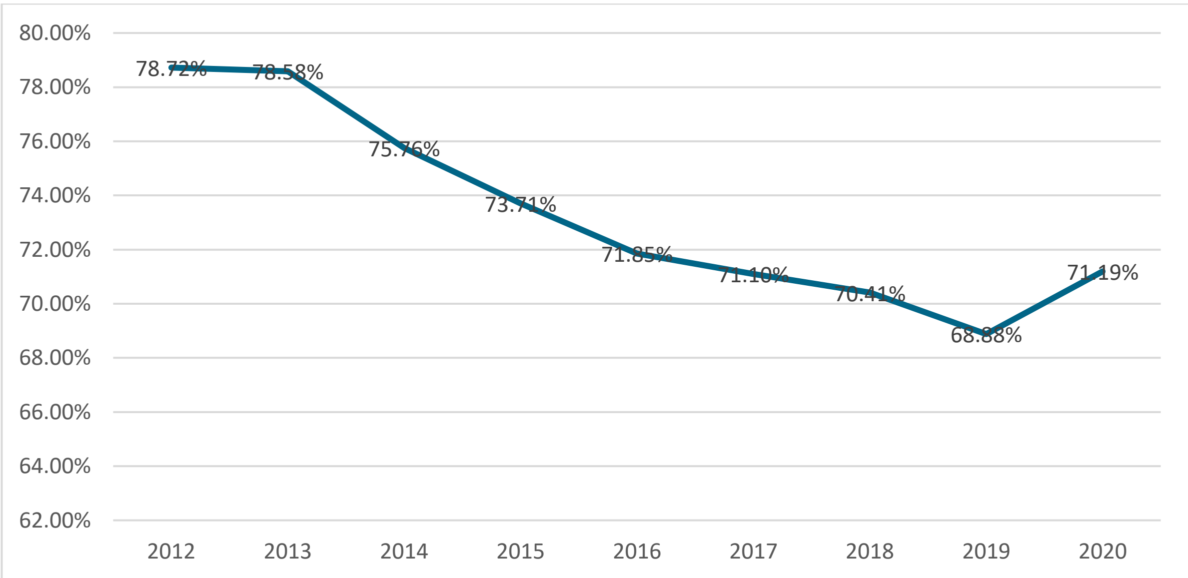


Source: National Bureau of Statistics

In terms of electric power, China's installed capacity of hydro, thermal, nuclear, wind and solar power is increasing year by year. Out of the 2,380 GW of generation capacity installed in China in 2021, 56.6% come from thermal power plants. Coal power plants make up 46.7% of the total capacity. The country's thermal power plant fleet has seen a reduction in the annual operating hours from the planned and designed 5,000-5,500 hours to an average of only 4,216 hours in 2020.

This is partly due to the integration of large-scale wind and solar power into the grid as well as some provincial overcapacities that only provide peak load. Thermal power plants are gradually changing their role and becoming a source of flexibility to facilitate structural adjustments towards a cleaner, low-carbon electricity supply system. The share of thermal power plants in electricity generation stands at about 70% (compare Figure 3).

Figure 3: Share of Thermal Power Generation 2012-2020



Source: China Electricity Industry Annual Development Report 2021

China’s energy sector is developing rapidly. The country’s resource endowment being “rich in coal, poor in oil, and short of gas” has led to the formation of an energy consumption structure dominated by fossil energy sources, mainly coal for a long time. This has in turn created ecological and environmental damage as well as energy resource bottlenecks. [8] Under the pressure of international climate agreements and domestic environmental regulations, China’s energy sector faces major challenges in ensuring energy security, meeting the demand for energy during structural change and industrial transformation, coordinating energy supply with economic, societal and environmental needs, and promoting high-quality development of the Chinese economy. As the global political and economic landscape underwent far-reaching adjustments after the COVID-19 outbreak, a green recovery is needed to accelerate the pace of green energy development worldwide. China’s commitment to developing a new pattern of mutually supportive domestic and international economic cycles and to peaking carbon dioxide emissions and achieving carbon neutrality has made the green transformation of energy particularly urgent since the start of the 14th Five-Year Plan period.[9]

1.2 Carbon peaking, carbon neutrality and a new type of power system

President Xi Jinping announced at the General Debate of the 75th Session of the United Nations General Assembly on September 22, 2020 that China will scale up its Nationally Determined Contributions by adopting more ambitious policies and measures to have carbon dioxide emissions peak before 2030 and achieve carbon neutrality before 2060 (“dual carbon”). Xi Jinping also presided over the 9th meeting of the Central Finance and Economics Committee on March 15, 2021, to make important arrangements for the energy and power development and proposed the “establishment of a new type of power system with renewable energy as the mainstay”, setting out core tasks for the energy industry to serve the “dual carbon” goal, and pointing out the direction of innovation and breakthrough.[10]

1.3 Analysis of power system flexibility in China

A new type of power system with renewable energy as the mainstay will have to accommodate a large share of renewable energy in the grid, and improve the safety and reliability of large-scale power grids. Power system flexibility will have a key role to play. Power system flexibility directly affects the overall power system balance and security, and determines the ability to integrate new energy sources. Flexibility resources are available at the supply, demand and grid level of the power system. At present, China's power system is more flexible on the supply side, as flexibility potentials on the grid and demand side have not yet been effectively explored.

Regarding supply-side flexibility, pumped hydro storage and gas-fired power generation are the main resources. China's supply side has long been rather lacking in flexible resources. The share of installed supply-side flexibility, that is the share of pumped hydro and gas-fired capacity of total installed capacity, was as low as 6% in 2020,[24] significantly lower than in countries with an early start in renewable energy development, such as Spain (34%), Germany (18%), and the United States (49%). The situation is even worse in the “Three-North” region, namely Northwest China, North China and Northeast China. With 72% of installed wind power and 61% of installed solar power capacity of the entire country, these regions’ flexible generation sources make up less than 3% of total installed capacity. At the same time, f retrofitting thermal power plants for enhancing flexibility is lagging behind.[2] The 13th Five-Year Plan for Electric Power Development[13] required flexibility retrofits of 133 GW thermal power units and 82 GW condensing units during the five-year period in the "Three North" region. By the end of 2020, however, only thermal power units with a capacity of 82.41 GW were retrofitted, a mere 38% of the target. Nuclear power is not yet ready for peak shaving and load regulation on a regular basis.

A variety of flexibility resources is potentially available on the demand side, such as loads in industries, in the transport sector with increasing electric mobility, in public utilities, commercial buildings as well as households.

However, the lack of appropriate infrastructures, tariff systems and incentive mechanisms make it difficult to unlock demand-side flexibility resources. As a result, the scale of demand-side response remains rather small and regulation mode relatively limited. In an effort to solve power shortage challenges especially during summers and winters, “peak shaving” is mainly done through load shifting of timely bases and orderly electricity use. The current demand-side flexibility is insufficient for “off-peak filling”, that ramping up flexible demand during times of high renewable generation. This further limit the integration of variable renewable energy. [15]

The source of flexibility on the grid-side comes mainly from the operation of the ultra-high voltage transmission system. At present, there are very few solutions available, and they all come with high technical requirements and limited scope of application. The ultra-high voltage transmission grid only allows for peak load adjusting at the consuming side to a certain extent, with fixed frequency and voltage, and without considering the needs from the generation side. [2]

Flexibility options through electricity and energy storage offer diverse technology routes, but the scale of application and installed capacity is limited. The technologies are still immature while costs are high. Consequently, it is difficult to recover investment costs under the current power market conditions that lack a supportive tariff system and compensation mechanism for storage flexibility. [2]

To peak carbon dioxide emissions, achieve carbon neutrality, and develop a new type of power system, it is necessary to vigorously develop non-fossil energy sources. Using renewables as alternative energy sources will enable a gradual increase of the share of renewable energy sources. The 14th Five-Year Plan on Modern Energy System Planning [11] has clearly pointed out the need to accelerate a green and low-carbon energy transition, and to comprehensively develop wind and solar power on a large scale. It is expected that by 2060, wind and solar power will account for more than 80% of installed capacity in China. At the same time, the share of electricity in final energy consumption will also increase significantly. In 2020, the share of electricity in final energy consumption in China was 26.5%, which is nearly in the same range as in developed countries. Along with ongoing electrification of different sectors, this figure is expected to reach to about 70% in 2060.[16] The increasing shares of renewable energy in the grid have put higher requirements on the power system to ensure power system flexibility and energy security. During the 13th Five-Year Plan period, China's power system lacked sufficient flexibility to accommodate the strong growth of renewable energy sources. Consequently, the power system faces many issues such as not enough capacity for renewable energy integration, decreasing system reliability, increasing energy security risk for users, and rising system costs.[12]

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In summary, achieving a high percentage of renewable energy and improving power system flexibility require more flexibility resources. The establishment of virtual power plants (VPPs) can assist in that regard. VPPs aggregate different generation sources such as steerable power plants or variable renewable sources (large-scale or distributed). VPPs are able to also aggregate different loads to achieve better integration of generation. Loads that can be integrated into a VPP can be adjustable industrial loads, energy storage units or electric vehicles. Microgrids and autonomous coordination of supply- and demand-side through algorithms allow VPs to trade on electricity markets while optimally aligning generation and loads with power system operation. VPPs can serve as "positive power plants" to supply power to the system for peak regulation, and as “negative power plants” to increase consumption to match generation for “valley filling”. VPPs can react swiftly to secure system stability and receive economic compensation from their participation in the normal electricity market as well as in auxillary and capacity markets. In China, the work on VPPs development has just started and the remaining challenges are:

- a lack of understanding of purpose and role of VPPs
- inconsistent standards and regulations
- inadequate incentives and market-based mechanisms for economic viability.

2. Power System and Virtual Power Plants in Shanxi

2.1 Power system development in Shanxi

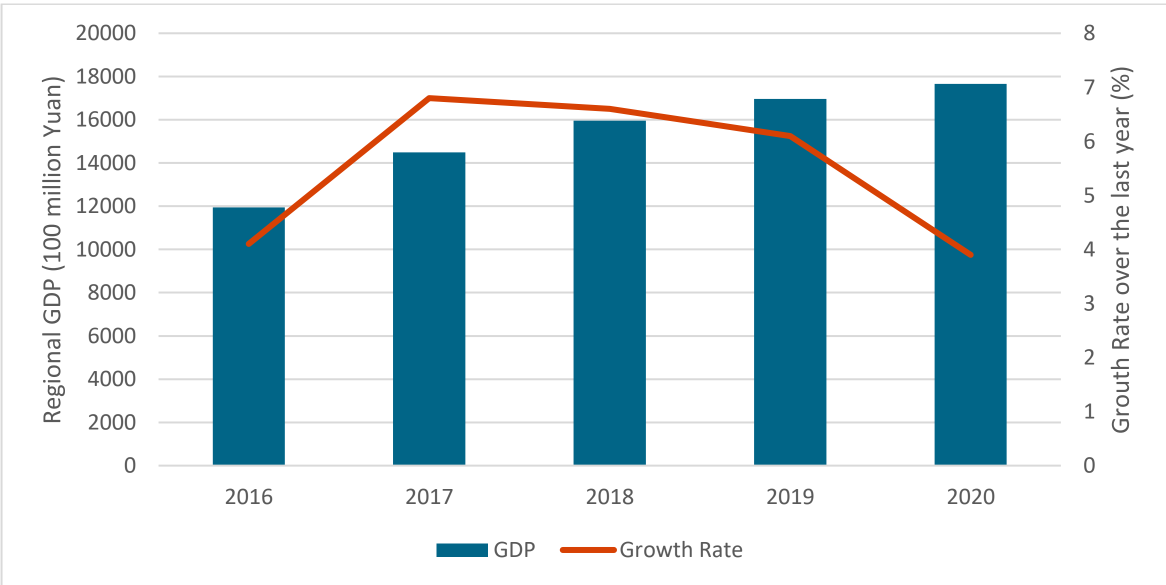
2.1.1 Socio-economic situation in Shanxi Province

Shanxi Province is located in northern China in the middle of the Yellow River Basin. It is a provincial administrative region of the People's Republic of China and has its capital in Taiyuan. With a total area of 156,700 square kilometres, the province has a permanent population of 34,915,600 as of 2020, and an urbanisation rate of 62.53%. Shanxi consists of 11 municipalities and 117 county-level administrative units.

As China's largest coal producer, exporter and chemical industry base, Shanxi produced 1.063 billion tons of coal in 2020, accounting for 29.2% of the country's coal production.

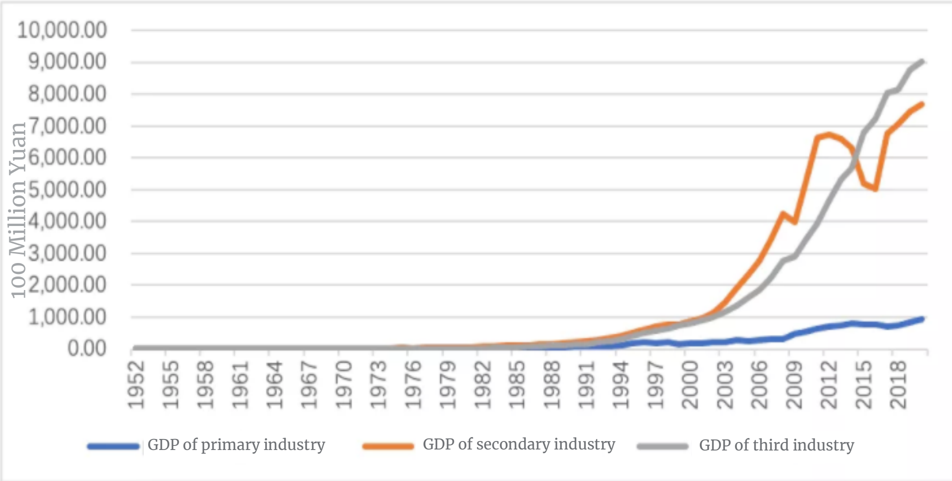
In 2020, the annual gross regional product (GDP) of Shanxi reached RMB 1765.2 billion, an increase of 3.6% compared to the previous year at constant prices. Specifically, the primary industry output was RMB 94.67 billion, also up by 3.6% and accounts for 5.4% of the regional GDP; the secondary industry added RMB 767.54 billion, up by 5.5% and accounting for 43.4% of the regional GDP; the tertiary industry was valued at RMB 902.98 billion, up by 2.1% and accounting for 51.2% of the regional GDP.[17] The secondary industry contributed a major part of regional economic growth.

Figure 4: Gross Regional Product and Growth Rate of the Province, 2016-2020



Source: Shanxi Province Economic and Social Development Bulletin

Figure 5: Change in Output Value of Three Major Types of Industries in Shanxi 1952-2020



Source: Shanxi Province Economic and Social Development Bulletin

In 2020, industrial enterprises above certain scale across the province generated revenues of RMB 2,067.33 billion, down by 1.7% in comparison to the previous year. By category, the mining industry made RMB 711.82 billion, down by 6.1%, the manufacturing industry generated RMB 1101.52 billion, up by 1.2%, and production and supply of electricity, heat, gas and water made RMB 253.98 billion, down by 1.2%. Industrial enterprises above designated size made RMB 96.38 billion of profit before taxation, down by 20.2%.

In 2020, the annual output of raw coal of Shanxi Province was 1.063 billion tons, up by 8.2%; coke output was 105 million tons, up by 5.6%; energy yield was 336.69 billion kWh, up by 2.1%; and unconventional natural gas production was 8.52 billion m3. Its annual primary energy production was 750 million tons of standard coal, an increase of 8.3%, and the secondary energy production was 640 million tons of standard coal, an increase of 19.6%.

Table1: Revenues and Growth Rate of Industrial Enterprises Across Shanxi in 2020

Category	Revenues (billion RMB)	Year-on-year increase
Industrial enterprises above certain scale across the province	2,067.33	-1.7%
Mining	711.82	-6.1%
Manufacturing	1101.52	1.2%
Production and supply of electricity, heat, gas and water	253.98	-1.2%
Industrial enterprises above designated size	96.38	-20.2%

Table2: The Annual Output and Growth Rate of Energy Production Shanxi Province in 2020

Category	Annual output	Year-on-year increase
Raw coal	1.063 billion tons	8.2%
Coke	105 million tons	5.6%
Energy yield	336.69 billion kWh	2.1%
Unconventional natural gas	8.52 billion m3	/
Industrial enterprises above designated size	96.38	-20.2%
Primary energy production	750 million tons of standard coal	8.3%
Secondary energy production	640 million tons of standard coal	19.6%

Table 3: Growth Rate of Industrial Added Value above the Designated Size in Shanxi in 2020 (%)[25]

Category	Year-on-year increase
Industry above designated size	5.7
Including: Mining	8.0
Manufacturing	4.2
Production and supply of electricity, heat, gas and water	-1.0
Including: State-controlled enterprises	5.4
Including: Collective enterprises	-7.6
Joint-equity enterprises	6.5
Foreign-funded and Hong Kong, Macao and Taiwan funded enterprises	5.1
Including: Coal industry	8.4
Coking industry	6.6
Power industry	-2.3
Heat and gas industry	6.4
Steel industry	8.3
Non-ferrous metals industry	-11.3
Building materials industry	4.5
Chemical industry	-0.7
Food industry	-1.7
Equipment manufacturing industry	5.7

2.1.2 Power industry development in Shanxi Province

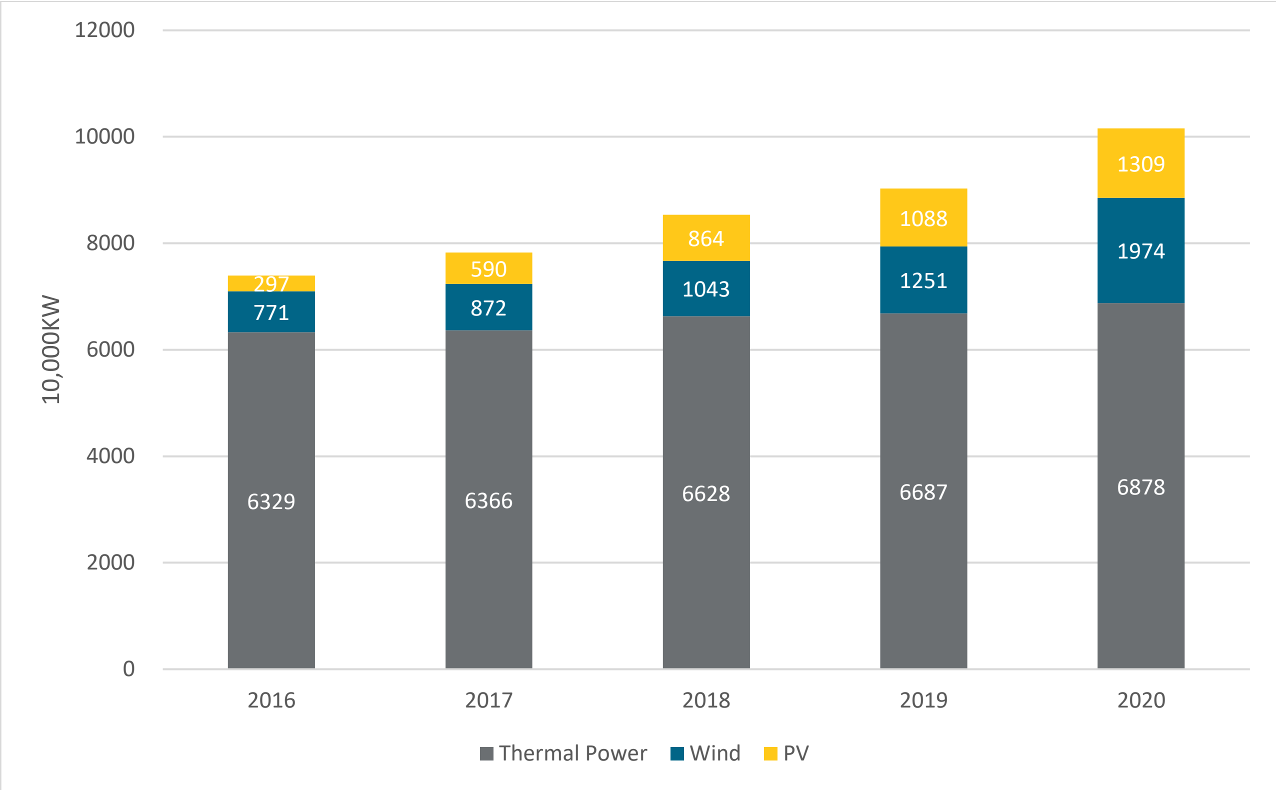
(1) Power generation

Given the abundant coal reserves in Shanxi Province, its electricity mix has long been dominated by coal-fired power generation. In recent years, the national "dual carbon" goal and the general trend towards a clean and low-carbon energy system have gradually improved the power generation structure of Shanxi, reducing the share of thermal power while increasing the proportion of renewable energy.

By the end of 2020, the last year of the 13th Five-Year Plan period, the installed power generation capacity in Shanxi province was 103.8 GW, up by 49 % from 2015, the end of the 12th Five-Year Plan period. Specifically, capacity of thermal power plants accounted for 66.2%, down by 19.1% from 2015 while renewable energy (wind and solar) capacity was the second largest in the province, accounting for 31.6%, up by 20.39% from 2015. The province generated 339.54 TWh of electricity, of which 42.43 TWh were generated by renewable energy sources. This accounted for 12.5% of the total electricity generation, an increase of 8.11% compared to 2015 and a consumption rate of renewable energy at 97.03%. The increase of renewable energy yield in Shanxi aggravates the lack of flexible power sources in the power system, resulting in a severe problem with peak load management.

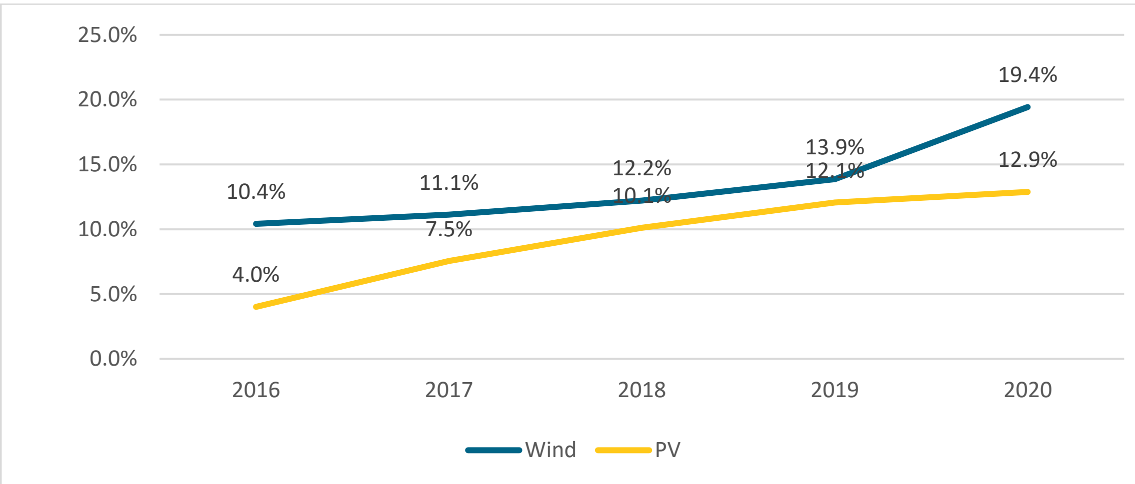
In order to promote and guarantee grid connection of renewable energy sources and use coal power as a supportive source, Shanxi Energy Bureau issued the Notice on Accelerating Flexibility Retrofit of Coal Power Units in 2020. It requires power generation companies to accelerate flexibility retrofits of coal power units. However, given the total coal power capacity and peak management limitations in Shanxi Province, the potential of increasing flexibility resources is limited and does not match the rapid growth of renewable energy. Thus, efforts on the supply side alone will not be enough to provide secure and flexible regulation required by a power system with variable renewable energy as the main source of electricity.

Figure 6: Change in the Installed Electric Power Structure in Shanxi Province



Source: Shanxi Province Economic and Social Development Bulletin

Figure 7: Change in the Share of Installed Renewable Energy Capacity in Shanxi Province



Source: Shanxi Province Economic and Social Development Bulletin

(2) Load side

The annual gross electricity generation of Shanxi Province in 2020 was 339.54 TWh, an increase of 4.4% year-on-year. A total of 105.36 TWh of electricity was exported to other provinces, an increase of 6.3%. Shanxi consumed 234.17 TWh of electricity, ranking 13th in the country. Among them, the primary industry used 1.85 billion kWh, accounting for 0.8% of the total electricity. The secondary industry used 180.43 billion kWh, accounting for 77.1%, including 178.06 billion kWh consumed by industry, or 76.04% of the total consumption. Industry still occupies a dominant position in electricity consumption, and over 50% of the large-scale industrial users are energy-intensive users. The tertiary industry consumed 28.84 billion kWh of electricity, accounting for 12.3% of the total. Urban and rural residents used 23.04 billion kWh, or 9.8% of the total.

Geographically, power generation in Shanxi Province is mainly concentrated in the North, but its industrial centre and heavy loads are located in the South. Thus, power generation and load centres need to be connected through electricity transport infrastructure. Distributed solar energy has increasingly been added to the grid in recent years and gradually intensifies the imbalance between power generation and consumption in timely matter. With the increasing amount of distributed energy sourced feeding into the grid, the morning peak load is clearly decreasing, while load valley at noon is even lower than that in the latter half of the night. Peak load generally occurs between 5 and 9 pm: the maximum load in summer is usually around 8 pm, in winter around 6 pm. The mismatch between location of generation and load centres as well as generation and load profiles has worsened with impacts on renewable energy integration in Shanxi. From January to February 2020, electricity consumption hovered at a low level for a longer period due to the COVID-19 pandemic and the Spring Festival holiday. The province's combined heat and power units operated at the minimum level for 30 consecutive days in order to ensure household heat supply and to integrate renewable generation., However, wind and solar curtailment remained as high as 660 GWh during that period, much higher than the national average.

(3) Grid side

Shanxi electricity backbone is a cross-provincial power grid with 500 kV "Three Vertical and Four Horizontal lines". Furthermore a 220 kV regional ring network exist. As a part of the national "West-to-East Power Transmission" project in the north of China, Shanxi has established three GW-scale converter stations in the Northern, Central and Eastern regions of the province and connected them with the ultra-high voltage lines running from West and North China to the Eastern coast of the country. Specifically, 1,000kV UHV AC line, namely Southeast Shanxi (Changzhi) - Nanyang - Jingmen, Inner Mongolia West - Jinbei - Tianjin South, Yuheng - Jinzhong - Weifang, four UHV outgoing channels including Jinbei (Yanmenguan) - Jiangsu (Huaian) ± 800kV DC and five 500kV outgoing channels. The highest outgoing capacity is 38.3 million kW, more than one-third of the total installed power generation capacity. The maximum outgoing power was 10.5 million kW in 2020.

The changes in Shanxi's power system in regard to generation, load and grid over recent years show improvements and were able to integrate a rapidly growing proportion of renewable energy. The power system is in a critical period of transition with renewable energy becoming the mainstay. As an important channel for the transmission of electricity from the West to the East, Shanxi plays a key role in supporting the national power system. With a higher proportion of renewable electricity than other provinces, Shanxi's power system is facing more challenges. There is a huge mismatch between the current power supply and load. The lack of flexibility capacity and only limited potential and incentives to increase flexibility on the supply side make it difficult to secure a safe and stable operation with a much higher share of variable renewable generation. The potential of flexibility resources should be explored as soon as possible: Virtual power plants should be developed to adapt to the characteristics of renewable energy in the power system and to create a new type of power system in Shanxi. This experience will also help to drive and support the establishment of a new type of power system with a high share of renewables nationwide.

2.1.3 Power market development in Shanxi Province

Improving the market mechanism and the decisive role of the market in allocating resources is the basis for China to build a new type of power system with renewable energy as the mainstay. Since the CPC Central Committee issued the document [2015] No. 9 Several Opinions on Further Deepening the Reform of the Electric Power System in 2015, China has promoted a market-based reform of the electric power system with remarkable success. Still, the transition towards a more market-based power system faces many challenges.

The common problem of the national power market is that the large-scale generation of renewable energy will lead to a gradually shifting role of conventional coal power stations: from being the main source of electricity generation to a regulating power source, undermining the operating model of coal-fired power plant operators of relying solely on power generation for revenue. In order to adapt to this power system transformation, it is necessary to fully explore the value of regulating resources in a market-based way, and guide coal power as a market player to actively participate in system regulation. This would allow coal-fired power plants to obtain a reasonable financial return through market mechanisms and helps to achieve a synergistic operation between renewable energy and conventional coal plants.

China is currently experiencing a boom in distributed (renewable) energy resources. In 2020, China added 48.2 GW of solar capacity. 15.5 GW were distributed PV installations, making up 32% of the total. A large number of small and medium-sized PV systems are being installed, creating a growing need for integrating distributed and small-scale power generation into the electricity market and trading system. However, if these transactions were to be directly included in the wholesale market, it would greatly increase the technical complexity of market clearing. At the same time, the transaction costs of integrating distributed sources would be higher than the value these small-volume power transactions provide.[18] With the rapid development of distributed renewable energy resources, it is necessary to develop a new business model in order to aggregate different resources spanning from distributed generation, energy storage to flexible loads. In such a model, aggregators participate as a single market player in the power market and effectively enable small and medium-sized resources to join power market transactions by flexibly allocating according to their characteristics and customer needs.

Shanxi, along with Guangdong, Western Inner Mongolia, Zhejiang, Shanxi, Shandong, Fujian, Sichuan and Gansu, is one of the first eight pilot provinces in China that preliminarily set up a power market trading system including medium and long-term trading, spot trading and power auxiliary services". Medium and long-term trading includes annual, quarterly, monthly, and intra-month trading. Spot trading allows for day-ahead and hourly real-time trading. Both medium and long-term trading as well as spot trading are available for direct intra-provincial, cross-provincial and cross-regional trading and it enables power producers to conduct transfer trading through contract between generators or consumers. The power market in Shanxi follows the original policy design to hedge risks and lock in returns with medium and long-term trades, discover prices and match demand and supply via spot trading, and ensure power system stability through market-based approaches. At present, its power market is able to guide various market players to participate through spot market price signals. On September 1, 2019, the Shanxi spot market was officially commissioned for a trial run. Mechanisms were implemented to link medium and long-term transactions with the spot market, as well as the integration of the spot market with peak shaving auxiliary services: The foundation for Shanxi to promote power system flexibility and VPPs to adapt to a high proportion of renewable energy were established.

As of 2021, Shanxi's trading platform had 11,051 registered market players. This figure includes 448 power generation enterprises (33 new), 529 electricity retailers (168 new), and 10,074 power consumers (2,561 new). There are 10,263 registered market players participating in the trading, accounting for 92.87% of the total. A total of 41 inter-provincial transactions were organized resulting in a trading volume of 47.716 TWh of electricity. The province's electricity exports have reached 123.465 billion kWh, an increase of 18.103 billion kWh, or a growth rate of 17.18%. Specifically, the amount of increased power transmitted towards North China accounted for 87.74% of the annual increase, and represents the main route of the province’s electricity exports. The cumulative volume of direct trading was 138.202 TWh, reaching 115.17% of the annual trading scale (120 billion kWh). 183 electricity retailers traded 130.649 TWh of electricity. 24 power consumers traded 6.822 TWh of electricity. The cumulative transfer transactions through contract reached 22.808 TWh.

The Shanxi power market system with spot market at the core has given full play to the role of spot market in price discovery, established a relatively stable medium and long-term trading mechanism and a competitive spot trading mechanism, integrated power auxiliary services, effectively enabled the market allocation of resources, mobilised various market players, and laid a good foundation for the implementation of new technologies and new models such as virtual power plants.

2.2 Virtual power plant development in Shanxi Province

A virtual power plant (VPP) can be defined as a component of a smart energy system that aggregates one or more available resources such as distributed generation sources from different locations, adjustable loads, energy storage, microgrids, electric vehicles to achieve autonomous coordination, optimal power system operation and participation in power market trading.[3][4]

The ninth edition of Shanxi Power Market Trading Rules (V9.0) introduced in 2021 has clarified the market role of a VPP: electricity retailers that aggregate power consumers with load regulation capacity through a market-based approach, so as to collectively provide peak shaving resources and services through the load-side VPPs. On February 19, 2021, the Shanxi Energy Regulatory Office issued the Implementation Rules for the Participation of Independent Energy Storage and User Controllable Load in Electricity Peak Regulation Market Trading in Shanxi (Trial), which further clarified the rules for various market players participating in peak regulation trading, including independent energy storage, independent users, user-side energy storage, electricity retailers, auxiliary service aggregators, and independent auxiliary service providers.

On August 31, 2021, the National Energy Administration released the Regulations on Grid-connected Operation of Grid-connected Entities (exposure draft)[20] and the Management Measures for Auxiliary Services of Power Systems (exposure draft)[20], which propose to actively engage new energy storage, user-regulated load, aggregators, VPPs, and other resources in power auxiliary services nationwide, providing a clear policy signal for accelerating the development of VPPs nationwide.

2.2.1 Virtual power plant development, operation and management mechanism in Shanxi Province

Based on the power grid, VPPs in Shanxi shall use the Internet, Internet of Things, big data computing, industrial automation control and other technologies to build a technical support system. They shall aggregate, optimise, coordinate and control resources to participate in power grid scheduling and operation as one entity. They shall participate in power market trading as a market player, execute trading results and complete settlement. They shall also aggregate grid flexibility resources and coordinate scheduling and dispatch. In June 2022, the Shanxi Provincial Energy Administration issued the Implementation Plan for the Construction and Operation Management of Virtual Power Plants. The document sets out clear requirements for the resource aggregation of three types of VPPs, i.e. supply side, load side, and energy storage side: The resources on the supply side should be photovoltaic, wind power, biomass power generation, etc., which are connected to the power grid in Shanxi. The resources on the load side should be the power consumers in the adjustable load resource database on the provincial intelligent energy integrated service platform. The resources on the energy storage side should be various energy storage facilities on the supply side, the grid side, and the user side in the province.

According to the local situation and next development steps, Shanxi Province has designed two VPP models, i.e. the "load-type" model and the "integrated source, grid, load and storage" model. The "load-type" model means that electricity retailers aggregate power consumers with load regulation capability through a market-based approach, so as to collectively provide load-side flexible response and regulation services (presented as a load state).

Operators of "load-type" virtual power plants should be electricity retailers or power consumers which have the qualification to trade in the Shanxi power market. At the early stage of market development, "load-type" virtual power plants participate in the medium and long-term, spot and auxiliary service markets. In the later period, adjustments will be made in due course depending on the development of the power market.

The "integrated source, grid, load and storage" model refers to inclusion in the pilot project of "integrated source, grid, load and storage". Upon completion, new energy, users and supporting energy storage projects will be integrated and aggregated through the virtual power plant. The virtual power plant of this model participates in the power market as an independent market player. In principle, it requires no peak load regulation capacity from the system, has the function of independent peak shaving and regulation, and can provide regulation services for the public power grid. Operators of the "integrated" virtual power plant should be the main body or authorized agent of the "integrated" project, and have the qualification to sell electricity in the Shanxi power market. They participate in the spot and auxiliary service markets. In the later period, adjustments will be made in due course depending on the development of the power market.

Shanxi Provincial Energy Bureau has set out clear technical requirements for virtual power plants, including resource aggregation capability, regulation capacity, data access, communication interface, safety protection, sensing capability and metering.

(1) Resource aggregation capacity: requiring an initial regulation capacity of not less than 20 MW and not less than 10% of the maximum electricity consumption load; response time: requiring the capability to continuously join the response for not less than 2 hours.

(2) Responsiveness: requiring a regulation rate of not less than (regulation capacity * 3%)/minute and not less than 0.6 MW/minute; accuracy: requiring that the deviation rate per 15 minutes of the "load-type" virtual power plant should not exceed ±15% and that of the "integrated" virtual power plant should not exceed ±10%.

(3) "Load-type" virtual power plants need to test and determine technical indicators such as regulation capacity according to the trading period, apply different medium and long-term trading volume constraints and financial arbitrage constraints, report the upper and lower limits of the spot market operation and the VPT (Volume Price Trend), and ensure the enforceability of the clearing power curve of the virtual power plant. It is required to participate in the spot market on the basis of "reported capacity and quoted price". The upper and lower limits of the electricity load and the electricity-price curve of decreasing 3-10 segments of electricity consumption should be reported separately for each trading period of the day. It is required to participate in the clearing of the spot market according to the "negative power generation" model, and form a curve of the electricity consumption plan on the spot operation day.

(4) The "integrated' virtual power plant should be quoted with reference to the quotation model of thermal power units. The maximum value of the electricity load and the power generation load on the operating day should be reported. The negative value of the maximum value of the electrical load should be used as the lower limit of operation, and the maximum value of the power generation load should be used as the upper limit of the operation. The VPT of 3-10 segments of incremental power generation should be reported as a basis for 24-hour participation in the clearing of the spot market. At the early stage of the market, the maximum value of the reported electricity load should be less than or equal to 50% of the load on the user side of the "integrated" project, and the maximum value of the reported power generation load should be less than or equal to 50% of the scale of the supply side of the "integrated" project.

2.2.2 Principles of virtual power plant development in Shanxi Province

The future development of virtual power plants in Shanxi shall adhere to the following principles:

1. Market-driven development. Market-driven development is the most important basis for VPP establishment. Relying on the Shanxi spot market for electricity, efforts shall be made to promote price signals among market players from day-ahead and real-time supply and demand, so as to guide the generation, consumption and storage-side resources to participate in power balancing by way of VPP, and to significantly enhance the flexibility and security of the power system.

2. Encouraging innovation. It is necessary to improve the market-based operation of VPPs, explore their commercial value in the power market, guide the use of Internet, Internet of Things, big data, automation and other technologies, attract talents to the VPP industry, and stimulate investment and innovation in R&D, construction and the operation of VPPs.

3. Strengthening management and regulation. Standards and regulations for the development, operation and management of VPPs shall be established. With strengthened process supervision and result orientation, VPPs shall play a positive role and achieve market revenues from trading. Regulatory measures shall be implemented to help VPPs prevent risk.

2.2.3 Practical cases of virtual power plant development in Shanxi Province

1. In December 2020, Shanxi launched its “renewable energy + electric vehicle” interactive demand-side response pilot project with a total of six pilots participating for a duration of four hours. The highest response load reached 5,000 kW. The project integrated 18,000 kWh from wind and solar that would have been curtailed otherwise and generated relevant experience for Shanxi to provide demand-side auxiliary services.

2. In mid-March 2021, four auxiliary service aggregators have been registered in the Shanxi Power Exchange Center, pooling more than 70 users. Shanxi officially started to organise auxiliary service aggregators to participate in the power market for peak regulation, with a maximum response load of 12,000 kW and a total response volume of about 36,000 kWh. As a result, Shanxi made a historic breakthrough in the practice of VPP development with market-based means.

3. In addition, energy service enterprises in Shanxi have also carried out VPP practice with controllable load in accordance with the characteristics of the local industrial, construction, transportation and urban electricity loads. The industrial sector mainly utilises adjustable loads from intermittent production for VPP use. The VPP resources in the building sector are mainly energy-using equipment such as air conditioners, lighting, elevators, pumps, and electric heaters in commercial buildings. In the transportation sector, VPP resources include electric vehicles and electric heavy trucks with large battery capacity and flexible charging times, as well as battery changing stations with integrated wind, solar and storage facilities, and urban super charging station platforms. In the urban area, VPPs mainly help maximize the consumption of renewable energy power by regulating the work plan and operation status of municipal facilities such as streetlights, air conditioners of public buildings, water pumps, heat exchange stations and waste disposal stations.

3. Development Potential of Virtual Power Plants in Shanxi Province

3.1 Favorable conditions for the development of virtual power plants in Shanxi

As the only pilot province for comprehensive energy transition and reform in China, Shanxi should further deepen the market-based reform of its electric power market, tap into flexibility regulation of the power system, increase the consumption of renewable energy, and accelerate the development of a new type of power system with renewable energy as the mainstay. VPPs are an important solution to enhance power system flexibility and establish a new type of power system. Shanxi Province has favourable conditions for VPP development:

(1) In terms of **policy environment**, in July 2021, the National Development and Reform Commission (NDRC) issued the Notice on Further Improving the Time-of-Use Electricity Price Mechanism, which requires that in places where the maximum peak-to-valley difference was or is expected to exceed 40% in the previous year or the current year, the peak-to-valley tariff difference shall be, in principle, no less than 4:1; in other places, no less than 3:1.[22] The introduction of this policy has driven the development of power system flexibility with economic incentives. According to the difference between peak load and off peak, renewable energy consumption and system regulation capacity, Shanxi has adjusted the tariff difference to 3.6:1, that is, peak hour tariffs are 60% higher than the usual tariffs, off peak hour tariffs are 55% lower than the usual tariffs, and the ultra peak hour tariffs are 20% higher than peak hour tariffs. The issue of power supply restrictions in the fall of 2021 also drove the reform of electricity tariffs. The Notice of National Development and Reform Commission on Further Deepening the Market-based Reform of Coal-Fired Power Generation Feed-In Tariff, released in 2021, requires the promotion of integrating all commercial and industrial users into the electricity market, and sets the original upward tariff range of no more than 10% and downward of no more than 15% to 20%. Energy intensive industries may determine electricity prices by market trading and are not subject to the 20% upward fluctuation limit. Shanxi has an energy intensive industrial structure with heavy industries consuming more than 75% of the total power. This reform accelerates the market-based development of all key market players, which is conducive to the formation of a more flexible tariff mechanism and the expansion of market player coverage.

(2) Regarding **institutional conditions**, as China's comprehensive energy transition and reform pilot, Shanxi shoulders a key mission to explore feasible ways for a green and low-carbon energy transition, and shall take the initiative to play a demonstrative and guiding role in the development of a new type of power system. In order to adapt to the rapid development of renewable energy and explore a safe, stable and flexible power system, Shanxi has a mission and advantages in VPP development, and carries out various pilots on VPP integration into the power market, while adjusting policies according to the actual situation. This approach drives the overall development in terms of VPP integration.

(3) On the **demand side**, VPP development in Shanxi offers the possibility to support the national power system, accommodate rapidly increasing renewable energy capacity in the province, correct the spatial and temporal mismatch between power supply and load, and improve the relative lack of supply-side flexibility resources. At the same time, more than 50% of large-scale industrial users in Shanxi are energy-intensive users with a strong will to participate in the peak regulation market with user-side resources such as controllable industrial loads, heat storage boilers, energy storage equipment and electric vehicles. They all provide a solid market foundation.

(4) Regarding the **technical basis**, Shanxi has laid out clear technical requirements for various VPP models, and organised pilots and market-based practices to foster digital energy operation enterprises, providing the technical foundation for VPP development.

(5) Concerning the **market basis**, Shanxi has established a relatively complete, adaptable and stable spot market through several rounds of market rule formulation and trial runs, cultivated a variety of market players, and clarified the development, operation and management mechanism of VPPs. The province has developed the market foundation and market roles for new VPP models.

3.2 Challenges of virtual power plants promoting in Shanxi

Although Shanxi Province has made achievements in its VPP development and has many advantages, challenges exist:

Technology:

(1) Running a virtual power plant requires **infrastructure support**, including smart sensors, remote control, automation systems and other metering and monitoring platforms, which currently struggle to meet the VPP standards. Infrastructure needs to be improved.

(2) **Information technology support** for the operation of VPPs requires the collection of a large amount of information, including user demand, subsystem operation, grid dispatch, power market prices and environmental conditions. Further required are advanced forecasting algorithms to process information and to develop optimal dispatch plans, regulate resources to participate in the power market and provide services for power system balancing. However, the forecasting and remote control technology of VPPs in Shanxi lacks accuracy for swift regulation and control. The use of digital and internet technologies means that VPPs have an interface with all processes of the energy system and become a large, multi-layered information system. Therefore, it is also crucial to secure the system at different levels and develop security technologies for large integrated power information systems that are compatible with virtual power plants.

Management:

(1) In terms of **operation mechanism**, despite the clear rules for VPPs accessing and joining the market trading, there are still problems in defining and managing VPPs accurately. As for VPPs with "integrated source, grid, load and storage", the aggregation of various resources further increases the difficulty in definition.

(2) Regarding **incentives**, the relatively sound power market in Shanxi also faces the problem of insufficient incentives for VPPs. VPP operation requires diverse and extensive energy dispatch resources, but the lack of incentives has led to poor performance of VPPs in Shanxi in terms of aggregator cultivation and the scale of user resources.

(3) Due to insufficient **public communication**, users also lack an understanding of demand-side flexibility resources.

3.3 Future direction of development of virtual power plants in Shanxi

(1) **Draw from international experience**: Shanxi is rather similar to Germany in terms of socio-economic conditions and energy development. Coal used to be one of the main sources of electricity generation in Germany. With the introduction of its climate goals, Germany is undergoing a green and low-carbon energy transition. As an important coal-producing province in China and an energy reform pilot, Shanxi should gradually reduce its dependence on coal, and achieve the green and low-carbon energy transition. Since Germany set the goal to achieve climate neutrality by 2045, the country's energy market actors have adopted VPPs as one of the solution to enhance power system flexibility, integrate renewable energy and promote energy transition. The experience and lessons learned from VPP development in Germany's energy transition can provide a reference for Shanxi.

(2) **Strengthen mechanism design**: One of the key success factors for VPPs in Germany is the broad pool of energy resources, including high-quality, highly flexible generation units such as biomass/biogas plants and pumped hydro plants along with small-scale and distributed rooftop PV. On the load side, industrial and commercial loads have been integrated into power and ancillary service markets since many years already. New distributed loads such as electric vehicles, heat pumps, residential energy storage facilities, and emerging resources such as electrolysers for the production of green hydrogen will play an increasingly important role. When building and operating VPPs in Shanxi under government leadership, it is necessary to further improve incentive policies and market-based trading mechanisms, actively introduce private capital, and strengthen the development of aggregators. Meanwhile, mechanisms should be set up to mobilise the participation of distributed resources and the demand-side in VPP development. This can be achieved by enabling cost savings for the demand-side through the tariff mechanism, by giving distributed energy resources a reasonable and clear economic incentive and providing guidance for them to participate in VPPs. In addition, it is im-

portant to establish communication channels and platforms for disseminate information, knowledge, and awareness related to VPPs. This can lay the foundation for building a broad and diverse pool of energy resources.

(3) **Improve the hardware infrastructure and information technology support necessary for VPP operations**: Running a virtual power plant requires advanced digital technologies to enable data collection (including power plant operation, meteorological data, market price signals, power grid conditions), and safe and fast communication among VPP, resources, transmission system operators and the power market for accurate regulation. It is necessary to introduce advanced communication technologies, build the VPP infrastructure platform and operation platform, and provide sound hardware infrastructure for relevant stakeholders.

(4) **Strengthen the safe and secure operation of VPPs**: Germany has adopted the balancing unit model in its electricity market for all power market participants. The model provides forecasts on load ,generation and traded volumes based on electricity generators, retailers, generation and load aggregators and large energy users within an individual balancing unit to the TSO This approach significantly improves the operational security of VPPs in terms of forecasting, scheduling and control. Shanxi shall explore feasible VPP development paths and designs to ensure the safe and stable operation of its power system, and guarantee information security on key equipment and data..

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