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Smart Grid Development in China: Achievements and Trends

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The report "*Smart Grid Development in China: Achievements and Trends*" summarizes China's achievements in smart grid development from 2014 onwards. Decarbonization, decentralization, digitalization and market transformation are the predominant features of China's smart grid development since 2014 and are expected to remain the main trends in China's smart grid development in the future. The report is published in the framework of the Sino-German Energy Partnership between the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the National Development and Reform Commission (NDRC) and the National Energy Administration of the People's Republic of China (NEA). As the central dialogue platform on energy between the two countries, the main objective of the partnership is to foster and advance the far-reaching and profound energy transitions ongoing in both countries by exchanging views, best practices, and knowledge on the development of a sustainable energy system, primarily centered on improving energy efficiency and expanding the use of renewable energy. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH implements the project under commission of BMWK. As a German federal enterprise, GIZ supports the German government in the achievement of its goals in international cooperation for sustainable development.

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Executive summary

Smart grid development in China is centered on decarbonization, decentralization and digitalization. Technological progress and market mechanisms are important levers for building a new electricity system.

Since 2014, China has stepped up efforts in its smart grid development. Although China's electricity system is still dominated by large public grids with distinctive features of a planned economy, new factors influencing smart grids have significantly increased. The factors are manifested in the strong development of renewable energies, the emergence of distributed generation (DG) and the increased demand for a fair market environment on the consumer side.

At the end of 2021, the total installed renewable energy capacity exceeded 1000 Gigawatt (GW). The strong development of modern renewable energies, represented by wind and solar photovoltaic (PV) power, is the most significant feature of China's smart grid. The country has the highest wind and solar capacity globally. As China proposed to achieve carbon neutrality by 2060, the large-scale expansion of new energy sources, mainly wind and solar as variable renewable energy (VRE), has become an essential pathway for achieving this ambition. However, since VRE is characterized by fluctuations in generation, the challenges of grid regulation and balancing electricity production and consumption is the first to be addressed by the smart grid.

Renewable energies are distributed over wider geographical areas. Thus, the need arises for transmitting and distributing the generated electricity over longer distances. Developing DG in the vicinity of load centers often becomes the most economical way of renewable energy development and is an increasingly important option. While the development of DG enhances demand-side capabilities to participate in grid regulation and power market transactions, it also complicates the traditional power dispatching and operation mechanism. This impacts the traditional power system governance and raises questions on how to reconcile the interests of different actors.

Despite the smart grid technology developments and market reforms being underway, China still faces challenges:

- Expanding VRE comes with difficulties in grid balancing and secure operation;
- Operational and implementation barriers to establish market mechanisms supporting the development of VRE and DG;
- Digital applications and utilization are uncommon, reflecting the early stages of a digital energy sector.

Possible development directions for smart grids in China can be oriented along the following five lines.

1. Development of different energy storage technologies that enhance the capability for VRE integration. Currently the most cost-effective energy storage method is pumped-hydro power. China has launched ambitious targets for pumped-hydro power storage development. The advancement and cost reduction of new energy storage technologies such as batteries can enable new technologies to become a key force in energy storage. The vast number of electric vehicles (EV) can serve as important demand-side energy storage sources and flexibility given appropriate guiding mechanisms.

2. Support the development of flexible power grids through local, DG-centered balancing. The development of DG will contribute to a more diversified pattern of China's power grid. It is expected that by 2030, China's installed capacity of distributed renewables will reach 400 GW. This growth can be accommodated with a large amount of local microgrids operating in coordination with the public transmission grids. The internal micro-balance of the microgrids will be important for achieving the balance of the entire power system.

3. Extensive application of digital technologies in all areas of the electricity system. Digital technologies can support a more efficient smart grid operation. They promote management improvements and business transformation within the power sector. The main applications are online equipment monitoring and control; smart operation and maintenance; comprehensive transaction support; planning, simulation, and operation of power systems with a high proportion of VRE.

4. Creation of a wide variety of new demand- and user-side entities to allow for diversified market participation modes. Examples are the interaction between EVs and the grid or the participation of aggregated controllable loads through virtual power plants (VPPs) in grid regulation.

5. Development of a sound green electricity trading system. Compared with traditional energy sources, renewable energy has the advantages of being increasingly cheap, low carbon and environmentally friendly. However, renewable energy also has disadvantages (e.g. fluctuating generation) that make it significantly less competitive in view of the entire power system. To make up for this lack of systemic competitiveness, a fully-fledged green power trading system for renewable energy should gradually be put in place.

To accelerate the development of smart grids, the support for novel energy storage, digital solutions, and smart microgrid technologies needs to be stepped up. Market mechanisms and their design need to accommodate a high proportion of VRE and user-side entities in the new power system. Policies for supporting green electricity, green certificates trading, and carbon markets need to be improved to highlight the environmental value of renewable energy and incentivize enterprises to actively purchase green electricity.

List of abbreviations

CHP:	Combined heat and power
DC:	Direct current
DG:	Distributed generation
EV:	Electric vehicle
GW:	Gigawatt
IoT:	Internet of Things
kWh:	Kilowatt-hour
LCOE:	Levelized cost of electricity
MIIT:	Ministry of Industry and Information Technology
NDRC:	National Development and Reform Commission
NEA:	National Energy Administration
PV:	Photovoltaic
TWh:	Terawatt-hour
SERC:	State Electricity Regulatory Commission
SGCC:	State Grid Corporation of China
tce:	Tonne of coal equivalent
UHV:	Ultra-high voltage
VPP:	Virtual power plant
VRE:	Variable renewable energy

Tables and figures

1. Smart grid developments in China

Around 2008, China put forward a smart grid development target that was geared towards increased automatization levels in terms of power generation, transmission, distribution, and consumption. Compared with European countries and the U.S., China's power grid has the following characteristics: The main goal of China's power grid development is and will be, for a considerable length of time, to meet the fast-growing electricity demand, to continue to strengthen the grid structure dominated by large power networks and to improve the power supply system with certain aspects of a planned system. Since 2014, China's electricity demand has been growing at a fast pace, and grid operators still operate in the inertia of the old large public grid development model. Smart grid development, however, increasingly gained traction due to new influencing factors: the strong development of renewable energies, the emergence of distributed generation (DG), and the increased demand for a fair market environment on the demand-side. These factors require an improved level of digitalization and market-mechanisms for the grid and the power system. As significant changes take place in the structure and shape of China's power system, smart grid developments are increasingly shaped by a coordinated development of centralized and distributed power sources.

China has also long been committed to implementing a power market reform, using price signals to promote active participation of all actors, breaking the traditional large grid-based governance pattern, releasing the power industry's innovative potential, and providing institutional safeguards for smart grid development. This progressive power market reform has become an important prerequisite for the development of smart grids, especially regarding the establishment of a unified power market adapted to the increase of renewable energy. The formation of a fair market environment with broad participation from all grid users is crucial for enabling a transition towards a green, smart, and open grid.

1.1 Evolution of the smart grid concept

In China, the concept and notion of what a smart grid is, has constantly been evolving. Currently, the parties involved in smart grid research and development mainly consist of grid companies, academia, and government. Each of them has a different focus on certain aspects of a smart grid. Grid companies generally focus on safe grid development and grid stability in response to challenges arising from the significant addition of new electricity sources. Academia and private enterprises focus more on VRE, DG, and innovation in business models of grid users with the hope of promoting significant changes in grid development and operation. Government is mainly concerned with developing a secure, efficient, and clean modern energy system, with particular emphasis on promoting the integration of renewable energy and the development of DG. Furthermore, the implementation of the power market reform and a coordinated development of the large public power grid and microgrids are important for government.

1.1.1 Smart grid strategy of power grid companies

As the most important actor of China's power grid development and operation, State Grid Corporation of China (SGCC) occupies a pivotal position in smart grid research and development. SGCC mainly focuses on the development of ultra-high voltage (UHV) electrical grids from the perspective of grid security. Another important focus is the adoption of digital technology to improve dispatching and operation of the large public grids.

In 2014, SGCC took the lead in proposing the concept of "Global Energy Interconnection (GEI)", an upgrade of the original term "Strong Smart Grid". [1] According to SGCC, GEI should be composed of an UHV grid, smart grids and clean energy sources. This highlights the role of a strong UHV grid as the backbone of a smart grid and a global electrical interconnection for promoting clean energy development and electrification. [2]

Since 2016, and in response to the rapid development of renewable energy in China, the SGCC concept of a smart grid has gradually transitioned to the term "energy interconnection". Energy interconnection (or also Energy Internet) can be understood as the comprehensive use of advanced electronics, information, and intelligent management technologies to interconnect a large number of energy nodes. These nodes consist of distributed energy data monitoring devices, distributed energy storage devices and various types of loads, such as power, oil and natural gas networks. A two-way flow of energy through peer-to-peer exchange and energy sharing should be achieved. Energy interconnection underscores the application of modern information and intelligent control technology as well as Internet of Things (IoT) technology to realize the interconnection and interoperability of the power grid with the heat/gas/transportation networks. In that way the resilience and regulation capability of different energy systems should be enhanced.

1.1.2 The notion of smart grid in academia and private enterprises

In contrast to SGCC's efforts in achieving interconnection at higher voltage levels and maintaining a unified large grid pattern, academia places more emphasis on enabling extensive interaction between the distribution and the demand side. The promotion of DG is a further key research area. [3] In April 2015, a symposium on "Energy Interconnection: Frontier Scientific Issues and Key Technologies", initiated by Tsinghua University, was held in Beijing. Over 50 prestigious scholars from 25 national and international institutions participated in the symposium. Their common view underlined the importance of the demand-side and DG in energy interconnection and grid development. [4] The academic notion of smart grid thus focuses more on complementarity and fair peer-to-peer participation on the consumer side. The introduction of concepts from network and internet theory into traditional energy networks is reflected in the following aspects.

Open interconnection: open interconnection of a variety of energy sources; open, peer-to-peer access of various devices and systems; open participation of different actors and end users; open energy market and trading platforms; open data and standards.

User-centeredness: innovation in business models centered on users' personalized and diversified needs; user recognition and extensive participation to effectively enhance the value of energy production, operation, trading, and services; user-centeredness is reflected mainly in user experience.

Distributed energy: distributed energy as important driving force for energy interconnection development; development of DG turns an increasing number of grid users into prosumers (both consumers and producers); demand for DG plug-and-play solutions and user needs for microgrid development will break the monopoly of grid operation; reciprocity of energy production and consumption as well as the formation of network-like transaction relationships. [5]

1.1.3 Government position and support for smart grid

The Chinese government understands smart grid development as an important part of upgrading the power grid. Crucial tasks of smart grids in that respect are smart dispatching, upgrading distribution grid digitalization and the integration of DG and VRE. Government has a holistic approach considering the development requirements of both large public and microgrids.

Since 2015, the government and relevant ministries, such as National Development and Reform Commission (NDRC), National Energy Administration (NEA) and MIIT (Ministry of Industry and Information Technology) published guiding opinions and plans on smart grid developments (Figure 1).

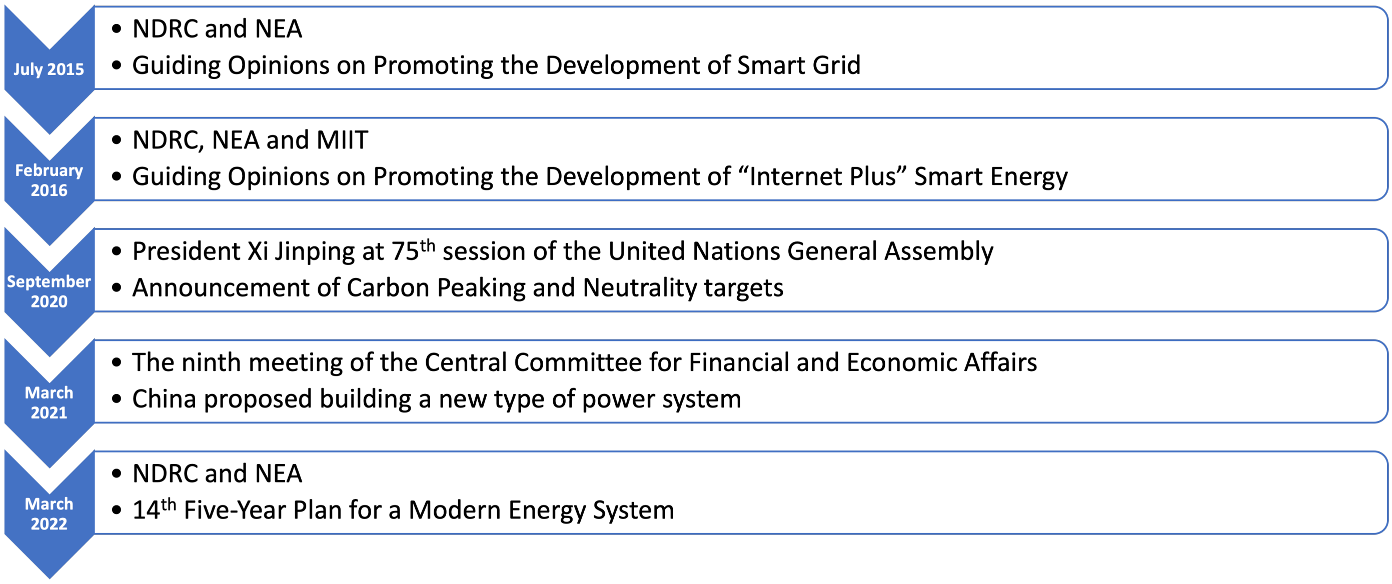

Figure 1: Relevant smart grid policy documents and announcements by the Chinese government

In the *Guiding Opinions on Promoting the Development of Smart Grid* from 2015 smart grids are defined as a new generation of power system. Smart grids are still based on the traditional power system but combined with new energy sources, new materials, new equipment, and new technologies (e.g. advanced sensing, information and control technology, and storage). Smart grid development lays an important basis for energy interconnection and the document proposes 10 tasks for smart grid development including the following major ones:

- Improving grid digitalization level;
- Enhancing VRE integration capacity;
- Providing guidance on user participation;
- Promoting energy saving and emission reduction.

The joint *Guiding Opinions on Promoting the Development of "Internet Plus" Smart Energy* from 2016 points out that "Internet Plus" Smart Energy represents a new form of energy industry development. The main characteristics and components are smart equipment, multi-energy collaboration, information symmetry, decentralized supply and demand, and non-discriminatory, easy, and open transactions. Such a new energy industry would featuring deep integration of IoT with energy generation, transmission, storage, consumption, and the energy market.

In September 2020, General Secretary Xi Jinping announced in the 75th session of the United Nations General Assembly that China strives to achieve *carbon peaking and carbon neutrality targets*. Thus, transitioning to green and low-carbon energy and electricity got more relevant.

At the ninth meeting of the *Central Committee for Financial and Economic Affairs* in March 2021, China proposed building a new type of power system. The development of smart grids constitutes an essential part of this new power system and should support the development of new energy sources to achieve China's green low-carbon transformation.

In March 2022, the *14th Five-Year Plan for a Modern Energy System* has been published and outlines the main technological development direction of smart grids in China. It proposes the promotion of demonstration applications for an automated dispatching system for renewable generation as well as the intelligent upgrading and transformation of distribution grids. For the development of DG, the construction of intelligent and active distribution grids alongside improved power-carrying capacity and flexibility is necessary to accommodate VRE, diversified loads, and the development and utilization of new energies locally. To achieve compatibility and complementarity with the large public grid, intelligent microgrids that mainly consume VRE need to be developed. The plan also calls for increased efforts in R&D and demonstration applications of flexible DC distribution grids, Vehicle-to-Grid, virtual power plants, microgrids, and other technologies.

1.2 Smart grid progress and achievements

Achievements of China's smart grid development since 2014 are mainly reflected in increased penetration levels of renewable energy, the initial scale-up of DG, and wider applications of digital technology.

1.2.1 Leapfrog development of renewable energy

China is the world's largest energy producer and consumer. Due to China's domestic energy resource endowment, that is "rich in coal, but lacks oil and gas", the country's carbon emissions per unit of energy consumption are higher than the world average. In 2020, China's CO2 emissions from energy consumption accounted for 30% of global CO2 emissions. Emissions from the energy sector took up over 85% of China's total emissions with emissions from electricity production accounting for over 40% of these. [6] Strong development of renewable energy and the promotion of a low-carbon transformation of the power industry are key to achieving the country's dual carbon goals (emission peak before 2030 and carbon neutrality by 2060).

Since 2014, China's renewable energy power generation has witnessed strong growth, with installed capacity, utilization level, technical equipment, and industrial competitiveness all reaching new milestones. At the end of 2021, the installed capacity of renewable energy exceeded 1000 GW, compared to only around 400 GW at the end of 2013.

Table 1 depicts key metrics of China's renewable energy development. Expansion of wind and solar have been impressive and China ranks first worldwide in installed wind and solar power capacity.

Table 1: Key development metrics of renewable energy in China since 2013

	Wind	Solar	All renewables
Installed capacity (2013)	82 GW	16 GW	400 GW
Installed capacity (2021)	329 GW	308 GW	1000 GW
Annual growth rate (2014-2021)	19%	44%	12%
Scale factor since 2013	4	19	2.5

The proportion of installed wind and solar capacity is now taking up nearly 27% of the national total installed capacity, as shown in Figure 2.

In 2021, China's renewable energy power generation reached 2480 TWh, accounting for 29.8% of the country's total electricity consumption[1]. Total renewable energy consumption exceeded 750 million tons of coal equivalent (tce), accounting for nearly 15% of China's total energy consumption in 2021. [7]

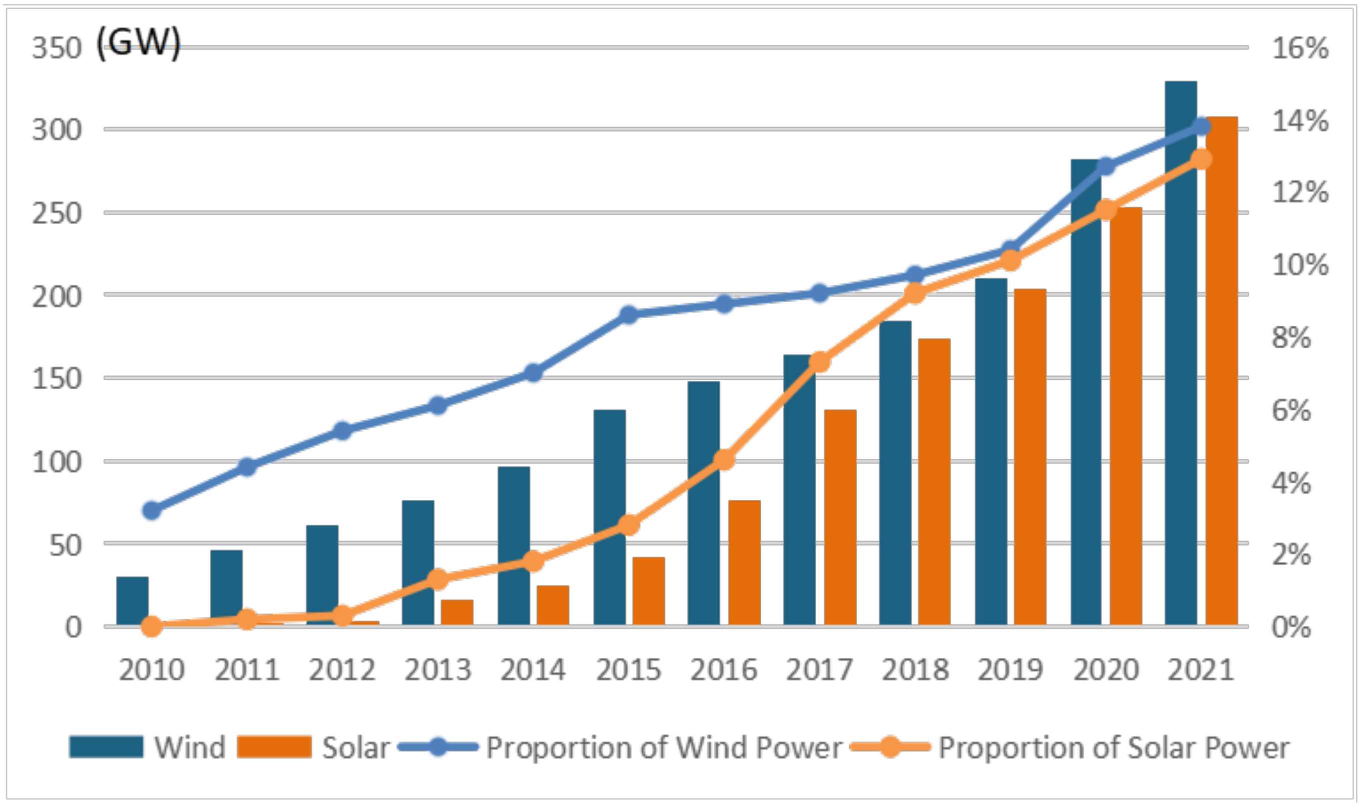

Figure 2: Development of installed wind and solar capacity in China (Source: Nation Bureau of Statistics)

[1] National Energy Administration, Transcript of the NEA 2022 First Quarter Online Press Conference, January 28, 2022, https://mp.weixin.qq.com/s/MLT03wDZEE-GJrFF699xDkQ

China's wind and solar generation in 2021 reached 978.5 TWh, accounting for 11.7% of total electricity consumption. Although the share of modern renewables such as wind and solar in China is still lower than in some European countries, several provinces, including Qinghai, Hebei, Ningxia, and Gansu, have seen renewable energy rise to the top of power generation. In Qinghai, renewable generation accounts for a share of over 60%. The same situation can be observed in other regions of China as well. [8]

China has achieved great improvements in renewable energy integration, too. Compared with a wind and solar curtailment rate of 15% in 2015, this number decreased to less than 3% in 2021 even though the total installed capacity of renewables increased by almost a factor of three during the same period. Expanding grid infrastructure and operational processes for integrating wind and solar during this time allowed for this success.

Advancements in technology and industrial production processes resulted in a significant drop of generation costs from wind and PV. At the beginning of this century, China mainly used subsidies combined with guaranteed grid access to promote the development of wind power and PV. These policies played an important role in the expansion of the new energy industry and allowed China to take a key position in today's global renewable energy industry value chain. China now boasts a complete wind power industry chain, with 7 comprehensive wind power equipment manufacturers ranked among the top 10 in the world. China has taken a leading position worldwide in the PV industry, with polysilicon, silicon wafers, cells and modules accounting for 76%, 96%, 83% and 76% of global production, respectively.

The development of this industrial value chain contributed to rapid cost reductions. Currently, the levelized cost of electricity (LCOE) of onshore wind power in China is 0.21-0.34 RMB/kWh, representing a decrease of about 50% compared with the 2014 level. The LCOE of PV currently stand at 0.17-0.30 RMB/kWh, representing a reduction of over 80%. Due to the declining costs, China has entered the era of generation cost parity for VRE in 2019.

1.2.2 Rapid DG development and the trend of grid decentralization

(1) Power system decentralization

Even though the "Large Strong Grid" at the transmission side is viewed as a distinctive feature of China's power system, the decentralization of generation due to distributed renewable energy development is inevitable. As renewable energy has a decentral character in terms of resource distribution, its rapid development is bound to boost DG. This development includes distributed PV, distributed energy storage and EVs with energy storage functions.

Distributed PV as an important component of DG is generally closer to electricity consumers. Electricity from distributed PV entails no fees associated with transmission and distribution tariffs or surcharges if used locally. This significantly reduces user costs for electricity. With declining PV costs, distributed PV in China has grown rapidly in recent years. In 2021, 29.3 GW of new distributed PV was added. This accounted for 53.4% of China's total new PV installations and more than half of added capacity the first time. With 21.6 GW of new PV capacity, household installations made up the majority of distributed PV and was up 113.3% year-on-year. This development reflects the deep integration of distributed PV and consumers and highlights the trend towards more decentralization. [9]

The development of demand-side distributed energy storage is accelerating as well. Energy storage is an effective means to cope with fluctuating renewable energy generation, in addition to being a tool to profit from arbitrage between times of peak and low consumption. Cutting the maximum power demand of users helps them to reduce capacity charges paid to grid companies, while enhancing power supply reliability on the user side is an additional benefit. The formation of energy storage systems with distributed PV can thus be popularized among consumers in cities where large electricity price differences exist between times of peak and low consumption.

Apart from PV energy storage systems, EVs are an important part of DG due to their energy storage and flexibility potential. The global EV industry has witnessed significant progress in recent years, with China playing a leading role in its development. In 2021, China's EV sales reached 3.3 million, accounting for 52% of global sales, and China's EV fleet exceeded 7.8 million. By the end of 2021, China had 2.62 million charging facilities and 1,300 battery-swapping stations installed. [10] Charging and swapping facilities have a distinctive peak load characteristic, which, if such facilities are operated in a disorderly manner, may result in an increase in peak load of over 10 GW. It is expected that by 2030, there will be more than 100 million EVs on Chinese streets, with potentially greater impacts on grid operation. Exploring possible ways to enable charging modes of EVs conducive to grid operation and bringing demand response into operation has become a widely discussed topic in the industry.

The substitution of end use energy demand with electricity through rapidly growing loads of heat pumps and air conditioning equipment (with pronounced seasonal peak characteristics) can lead to a significant increase of the maximum load of the power grid. Challenges to power system adequacy and regulation capacity can thus be expected. Using technical means to aggregate and control such loads and form distributed actors participating in grid regulation has become an important development direction.

(2) Active demand-side participation in grid regulation

Demand response is already taking shape in smart grids development in China. Many DG units connected to the distribution network along with electrification of end user demand will lead to higher local power generation and consumption. These developments result in greater load uncertainty and higher requirements for users to actively participate in grid regulation. Applications of demand-side digital technology for aggregating controllable resources can enable participation in grid regulation through virtual power plants (VPP). [11]

A VPP is a collection of DG, energy storage and controllable loads integrated by IoT technology to realize unified response to grid operation. Small-scale regulation units will be more prominent in the future. To reduce the pressure on dispatching units and trading centers, it is necessary that VPPs can be regulated. Based on individual DG regulation agreements, the degree of user participation within VPPs and the internal regulation efficiency can be improved. Given the superb regulation performance of battery storage, these units will assume a pivotal role. By guiding those units to perform a regulating and balancing functions, VPPs can effectively enhance smart grid flexibility, renewable energy integration capacity, and the level of grid security.

(3) Development of smart microgrids

Smart microgrids refer to small power generation and distribution systems consisting of DG, consumers, and local energy management systems with integrated functions of power generation, distribution, and consumption. The internal power generation units, loads and distribution networks can form a relatively independent microgrid which is connected to the public grid through an interface. Smart microgrids utilize the internal DG and storage capacity as much as possible and aim to achieve a balance of electricity generation and consumption for internal users while being able to interact with the public grid for power exchange. Off-grid microgrids that are not connected to the public grid due to restrictions also exist. In the case of exchanging electricity between a microgrid and the public grid, the former accepts the dispatching and management of the public grid dispatching unit. For consumers, microgrids can provide services to suit their individual needs. Microgrids effectively introduce competition on the power supply side and can improve the quality of power supply services while reducing the cost of electricity consumption.

In July 2015, NEA issued the *Guiding Opinions on Promoting the Construction of New Energy Microgrid Demonstration Projects*, followed by additional relevant documents supporting the promotion of microgrid pilot demonstration projects. To date, there are 28 microgrid demonstration projects in China, including 24 grid-connected and 4 off-grid projects.

In the field of smart microgrids, DC power distribution technology is anticipated to witness rapid development. In microgrids where DG sources are ubiquitous, DC distribution technology allows VRE generation, energy storage and loads only need to be converted once. In that way the installation of many converters in the whole electricity system can be avoided, reducing both costs and losses as well as improving microgrid reliability. DC power distribution technology has obvious technical advantages in areas where distributed PV and battery energy storage are present.

1.2.3 Extensive application of digital technology in smart grids

Application of digital technology in the power system is the main technical means to create smart grids. With the rapid development of IoT and digitalization, the characteristics of decentralization and the multi-purpose applications of smart grids have the potential to increase automation and intelligence of the power grid. With the large-scale development of VRE, the dispatching and operating modes of the grid have undergone significant changes. Extensive demand-side participation will lead to a massive increase in the number of regulating entities. The concept and application of Internet of Things in power system (IOTIPS) aims to enhance the grid's capabilities in sensing, communication, dispatching, control, and response. The application of digital and information technology in smart grids is growing fast and is mainly reflected in the following aspects. [12]

Digital technology enables the intelligent integration of traditional energy equipment.
Traditional power equipment focuses on the performance of load capacity, voltage tolerance, and reliability. Traditional modes of operation pay little attention to automatic monitoring, the transmission and reception of various electrotechnical parameters or environmental variables. Advanced computing methods and associated decision-making is also not part of traditional energy equipment operations. The integration of primary and secondary equipment into equipment design and production will be the norm in the future. The information infrastructure made up of 5G, Industry 4.0, data centers, and artificial intelligence will be deeply integrated with the energy infrastructure. This integration can support the transformation and upgrading of traditional energy equipment and promote more intelligent ways of energy production and consumption.

Digital technologies can help to solve the "dual high" problems associated with the new power system.
The so-called "dual high" problems of the Chinese power system are:

- A high proportion VRE challenges inadequate grid flexibility;
- The high proportion of power electronic equipment added to the traditional AC synchronous power grid poses a serious challenge to grid stability.

Fluctuating feed-in of vast quantities of electricity from renewable sources, coupled with the characteristics of power electronic equipment, add to the complexity of grid planning and operation. However, digital technology is considered a key tool to solve these challenges. At the planning level, the application of big data technology can make multi-dimensional complexities solvable. When combined with modeling, big data can help make the planning process of new energy development more efficient and fact-based. At the operation side, digital technology can improve the "observable, measurable, and controllable" levels of renewable power plants. In that way problems of grid balancing in the new power system can be addressed, while improving the capacity for integrating VRE. Based on high-performance calculations and more accurate control systems, digital technology can improve the ability of intelligent regulation and control. Optimal scheduling and steering of a large number of distributed entities and controllable loads allow to improve the safety and stability of the power grid.

Data empowerment achieves quality and efficiency improvements of power system enterprise operation.
Through online fault diagnosis and inspection technologies, the knowledge about the power system's operational status can be improved. At the same time, the level of digitalization and automation of grid operation and maintenance departments can be enhanced. Savings in human and material resources can be realized. The digital basis of smart grid leads to increased potential for sharing data resources important for grid operation. Reduced costs for both government supervision and enterprise management along with a complete reshaping of the internal management process of power system enterprises will enable higher production efficiency and service quality.

Digitalization will help promote the development of the energy market.
Digital technology allows for efficient market clearing by assigning electricity its "true" value depending on generation, demand, and the grid situation. The creation of an open power trading platform centered on

data sharing and interconnectivity will help reduce market information asymmetry. This provides an effective guard against abuse of market power. A maximum degree of openness for market information will help enhance trading strategies and the participation of small and medium-sized actors and grid users. The widespread application of digital technology in the power market will also improve the attractiveness of DG and demand response participants at the retail end. Consequently, demand-side flexibility is incentivized further by facilitating greater innovation in business models.

1.2.4 Smart grid case study

China started the first batch of "Internet+" smart energy demonstration projects in 2017. A typical example currently in operation is the Jiaxing Urban Energy Interconnection Project (Urban Smart Grid).

The project is located in Jianshan New District, Haining, Jiaxing and covers an area of 42 km^2. Supported by subsidies from the National Government, Zhejiang Province, and Jiaxing City, the Jianshan New District has witnessed rapid development in distributed PV. Combined with a growing offshore wind power capacity, the total installed renewable capacity of Jianshan New District reached 275 MW in 2020. Distributed PV from rooftops of the industrial park makes up 175 MW of the total capacity. In contrast, the Jianshan New District's average daily load only reaches 115 MW. The development of VRE brings challenges for the local power grid. It must cope with insufficient integration capacity. The new role of the distribution grid turns it into an active grid with new power flow dynamics causing operational safety problems.

Based on a "smart energy + distributed + new energy" model, Jiaxing aims to become a smart city based on smart grids, that fully realizes the integration of VRE, low-carbon buildings, smart energy, and green transportation. The city wants to provide clean energy, green transportation, increased building energy efficiency and a greater interaction of supply and demand to effectively achieve the local integration of high-density renewable capacity and generation. Ultimately, these developments should allow for a safe, efficient, and reliable sourcing of VRE to ensure the economic development of the city. A successful energy consumption model featuring digitalization, openness, sharing, diversity, and interaction should be created. Figure 3 shows the urban smart grid architecture of Jiaxing City. [2]

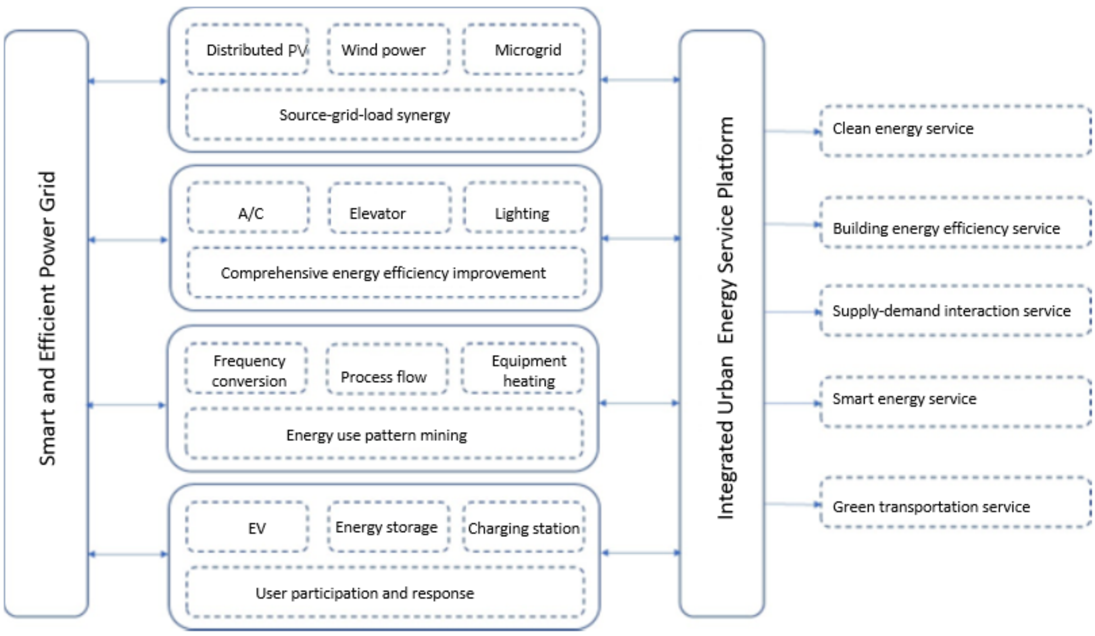

Figure 3: Urban smart grid architecture of Jiaxing City

1.3 Institutional reforms supporting smart grids

Advancing the power market reform is crucial to increase innovation in the power system. The effects of promoting the power market reform on smart grid development are reflected in a tightened supervision over power grid operators. The aim is to reduce the utility-character and essentially electricity sales operations of transmission and distribution companies. Furthermore, market conditions need to be created for DG, microgrids, and incremental distribution grids to participate fairly in market competition. Another focus is the strengthening of price regulation in promoting renewable energy development, stimulating DG development, and increasing active demand-side participation in grid regulation. This approach supports the formation of diversified and intelligent governance structures and business models.

1.3.1 Results of the power market reform

Since the end of the last century, the Chinese government has been committed to reform the power sector. The milestones were the 2002 and 2015 reforms.

The Notice on Issuing the Power Sector Reform Program (Guo Fa [2002] No. 5), promulgated by the State Council in 2002, signified the start of the Chinese power sector reform. The main targets were to "separate plants from grids, bid for grid access, break monopolies and introduce competition". SGCC was split into two major grid companies and five major power generation groups. In addition, four major auxiliary companies (engineering and construction of power plants) were established to separate power plants from grids and to realize the separation of operation and construction in the power sector. Subsequently, some governing bodies, including the State Electricity Regulatory Commission (SERC) and the National Energy Administration (NEA), were set up. The reorganization of SERC saw parts of its functions merged into the NEA in 2013. Meanwhile, China rolled out a slew of tariff reform measures, such as feed-in, transmission and distribution, and sales tariffs.

In 2015 the State Council announced the *Several Opinions on Further Deepening the Power Sector Reform (Zhongfa [2015] No. 9)*. This policy marked the kick-off of a new round of power sector reform. The main reform direction can be summarized as *"Controlling the middle and releasing the two ends". Controlling the middle* refers to strengthening supervision over power grid operators and approving transmission and distribution tariffs separately. *Releasing the two ends* refers to the introduction of competitive mechanisms on the power generation side and the sales side. Specific reform measures included:

- Fully competitive mechanisms to determine electricity tariffs on the power generation side;
- Implementation of an incremental distribution network and sales reform;
- Encouraging users to participate in grid regulation through demand response and other mechanisms.

(1) Regulation of transmission and distribution tariffs and transformation of grid functions

To break the natural monopoly of grid companies, a comprehensive transmission and distribution tariff system must be implemented. This serves to achieve fair conditions for the operation of transmission and distribution grids with grid companies assuming decisive roles in carrying out market-oriented transactions. Especially important is a market environment accommodating the needs for smart grid development: DG, microgrids, incremental distribution grids, and other entities have to be able to participate in a fair market. Prior to 2015 and even though "plant-grid separation" was officially realized, the grid side still operated in a vertically integrated way. Grid enterprises made unified electricity purchases and sales.

For grid enterprises to give up the utility aspects of electricity sales, the new round of reforms launched in 2015 took on the task of setting up an independent transmission and distribution tariff system built on clear rules, reasonable levels, powerful regulation, and scientific transparency. The separation and independence of grid enterprises from electricity purchases and sales allows for fair, standardized, and transparent market-based transactions. In that way the price reductions from the generation side can be transferred to the user side. An independent transmission and distribution tariff system ensures a healthy development of grid enterprises and a more reasonable control of grid investment.

According to the transmission and distribution tariff approval method published by the authorities in charge, grid enterprises now mainly operate on the basis of "permitted costs + permitted revenues". The approval method of the transmission and distribution tariff system functions as follows: The permitted revenue from the transmission and distribution business needs to be approved first. Then, the transmission and distribution tariffs are approved based on this permitted revenue. Approval of the transmission and distribution tariffs of provincial power grids happens prior to the start of each regulatory cycle of three years duration.

By enforcing approval and effective regulation on transmission and distribution tariffs, and through mandating lower tariffs by administrative measures, the Chinese government has been successful in achieving a continuous decline in China's transmission and distribution tariffs. Currently grid tariffs are at the lower end when compared globally (see Figure 4 for the decline). In 2020, China's average transmission and distribution tariff was 0.186 RMB/kWh or 0.027 USD/kWh. The only country with a lower grid fee among major economies is South Korea. The transformation of grid functions and the approval of transmission and distribution tariffs at all voltage levels provide a level playing field for all types of players to compete in the market.

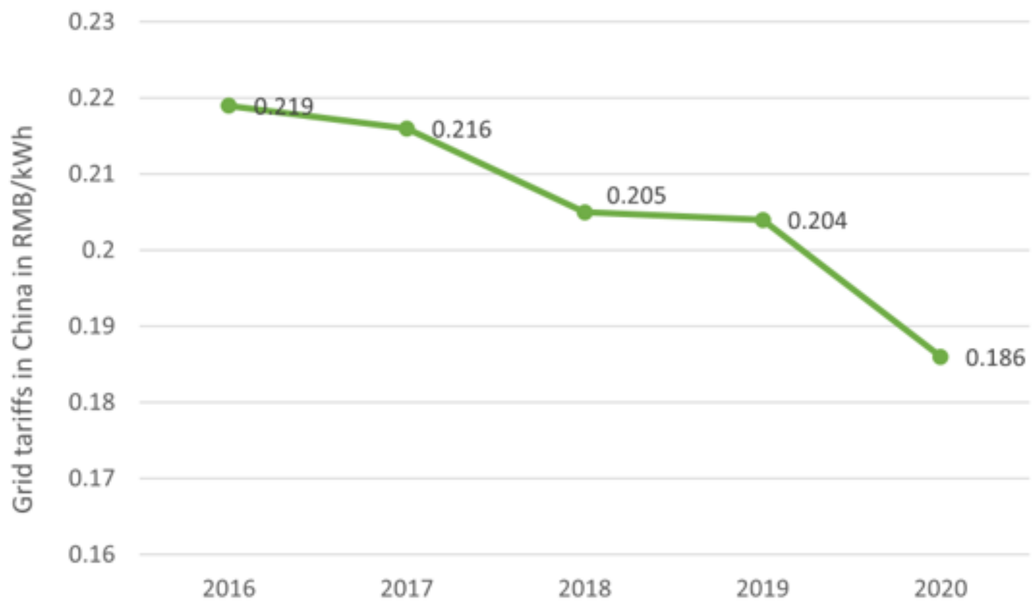

Figure 4: Trend of transmission and distribution tariffs in China during the 13th Five-Year Plan period (unit: RMB/kWh)

Source: State Grid Energy Research Institute, Domestic and International Energy and Power Price Analysis Report 2021

(2) Introduction of competition on the generation and consumption side

Introducing a competitive mechanism on the generation and consumption side to discover the real price of electricity by free transactions is an important component of the power market reform. Since 2015, China has gradually put in place medium- and long-term market mechanisms. Later, they were accompanied by spot market mechanisms. These markets help to quantify electricity demand and thus inform price discovery.

Increased share of direct transactions

China continues to liberalize power generation and consumption to effectively activate market innovation of involved actors and reduce electricity costs. To date, a market environment with diverse actors including power generation and sales enterprises as well as consumers, has formed. The new actors gave rise to a strong market atmosphere and increased activities on both the purchase and sales side. By the end of 2020, the total number of registered market entities exceeded 256,000, including 29,000 power generation enterprises, over 4,600 power sales companies, and over 224,000 electricity consumers. In 2021, power trading centers completed a total of 3779 TWh of market transactions, an increase of 19.3% year-on-year. Those transactions accounted for 45.5% of China's total electricity consumption. Over 90% of the transactions still take place intra-provincially and less than 10% of the transaction are concluded across province borders.

Affected by the power shortage during 2021, NDRC issued the *Notice on Further Deepening the Market Reform of Coal-fired Power Generation On-grid Tariffs (NDRC Price [2021] No. 1439)* in October 2021. It requires that in principle all coal-fired electricity generation must be sold at the market. Also, all commercial and industrial consumers have to take part in the electricity market and the range of medium and long-term price fluctuations was broadened. This policy document is of great significance for promoting the expansion of market-oriented transactions because it establishes an electricity price mechanism that can both "rise and fall". Due to the policy requirements the amount of electricity directly traded in the market is expected to increase significantly, possibly accounting for over 2/3 of the country's total electricity consumption in 2022.

Acceleration of the spot market reform

While building a medium and long-term market, China has gradually put a spot market in place to allow for short-term price discovery. In 2017, China launched the first batch of spot market pilots. Provincial-level pilots projects from Guangdong, Western Inner Mongolia, Zhejiang, Shanxi, Shandong, Fujian, Sichuan, and Gansu were included in the first batch. These pilot projects have helped China to accumulate experience in promoting competition on the power generation side. Also, generation from VRE has been partially integrated into the spot market, effectively bringing additional price signals based on renewable availability into play. In May 2021, China expanded the scope of power spot pilots by selecting six provinces and cities, including Shanghai, Jiangsu, Anhui, Liaoning, Henan, and Hubei, as the second batch of power spot pilots. [13]

In November 2021, China kicked off the inter-provincial spot market. Following the proposal of SGCC and China Southern Power Grid concerning *Inter-provincial Electric Power Spot Trading Rules*, spot transaction settlement between provinces is scheduled to start with a trial operation in 2022. Inter-provincial spot trading is an important improvement to the existing system based on experiences in the provincial spot market pilots. Merging the intra- and inter-provincial spot markets is a key step for enabling electricity price signals to have a greater effect across the country.

To accelerate the spot market reform NDRC and NEA jointly issued the *Notice on Accelerating the Construction of Electricity Spot Market* in 2022. The document proposes a step-by-step approach for the introduction of a spot market until all provinces are covered in the end. Areas with favourable conditions are required to launch uninterrupted spot trading pilots (during the pilots the spot markets were sometimes interrupted to adjust market mechanisms) and to form long-term and stable spot markets as soon as possible. The first batch of pilot areas should start the long-term spot market trial operation in 2022. The second batch of pilot areas should in principle start the spot market trial operation before the end of June 2022. Other areas will have to submit a market implementation plan by the first quarter of 2022 with an anticipated start of the trial operation in

2023. The focus on electricity supply adequacy in China currently supersedes the spot market developments.

(3) Advancing the reform on incremental distribution networks and the sales side

To introduce competition on the distribution network side, NDRC and NEA jointly issued the *Administrative Measures for Orderly Liberalization of Distribution Network Business* and *Administrative Measures for the Admission and Withdrawal of Electricity Sales Companies* in 2016. The incremental distribution network reform refers to the construction of new distribution networks by private, non-state-owned enterprises or joint ventures formed between them and existing state-owned grid enterprises. Operators of incremental distribution networks mainly charge distribution service fees according to the corresponding transmission and distribution tariff standards, broker power sales, and perform user-side operation and maintenance.

NDRC and NEA have approved five batches of a total of 483 incremental distribution network reform pilot projects by the end of 2020. These projects aim to stimulate private capital investments into incremental distribution networks and to facilitate the construction of distribution networks. The participation of private capital is supposed to help promote the efficiency of distribution network operation while improving the quality of power supply service. However, among the many pilot projects only few have been successful. This is mainly due to the following reasons.

Incremental distribution networks are usually in competition with the grid expansion by the existing grid companies.

Owing to the need for interconnection with higher-level grids and the dependence of incremental distribution networks on power supply from the transmission grid, incremental distribution networks projects have been constrained by higher-level grid governance, management, and capacity.

Incremental distribution networks are generally built in newly planned industrial parks.

To attract enterprises to move in, building a good distribution network system in advance is a prerequisite. However, this leads to significant investment needs in the distribution network prior to having paying consumers. In many cases, the construction period of new industrial parks is very long. If the electricity consumption of enterprises eventually moving into the industrial parks is considerably lower than expected, the incremental distribution network may face insufficient revenues from the operation and incur serious losses.

(4) Demand response participation in grid regulation

The increasing share of renewable energy demands higher requirements on the flexibility and the regulation ability of the power system. It necessitates a transition from the traditional "*generation-follows-load*" operation mode to a "*generation-interacts-with-load*" mode. Load participation in grid regulation, i.e. demand response, has the characteristics of low investments and quick results compared with the construction of flexible power generation sources. Hence establishing a market mechanism for promoting load participation from users in grid regulation has become an important means to enhance grid flexibility.

The Chinese government attaches great importance to the development of demand response. In 2021, the State Council issued the *Notice on Action Plan for Carbon Dioxide Peaking Before 2030 (Guo Fa [2021] No. 23)*, requiring that "by 2030, provincial-level power grids will basically have the ability to respond to more than 5% of peak loads." The *14th Five-Year Plan for Modern Energy System Development* emphasizing the creation of power system flexibility and puts forward a clear development target. Among others, a demand-side response capacity of 3% to 5% of the maximum electricity consumption should be reached by 2025.

It is important to facilitate users to mobilize flexible loads, promote user-side energy storage, EVs, and other resources to actively respond to grid operation. Appropriate market policies must be designed accordingly. An example is the market-based demand response compensation mechanism in Guangdong Province. Consumers receive a maximum incentive of 3.5 RMB/kWh or about 15% of the electricity price for participating in demand response to enhance user motivation. Load aggregators with resource aggregation and management capabilities are introduced to broaden the scope of demand response implementation via market competition. In that way a response capacity of 5% of the annual maximum electricity load should be gradually formed and play a role in utilizing demand-side resources to provide balancing between times of peak and low demand. The adaption to generation characteristics of VRE should be promoted while balancing electricity supply and demand.

1.3.2 Accelerating the reform through a unified electricity market

To accelerate the development of a new power system with greater VRE integration capacity suitable for China's national conditions, NDRC and NEA jointly issued the *Guiding Opinions on Accelerating the Construction of a National Unified Electricity Market System (NDRC [2022] No. 118)* on January 28, 2022. The document sets out systematic requirements for the upcoming deepening phase of the power market reform and provides an overall outline for the future reform of China's power market.

By 2025, the national unified electricity market system will be initially in place. The national market and markets at provincial /city/regional levels should operate in a coordinated manner. The allocation of cross-provincial/regional resources along with a scaled-up trading of green electricity through market-based pricing mechanisms should also facilitate the development of wind, solar and energy storage. By 2030, the goal is to have a national unified electricity market in operation that conforms to the requirements of the new power system. Specifically, the participation of VRE in market transaction should be facilitated, while a level-playing field for market players allows for an optimized resource allocation across the entire country. The unified electricity market framework has four main features.

A multi-level electricity market system.

This involves efforts to steadily promote the construction of provincial/regional electricity markets. The role of provincial/regional markets within the national market is to improve intra-provincial and regional allocation efficiency of power resources and to guarantee the local power balance. This includes the conclusion of cross-provincial and cross-regional medium- and long-term transactions as well as frequency regulation, black start, and other auxiliary services. The coordinated operation and coupling of the electricity markets at several levels should be strengthened.

Improved linkages between different power market products.

The medium- and long-term markets should play a more pronounced role in balancing long-term supply and demand and stabilizing market expectations. The development of increased price spreads between peak and base load through trading should guide users to cut peak demand and shift consumption to times of low demand. The stable operation of the electricity spot market and increased linkages between spot, medium- and long-term transactions must be implemented. The continuous improvement of the auxiliary service market should better reflect the market value of flexible resources.

Lowered market entry threshold.

Market participation of preferential power generation entities (e.g. gas, CHP, VRE, nuclear power) should be promoted and full market participation of commercial and industrial consumers of different sectors be enabled. New market players, such as flexible loads, energy storage, DG, and EVs should participate in market transactions to fully stimulate and release flexibility on the demand side.

Implementation of a capacity cost recovery mechanism.

A cost recovery mechanism for power generation capacity in accordance with local conditions should be implemented. This mechanism includes the construction of emergency backup and peaking power capacity. A combination of methods, such as capacity compensation mechanisms, capacity markets, and scarcity tariffs, can be used to ensure fixed-cost recovery and long-term power supply security. The mechanisms should also incentivize investment in and construction of pumped hydro and battery storage, VPPs and other flexibility sources. [14]

2. Challenges of smart grid development in China

Despite the progress in China's smart grid development and market reforms, many technological and institutional challenges remain. The development of VRE complicates balancing of the grid. The establishment of market mechanisms supporting the development of renewable energy, DG, and broader demand-side participation still faces constraints. The application and wide-spread use of digital technologies is relatively uncommon. Thus, the level of digital business operations is only at an early stage.

2.1 Impact of high shares of variable renewables

Electricity production is the largest carbon emitting sector in China. With growing electrification, China's electricity demand shows no sign of slowing down. To achieve the Chinese government's commitment to *"striving to peak carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060"*, the power industry's huge task is to accelerate its low-carbon transformation. [15]

Despite the progress in the field of renewable energy, China still relies heavily on fossil fuels. Coal power accounts for over 60% of total electricity generation. The proportion of renewable energy generation in China stands at 30%, largely dominated by hydropower, with wind and solar only accounting for 11.7% in 2021. Due to limitations of hydropower and biomass resources, the future development of renewable energy in China is anticipated to rely mainly on the growth of wind and solar.

To accelerate the green transformation of the energy and electricity sector, China aims at a total renewable consumption of around 1 billion tce by 2025. This represents an increase of 1/3 compared to 2021. Renewable energy should cover over 50% of primary energy consumption growth and in 2030 total installed wind and solar capacity should reach 1,200 GW or more. By 2060, the targeted share of non-fossil energy consumption is at least 80%. However, the current power system is not yet well adapted to the development of a high proportion of fluctuating renewable generation. This presents a challenge for achieving the expansion goals.

One of the pressing issues relates to the adequacy of power system flexibility. The growing generation from VRE is bound to exacerbate existing problems of insufficient power system regulation capacity and the balance between power generation and consumption. If peak regulation pressure on the power system increases, security and stability problems might become more serious. It would not be unlikely that higher curtailment of wind and solar re-emerges.

If conventional power generation does not grow accordingly, or if there are no large-scale energy storage investments, a high proportion of VRE generation could lead to power supply inadequacy. Repeated intermittent power outages could be a result.

In addition, the cost of power supply may rise. International experience shows that VRE require increased investment in transmission and distribution networks. The cost of grid regulation can also rise. A rising share of VRE has the potential to increase the full-cycle cost of energy supply. To achieve the low-carbon electricity target, many coal power plants in China need to be retired early. This may result in a large amount of stranded assets and indirectly increase electricity cost for society.

The above problems hinder the expansion of VRE and DG and could slow down the development of smart grids and the transition towards green, low-carbon, and decentralized sources.

2.2 Market reform challenges

China's electricity market still operates with several imperfections.

Incomplete power market.
There is no flexible and effective spot market mechanism that can reflect short-term supply and demand. Currently, the electricity market is still largely dominated by medium- and long-term transactions. Even

though two batches of spot market pilots have so far been launched, the number of provinces that realized uninterrupted settlement operation is still low. In addition, small-scale users only play a price-taker's role in the spot market, while the price is decided between generators and large-scale users. Thus, spot market price signals are not effectively influenced by the small-scale user side. Market-based auxiliary service mechanisms are uncommon. This reduces the effective activation and utilization of flexibility resources on the power generation and load sides.

No mechanism exists for introducing effective competition on the sales side.
Compared with the competition introduced at the generation side, the electricity sales side remains relatively undiversified. This is reflected by the low market participation of consumers and limited direct transactions between generators and users. Only few choices for buying electricity are available for users.

Inter-provincial barriers remain.
China has long been implementing a province-based power balancing mechanism. Given the large gaps in power market reform and power system structure between provinces, the inter-provincial electricity exchange is limited. Therefore, improvements for both power market mechanisms and technology are important to adapt to the needs for efficient large-scale and inter-provincial resource allocation.

A green electricity trading system reflecting the environmental value of VRE is not yet in place. China's wind and solar capacity is expanding rapidly, but a market-based renewable consumption mechanism has not yet been established. Due to the fluctuating character of wind and solar generation, difficulties exist in predicting and regulating the output. Without accurate forecasting and digitalized trading tools, VRE is disadvantaged in participating in power market trading. Hence, it is imperative to address this challenge by, for example, creating a trading system that highlights the green value of VRE. Such a mechanism can be a key factor to promote China's green and low-carbon energy transformation.

2.3 Inadequate digital technology

The development of digital technology and smart grid needs innovation and breakthroughs. However, digital technology has not yet been widely utilized to produce a systemic effect in the Chinese power sector. Neither the amount of intelligent equipment applied in the power sector, nor the performance is sufficient. Not many types of new intelligent sensors, calculators, and microprocessors are available for use. In addition, both the number of data collection points and the data collection frequency remain inadequate to gain relevant systems insights. The different data collection devices and information systems are often incompatible, thus resulting in information silos and reduced value of shared information. Finally, there are bottlenecks in data acquisition and information security. Data barriers are prevalent across different enterprises, but also across business divisions within enterprises. Meeting the requirements of user information confidentiality and security is a challenge for existing technology. Inter-user data channels cannot yet fully tap into the value of the recorded data.

3. Outlook for smart grid development in China

This chapter proposes direction and policy recommendations for China's smart grid development based on national conditions. China's smart grid development should focus on improved flexibility of power supply, grid, and loads to enhance the ability for VRE integration. The promotion and integration of renewable energy should be achieved via price signals from the coupled electricity and carbon market mechanisms. The application of digital technology will be increasingly relevant for the development of VRE and DG as well as for managing the widespread emergence of market transactions. Digitalization will play a key role for enabling the adoption of new business models.

3.1 Direction of smart grid development

China's power system is preparing for a future of increased diversity, where fragmentation, peak demand flattening, and decentralization become more relevant characteristics. Rapid development of DG and the transitions in both centralized and decentralized energy production also necessitate a change in the power grid structure: from an operating mode of centralized generation bases and large networks to a mode of parallel operation with (smart) microgrids. New energy storage technologies and hydrogen are expected on a large scale and will drive fundamental changes in the energy system. The intelligent upgrading of the energy industry will be accelerated by use of IoT, big data, artificial intelligence, and other modern information technology. The integration of digitalization with the grid can facilitate new energy services and a proliferation of intelligent energy use models in industrial parks, urban communities, public buildings, and other places. Low-carbon generation, digitalization, interaction, and fairness will become the themes of smart grid development.

(1) Renewable energy development requires the support of storage technologies

China's fossil fuel-based power supply structure will be transformed into a renewable structure. This transformation causes an increased need for energy storage in the power system. The application of energy storage technology enables real-time balance of generation and consumption. Storage can reduce constraints of the conventional power system by adding flexibility to the old rigid system and mechanisms. Hence, energy storage is a key technology for bringing the energy transformation to a success.

In terms of electricity storage, pumped-hydro storage is still considered the most promising technology for large-scale development. Currently, a total of 36 GW of pumped-hydro storage capacity is in operation in China. To meet the challenge of VRE integration, China has embarked on the large-scale construction of new pumped-hydro storage plants in 2021. According to the *Medium and Long-Term Development Plan for Pumped Storage (2021-2035)*, the total commissioned capacity of pumped-hydro storage in 2025 should reach more than 62 GW. By 2030, a capacity of 120 GW is envisioned while the long-term goal of 421 GW is very ambitious. In addition to pumped-hydro, electrochemical, mainly battery energy storage has witnessed great progress. The cumulative installed capacity of electrochemical energy storage in China exceeded 5 GW in 2021. Nevertheless, compared with the annual capacity addition of about 100 GW from wind and solar, the scale of battery storage still needs to be rapidly expanded. According to data from SGCC, the installed capacity of electrochemical energy storage within its operating area is expected to reach 100 GW in 2030.

Aside from storage in batteries, the characteristics and possibilities of storing energy in chemical form, i.e. synthetic gas or thermal systems is extensively explored. New forms of energy storage technologies can become available in that way. The development of technologies such as P2G (power-to-gas) and V2G (vehicle-to-grid) can create conditions and opportunities for cross-sectoral energy storage.

(2) The development of DG facilitates grid microbalance

Compared with traditional energy generation equipment, DG is environmentally friendly, flexible, and efficient. Very likely it will be located close to the demand and can be utilized to match local supply and demand. The development of DG will increase the diversification of China's power grid. It is anticipated that by 2030, China's installed distributed renewable capacity will reach 400 GW. This generation will contribute to an operating pattern where massive microgrids co-exist with the larger utility grid. The microbalance within microgrids provides the basis for the entire power system's balance. With the help of intelligent control mechanisms microgrids assist in linking of and decision-making in the centralized and decentralized parts of the power system.

Advanced information technology can help to establish a microbalance that extends to the consumption side where different loads and demand-side entities participate in the electricity system. With an increasing number of smart communities, smart homes, EVs, and CHP interconnections – in short smart power systems – the flow of electricity will occur not only in one direction, but both ways. The participation of loads and demand-side entities in keeping the power system balanced can improve both network flexibility and efficiency, ultimately achieving a win-win situation for all parties.

The promotion of flexible DC technology will also become an important technical route for microgrid development, especially in the building sector where photovoltaic, energy storage, DC, and flexibility will become standard. With the widespread application of rooftop and building-integrated PV coupled with the development of DC appliances and batteries, whole buildings will be able to switch to DC power supply. This brings along efficiency gains compared to an AC power system. The DC system can also facilitate demand response at the building-level because power consumption of the building can be easily controlled by voltage adjustments on the DC distribution network.

(3) Power generation to be monitored by digital technology

The development of massive DG leads to additional important and potentially fluctuating variables for grid operation. A rapid deployment of digital technologies to provide basic data acquisition and applications at several levels is required.

First, a huge and layered network of sensors must be put in place. The data sources required for smart grid operation are widely distributed in space and come in large numbers. The information source is not only the public grid, but extend to DG units, energy storage, and users. The type of information to be monitored is becoming increasingly complex, as not only electrotechnical quantities, but also non-electrical quantities such as temperature, humidity, pressure, and wind speed need to be recorded. Deploying various types of sensors for different purposes without significantly increasing costs is a basic requirement for any new sensing systems.

A data transmission network layer needs to be designed and build. It will receive data from the sensing layer and transmit it to the application layer. The data transfer layer must be able to receive commands from the application layer and pass them on to the sensing layer. To enhance bandwidth and meet various service needs, the construction and application of powerful network services such as 5G is required.

The third level is the platform layer. With massive data generation of smart grids, traditional data management systems and analysis methods come to their limits in respect to management, analysis, and application needs. The data obtained from smart grids covers power production, transmission, conversion, regulation, transaction, and consumption as well as relevant environmental, social, and economic data. Only through advanced big data technology, effective data storage, processing, visualization, and value extraction can open exchange and sharing of value in smart grids be realized.

The final step is to build an application layer to fully support more efficient smart grid business operations. Big data and the extraction of valuable information is required to promote improvements in power enterprise management and business transformation. The main areas of the application layer are:

- Online equipment monitoring and control;
- Intelligent operation and maintenance;
- Comprehensive trading support;
- Planning, simulation, and operation of a system with a high share of VRE.

(4) Development of new types of entities drives diverse participation models

The development of EVs, distributed energy storage and other controllable power sources on the consumer side will deeply change both the form and operation mode of distribution networks.

Vehicle-grid interaction

China is anticipated to have more than 100 and 350 million EVs in 2030 and 2060, respectively. EV charging infrastructure with hundreds of GW of charging power will be required. Unmanaged charging patterns would have a huge impact on the grid. However, the rational use of EV batteries represents a considerable energy storage potential. Proper guidance and management of EV charging can reduce peak load time windows. Intelligent technology is needed to effectively improve the interaction between the grid and charging facilities by spreading charging across longer time periods and avoiding peak times. A deep integration and interaction of EVs with smart grids requires the application of digital technologies. Combined with DG and energy storage, EVs can provide a regulating function for the grid through charging and discharging processes in sync with the power system's demand and supply situation.

VPPs and demand response

VPPs are important actors for an effective management of DG connections to the grid. Their unique business model of aggregating DG, controllable loads, and energy storage devices at the distribution level, allows VPPs to participate in grid operation and dispatching. VPPs are relevant in mediating the conflicts between grid operation and DG by fully reflecting the value and benefits DG bring to the grid and users.

With the development of VPPs, loads also become essential components of smart grids. VPPs can exploit flexibility potentials at the consumer and their loads. A dynamic regulation of VRE and peak load shaving can ultimately lead to reduced investment needs into power generation and the grid. According to Chinese government documents, future demand response capacity needs to reach 5%-8% of the maximum load. In 2030, the demand response capacity is anticipated to exceed 100 GW.

(5) Improvement of the green trading system

Compared with conventional energy sources, renewable energy is low-carbon. However, the limited regulation potential renders VRE at a disadvantage in power market competition. To improve competitiveness of low-carbon VRE, the green trading system of renewable energy must be improved.

Green power trading

September 2021 saw the official kick-off of the national green power trading pilot. It provides a convenient channel for users to procure green power on the one hand and helps to enhance the environmental premium of wind and solar on the other hand. From the end of 2021 onwards, NDRC and NEA in conjunction with other ministries and commissions have issued, a series of documents requiring the acceleration of green power trading innovation to increase VRE development. The governmental agencies strongly advocate consumer participation in green power procurement.

However, behind the buzz of green power trading, several difficulties and problems need to be solved. Barriers for cross-provincial and cross-regional green power trading need to be lifted. The possibility of linking the green power and the carbon market could provide further impetus for VRE developments. Green power trading will become a key method for VRE to enter the market. So, both the geographic areas and the volumes in green power trading will be gradually expanded to provide more convenience for cross-provincial and cross-regional green power transactions.

Green certificate trading

A green certificate represents a certain amount of renewable power generation. Green certificate trading takes place on a separate market established specifically for the purchase and sale of green certificates. The aim is to realize the environmental value of VRE through price signals of green certificates.

Green power and green certificate trading will become an important means for enterprises to fulfil their renewable energy consumption obligations mandated by NEA. At the same time the environmental value of renewable electricity can be realized.

3.2 Policy recommendations for smart grid development

Promote development of digital technology.
Power and information flows needs to be deeply integrated by the utilization of digital technology such as cloud computing, big data, and blockchain in the power grid. To create smart grids that support the necessary two-way electricity flows in the future power system, the grids and their operating parameters need to be better observable, measurable, and controllable. The compatibility and complementarity of smart grids with the public grid is necessary to create a new model of layered electricity grids and operating modes.

Incentivize smart microgrid development, give preference to developing DG and VRE locally and generate green power close to the user.
More efforts to promote the development of distributed PV, decentralized wind power, and low-carbon microgrids is necessary for industrial parks and commu-

nities. In the central-eastern areas of China with suitable conditions, demand-side flexibility through diverse technologies, such as new energy storage, high-efficiency heat pumps, EVs (including V2G interaction), and fuel cells will be required. They can help to accelerate the transformation and upgrading of distribution grids to smart distribution grids.

Improve market mechanisms supporting a power system with high shares of VRE.

A national unified power market system needs to be established. Its mechanisms must break the concept of electricity balancing within provincial boundaries. Interconnection of cross-provincial and cross-regional power grids need to be strengthened.

A power price compensation mechanism for flexibility must be developed in a scientific, reasonable, fair, and effective manner. This could take the shape of a compensation or market-based trading mechanism for auxiliary services. Grid-connected entities need to be incentivized to participate in system regulation while grid-connected VRE must enhance their capabilities in providing system stability through improved generation forecasts and regulation. Those measures improve the adaptability of VRE and the new power system. A capacity market mechanism needs to be created alongside improved pricing mechanisms for new energy storage. In that way investment in energy storage facilities can be increased and existing facilities are incentivized to play a more active regulating role.

Improve and coordinate policies on green power, green certificates, and carbon markets.

The differences and interaction potentials of green power, green certificates, and carbon markets need to be established through cross-departmental cooperation. Market mechanisms for green certificates and green power need to promote efficient matching and synergies between the two markets must be leveraged. The eligibility of green power and green certificate purchases for zero emission claims and in carbon markets need to be analyzed and implemented so that enterprises are encouraged to actively purchase green power.

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