China's flexibility challenge in achieving carbon neutrality by 2060

Jianglong Li [a], Mun Sing Ho [b], Chunping Xie [c], Nicholas Stern [c]

a. School of Economics and Finance, Xi'an Jiaotong University

b. Harvard-China Project on Energy, Economy and Environment, Harvard University

c. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science (LSE)

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Abstract

As a response to global concern on addressing climate change, China announced its ambitious goal of carbon neutrality by 2060. The electrification of final energy use and high penetration of renewable energy generation are essentials to achieve the goal of carbon neutrality, while the change in the demand curve profile and strong growth of renewable energy highlight the rising flexibility needs in the power system to meet the real-time balancing. Accordingly, flexibility is increasingly becoming the corner-stone in top-level policy design to achieve the carbon neutrality target. However, the dual-track with both plan and market in China's power system makes it challenging to operate in a flexible manner. This paper shows why flexibility is going to be one of the serious challenges for China during the pathway of achieving carbon neutrality, and discusses the options to improve flexibility, including power plants, power grids, demand-response measures, and storage technologies. Particular attention is paid to the associated policies and regulations, especially power market reform in China, that are considered to unlock the flexibility potentials of such sources. We observe that non-market-based electricity price in China is a major obstacle to improving flexibility from almost all sources. We are cautiously optimistic that, with the ongoing market-oriented reforms especially in the electricity market, the market-based measures could play a critical role in addressing the challenges of flexibility.

Keywords: Flexibility; Carbon neutrality; Power system; Market reforms; China

1. Introduction

In September 2020, the government of China announced its ambition to strengthen climate policy by targeting carbon emissions to peak before 2030 and to achieve carbon neutrality by 2060. To reach these goals, China must start to limit, then reduce, the burning of fossil fuels. One way China is doing this is by promoting the generation of electricity from renewable and nuclear sources. However, renewables like wind and solar are intermittent and nuclear is a baseload source that is more costly to use to follow loads. China does not have low-cost local gas supplies and thus flexibility in the power system will be the big challenge in achieving the carbon peak and neutrality commitments. In this paper, we discuss the options for China to improve the flexibility of the power system and their associated challenges.

Electricity is an essential element in modern life and a key input for various production processes in all sectors. In China, electricity today accounts for around 25 percent of final energy consumption, which generally highlights the importance of electricity in the economy[1]. In a low-carbon future with less oil and gas use, electricity will have to play an even bigger role since it is generally agreed that we will have to decarbonize the power sector and then increase electrification of end-use. The dominance of coal in electricity generation today makes the carbon pledges very challenging. It requires China to invest more in renewable generation while expanding electricity production for electrified transportation, heating, and industrial processes. Accordingly, for the low-carbon transition, renewable electricity is expected to play a very important role in the future.

Renewable and nuclear energy are largely not dispatchable, that is, they are not easily ramped up or down on short notice. They rarely help to meet the real-time balancing between electricity supply and demand, making it challenging to maintain continuous service when there are rapid and large swings in supply or demand. That is, they are not "flexible." Flexibility is described by the International Energy Agency (IEA,

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[1] This number is calculated by dividing the electricity consumption by total final energy use in the Table 5-10 of China Energy Statistical Yearbook 2019.

2011) as "the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise". Hence, flexibility is increasingly becoming the cornerstone of China's energy system with the ambitious low-carbon targets. China needs to improve flexibility in the power system urgently if is to meet the near and mid-term carbon targets without compromising power supply security.

The urgent need to meet the flexibility challenge motivates us to discuss the following research questions:

a. How much flexibility is necessary with China's ongoing low-carbon transition?

b. What options does China have to cover a given flexibility demand?

c. Do the current policies and market designs encourage investors to participate in improving flexibility? In particular, does the unique dual-track system with both plan and market elements in China's power systems affect the incentives of participating in flexibility?

Various options to address the challenge of flexibility with growing renewables have been explored in literature, including flexible generation (e.g., Gonzalez-Salazar et al., 2018), grid network (e.g., Das et al., 2018), demand response (e.g., Heffron et al., 2020), and energy storage (e.g., Yao et al., 2016). To the best of our knowledge, Lund et al. (2015) provide perhaps the most comprehensive summary of the various aspects of flexibility options, focusing more on technologies. Martinot (2016) pays particular attention to cross-country experience on improving flexibility. As existing literature mainly focuses on few aspects of flexibility options and is mostly about the US and EU institutions, in this paper, we elaborate from a China perspective, in particular how the current reforms of the highly centralized controlled electricity system affect efforts at increasing flexibility. We first describe the urgent flexibility needs in China's electric power system and then give an overview of the challenges related to reforming the power market policies that disincentivize the improvement of flexibility. China is currently the country with the highest flexibility requirement due to its rapidly increasing proportion of intermittent renewables in combination with the rising electricity demand. There is a number of engineering studies and bottom-up modelling of how the electricity system in China might evolve to deliver a low-carbon system, however, they mostly focus on the technical aspects and rarely emphasize how institutions may need to be redesigned to deliver the modelled set of technologies and distribution networks[2]. Given its crucial role in addressing global climate change, a well-functioning Chinese electricity system with market incentives to provide adequate flexibility will be indispensable for a sustainable future. China's experience in addressing the flexibility challenge during its low-carbon transition may be extended to emerging and developing countries that could benefit the global efforts to fight against climate change.

The remainder of this paper is organized as follows. In Section 2, we show how electrification with renewables for a low-carbon transition increase the flexibility needs in China's power system. Section 3 demonstrates the economic and social consequences of lacking sufficient flexibility, so that it is urgent to meet the increasing flexibility needs. In Section 4, various options and the associated challenges are discussed, including power plants, power grids, demand-response measures, and storage technologies. Section 5 pays particular attention to policies and reforms, especially in electricity markets, so as to unlock flexibility potentials. Section 6 is concluding remarks.

2. Electricity system flexibility needs for a low-carbon transition

2.1 Electrification coupled with renewables for a low-carbon transition

Alongside the remarkable economic growth in the past four decades since the market-oriented reforms that begun in the late 1970s, China experienced explosive growth in energy demand. It is now the largest economy in purchasing power parity (PPP) adjusted terms in the world with 1.4 billion citizens, and China is by far the largest energy consumer. Moreover, coal has always played a dominant role in China's energy mix, leading to its dramatic growth in CO_2 emissions. According to British Petroleum (BP, 2020), 28.8% of global CO_2 emissions from anthropogenic activities in 2019 are generated from China, following by the United States (14.5%), the European Union (9.7%), India (7.3%), the Russian Federation (4.5%), and Japan (3.3%). In China, energy-related CO_2 emissions account for 85% of man-made CO_2 emissions. Progress toward

[2] See, e.g., Zhong et al. (2015) and Lugovoy et al. (2021).

carbon neutrality will be a daunting challenge as energy demand in China is still growing with the fast-rising incomes.

To address the global concerns on climate change, accelerated electrification coupled with renewables is the most likely path to a low-carbon future. Nevertheless, both electrification and energy decarbonization are difficult and time-consuming for China, as they are for many other countries. Figure 1(a) gives China's electrification rates by sector in 2018 and 1(c) further reveals the sources of electricity and a comparison to other major economies. Figure 1(b) shows the total primary energy mix in China. In 2019, total electricity consumption reached 7226 TWh, an increase of 4.5% from 2018, accounting for 27.8% of global consumption. Even with such level of electricity use, the share of electricity in final energy use is only 24.6% on average in China - though this share is not small compared to most other countries[3], and many expect it to continue rising. For example, China National Renewable Energy Centre (2018) projects the share of electricity in final energy use to be somewhere between 48% and 53% in 2050. Figure 1(a) shows that end-use is still dominated by coal and oil products, especially in the industry and transport sectors. Even in sectors such as the residential and service, electricity accounts for less than 50% of their final energy use.

[3] As a comparison, the share of electricity in final energy use in 2018 was 19.3% worldwide, and 22.1% in OECD countries according to the IEA (https://www.iea.org/reports/key-world-energy-statistics-2020/final-consumption accessed at April-19, 2021).

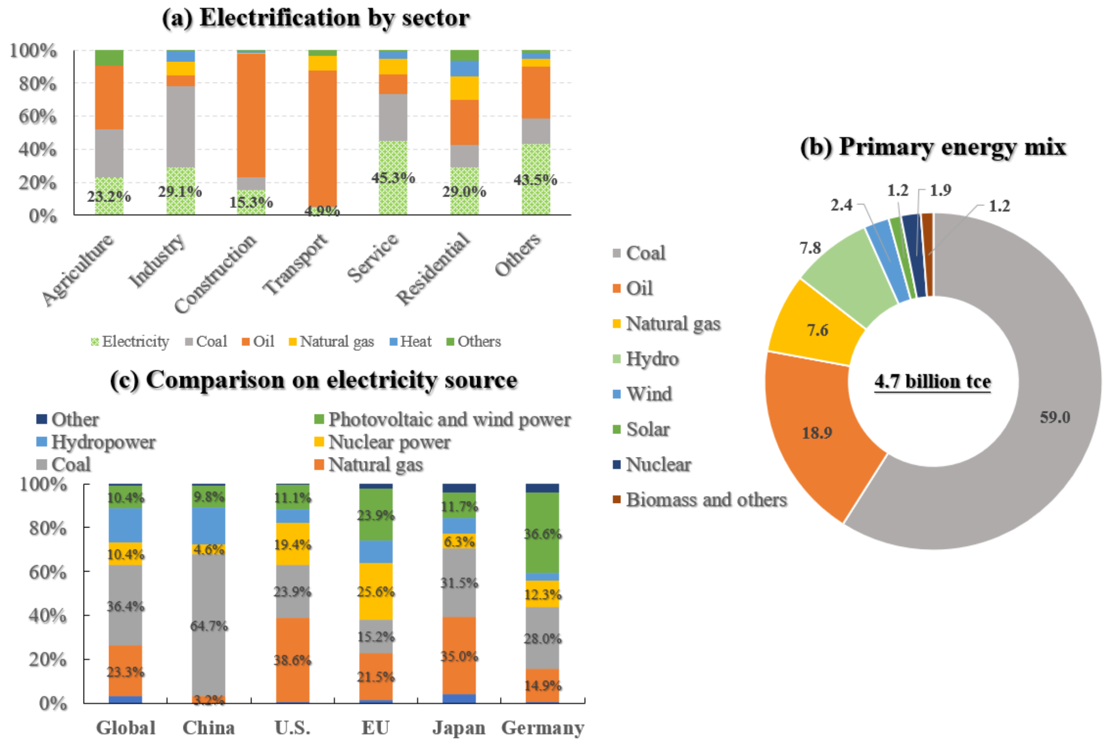


Figure 1. China's electrification and renewables in 2018

Notes: Fuels used as raw materials (e.g., in chemicals) are excluded in the data of industry. "tce" is the abbreviation of tons of coal equivalents which is the official unit in China statistics. The data in Figures 1(a) and 1(c) are obtained from China Energy Statistical Yearbook 2019, and data in Figure 1(b) are available in BP (2020).

Electricity is thus expected to become an increasingly important energy source with fossil fuels being replaced. In the manufacturing sector, as many factories combust coal or oil products directly to provide energy, the government must work with these factories to switch from coal towards electricity through replacing inefficient coal boilers, or from oil engines to one running on electricity. Power-to-X technologies such as electrolytic hydrogen production is an important option for the low-carbon transition with the hydrogen substituting for liquid fuels. In the transport sector, energy demand has been dominated by oil products, but the government is putting in place policies to motivates companies to produce electric vehicles and consumers to buy them. These include national fiscal subsidy policies for private EV buyers, incentive funds for charging infrastructure and preferential tax, such as the exemption of purchase tax, vessel tax and consumption tax on lithium-ion battery. A rising electric vehicle fleet could significantly increase the electrification of the transport sector. In the residential sector, non-electricity energy use mainly lies in heating (using coal) and cooking (using gas). Policies are being implemented to get millions of homes to replace coal heating and gas cooking (Liu and Mauzerall, 2020). In recent years, the Chinese government has issued a series of electric heating policies, as a major part of the efforts on transforming heating. For example, the “instructions for substituting electric heating for coal” issued in 2016, sets a target of reducing 130 megatons of coal for rural heating from 2016 to 2020. With the electrification of heating and cooking devices, electricity is also expected to take a larger share in the final energy use of the residential sector.

All these policies make electricity more crucial in the future and thus a low-carbon power supply is a fundamental precondition for achieving the carbon-neutrality goals. However, as shown in Figure 1(b), of the 4.7 billion tons of coal equivalent (tce) primary energy consumption in 2018, carbon-intensive coal has a 59% share while renewables only account for 14.5%. Figure 1(c) shows that coal-fired plants still provided 65% of electricity in 2018, after dropping substantially from ~80% in 2008. This share of coal in power generation is much higher than the global average (~36%) and that in advanced countries such as the US (~24%) and EU (~15%), even though the US relies heavily on gas which is also carbon intensive.

The good news is that the global electricity supply, including China’s, is being reshaped by technological developments and by low-carbon policies. In 2020, China’s coal-fired power capacity fell below 50% for the first time[4]. Hydropower remains the largest low-carbon source of energy and electricity in China, but the untapped potential is now limited, and the country has to turn to other renewables, especially wind and solar power. The cumulative planned solar and wind capacity for 2030 is more than 1200 gigawatts (GW), compared to 414 GW in 2019, raising the share of renewables and nuclear in primary energy consumption to around 25% by that year. To incorporate such a large scale of intermittent renewables, the power systems must have sufficient

[4] Source: https://www.scmp.com/economy/china-economy/article/3122419/chinas-carbon-neutral-push-gathers-pace-coal-fired-power (accessed at May-04, 2021)

flexibility to balance supply and load demands continuously.

2.2 Flexibility needs in the power system to overcome the variability challenge

While technologies such as carbon sequestration or hydrogen production may be important in the future, renewable generation is currently the most important decarbonization option besides nuclear in the power sector, with wind and solar power providing a large proportion of recent increases. But wind and solar power are both variable sources of energy, depending on wind and sunlight which cannot be well forecasted even just days ahead of time. Accelerating electrification of the economy will likely change the time profile and uncertainty of electricity demand, including a likely increase in the variability of electricity loads.

Figure 2(a) shows the relationship between the share of renewables in total monthly generation at the provincial level and the coefficient of variation (CV)[5] of electricity supply across months within the same year, 2009-19. We use the CV as a simple measure of the variability of the monthly electricity supply. Figure 2(a) indicates that the variability in monthly supply is positively correlated with the share of renewables.

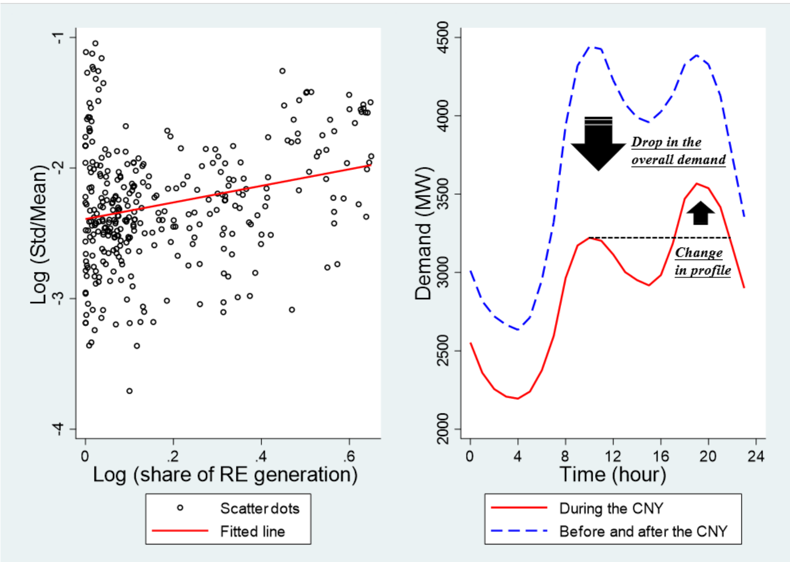


Figure 2. The variability challenges from supply and demand

(a) Renewables (RE) and variability of monthly supply across provinces; (b) Demand

[5] The coefficient of variation is defined as the ratio of the standard deviation to the mean. It shows the extent of variability in relation to the mean of the population.

variability, an example of the holiday effect

Notes: In Figure 2(a), the monthly generation data are from 2009 to 2019 at the provincial level. The coefficient of variation of electricity supply in the y-axis is measured by the ratio of standard deviation to the mean of electricity supply within the same year. In Figure 2(b), the red solid line shows the average loads over 24 hours during the week of the Chinese New Year (CNY) holidays of 2017, while the blue dash line shows the average loads before and after the weeks of CNY holidays.

On the demand side, there is also significant daily and seasonal variability. Even though load forecasting is usually quite accurate, the variability on the demand side also requires flexibility in power systems to match the supply with the fluctuating demand. Demand variability is especially large in the residential and services sectors where the load is sensitive to weather conditions and seasonal shocks (such as holidays). Figure 2(b) shows an example of daily load variability over 24-hours due to holidays in the city of Xi'an. During the Chinese New Year (CNY) holidays, the load drops significantly over all 24 hours because most factories and offices are shut down. At the same time, the gap between the valley and peak hourly demand is even larger during these holidays. With accelerating electrification in the future, the load could be even more volatile.

The physical nature of electricity implies that generation and consumption must always be in balance instantaneously and the low-carbon transition requires more flexibility in the power system to meet this requirement. More flexibility is needed to modify electricity production or consumption to balance them at scales of seconds, hours, days, and even seasons. Accordingly, in the context of carbon neutrality, flexibility is rapidly becoming the cornerstone to ensure the security and reliability of power systems.

Accordingly, IEA (2020) projects the power system flexibility needs in China over 2020-2030 and compares them to other regions. Here, flexibility needs are projected by taking the average values of the largest 100 ramping requirements over hours when wind and solar capacities are blocked out from electricity demand. As shown in Figure 3, the flexibility needs in China by 2030 are much larger than other selected major regions, and the increments from 2020 to 2030 are also quite substantial compared to the others. The large flexibility needs in China are associated with its energy mix shifting to renewables as well as the fast-growing electricity demand from the resident and service sectors, leading to a large gap between the existing flexibility and the future needs (IRENA, 2018). Such flexibility increments can be met by multiple sources, including power plants, power grids, demand-response measures, and storage technologies. Policies and regulations, especially power market reform in China, are also required to unlock the flexibility potentials of these sources until the existing flexibility is exhausted.

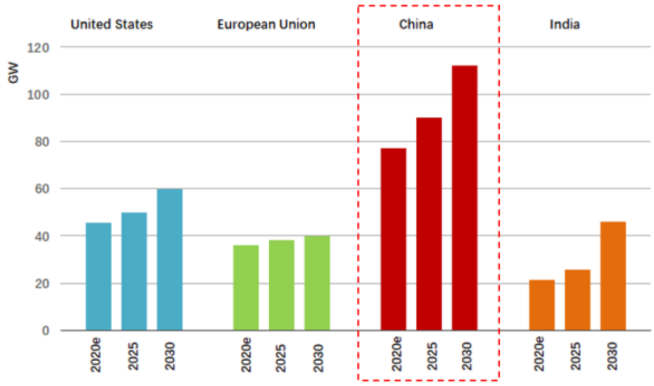


Figure 3. Power system flexibility needs over 2020-2030

Source: IEA (2020), adjusted. 2020e means estimated values for 2020.

3. Why flexibility matters: Consequences of insufficient flexibility

3.1 Rising renewable curtailment and falling reliability of power supply

Lacking sufficient flexibility could result in undesirable outcomes, including curtailment of renewables and power outages. Figures 4(a) and 4(b) show the very high curtailment rates of wind and solar before 2016, and while the situation has been getting better since then, it was still as high as 9% in 2018 for wind. As a comparison, the average curtailment in the U.S. in 2018 was 2.2% (US DOE 2019). A fundamental goal of ensuring flexibility is to "keep the lights on" (Martinot, 2016). Figure 4(c) shows the map of the average total annual hours of power outage by county in 2018. Over entire China, the outage duration (including large-scale power rationing for meeting given energy and environmental targets) is ~14 hours on average, with ~4 hours in urban areas and ~17 hours in rural areas. While this is poorer than the U.S. performance where customers experienced an average of ~6 hours of power outage in 2018[6], it compares well with other countries. In a World Bank study, Samad and Zhang (2016) report that firms in about a third of developing countries experience at least 20 hours of outages per month on average and it is even worse in South Asian countries where firms report almost one outage a day with an average duration of 5.7 hours. The reasons for the relatively good performance in China include the technical capabilities of the grid companies, the recent retrofit of coal-fired plants for enhancing flexibility, and the increasing trade in electricity between provinces. Overall, the evidence on curtailment and outages implies that the current power system in China is able to cope relatively well with the variability challenges accompanying renewable energy and demand uncertainty.

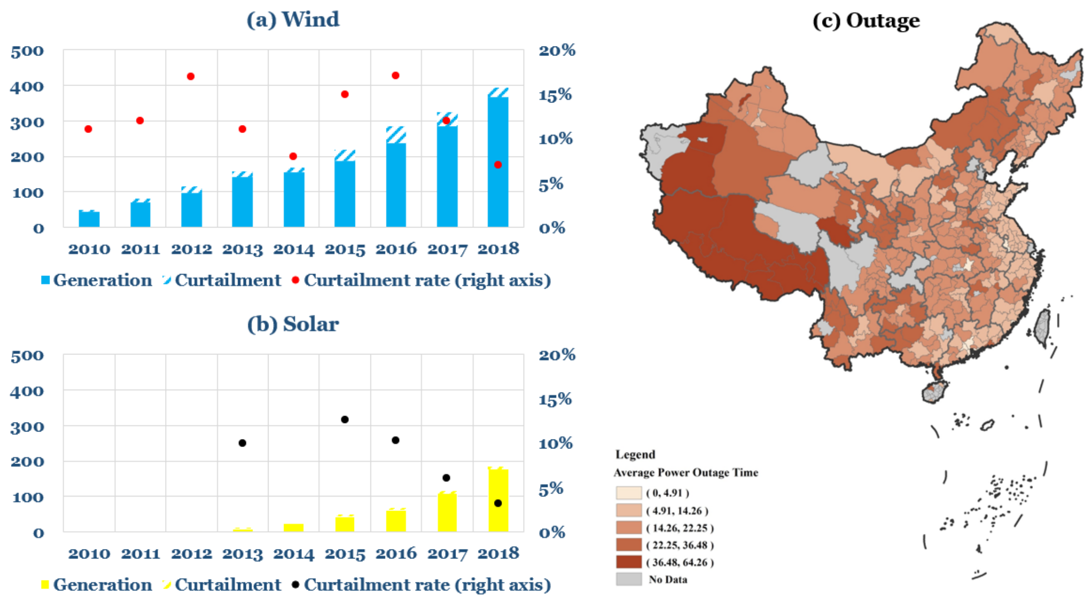


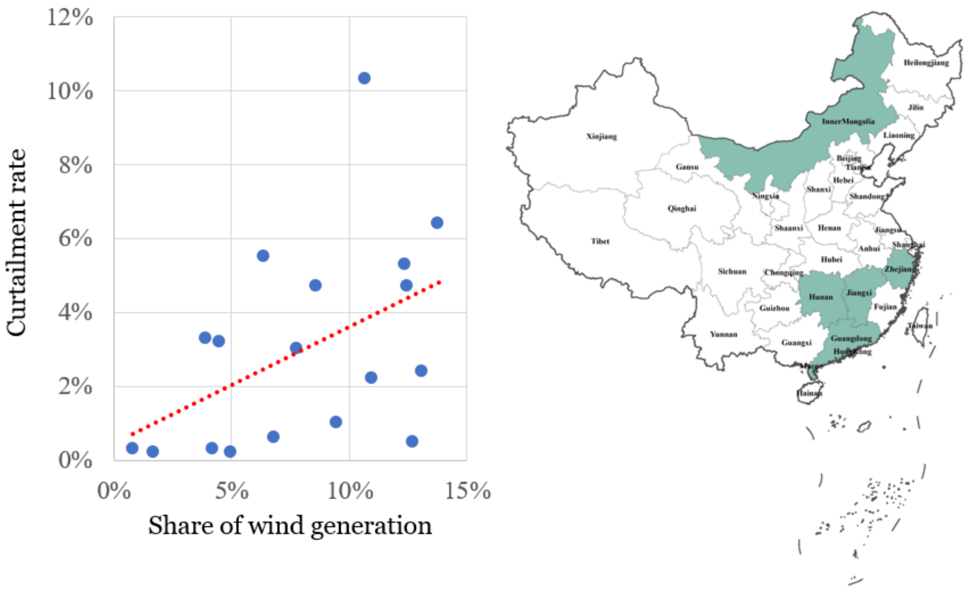
Figure 4. Current status on the outcome of insufficient flexibility

Notes: Figures 4(a) and 4(b) show the curtailment of wind and solar power respectively (units: kWh, %). Figure 4(c) presents the average annual power outage hours (including rationing) by city in 2018.

While the curtailment rates are improving under current levels of renewable penetration, flexibility will be a major challenge given the accelerating electrification on

6 Source: https://www.eia.gov/todayinenergy/detail.php?id=43915 (accessed at March-22, 2021).

the demand side coupled with rising shares of renewable energy on the supply side to meet the ambitious climate goals. First, without sufficient flexibility, operators may have to curtail more wind and solar energy in the future as their capacities expand. To illustrate this, Figure 5(a) shows the relationship between the share of wind generation and the associated curtailment rate across provinces in 2020. On average, the curtailment rate at the provincial level is expected to increase 0.3% when the share of wind generation increases by 1 percentage point. ETC & RMI (2021) projects that the share of wind generation in total electricity generation will increase from 5.6% in 2019 to ~16% in 2030. Similar rapid growth is projected for solar energy. If the current curtailment rate, as shown in Figure 5(a), continues, this would mean a huge level of unused renewable power. If the curtailment rate will have to rise even more due to the very high penetration of renewable that the system has yet to experience, then project revenues may fall which could degrade investor confidence and lead to higher electricity prices for consumers.



(a) Curtailment and the scale of provincial wind power, 2020; (b) Provinces experiencing electricity shortages in winter, 2020

Figure 5. Effects of insufficient flexibility: curtailment and shortages

Note: The data source of curtailment rate is from the National Monitoring Center of Renewable Energy, https://www.china5e.com/news/news-1109534-1.html.

Second, flexibility in power systems also requires some generation capacity ramping up quickly and efficiently when there are extra demand or supply disruptions in electricity, otherwise, outages or rationing may occur. For example, Figure 5(b) shows the provinces experiencing electricity shortages during the winter of 2020, when low temperatures induced high electricity consumption, and the power systems could not provide sufficient flexibility to overcome the unexpected load change. A similar situation of electricity shortage caused by unusually cold weather also occurred in the U.S. state of Texas in the early Spring of 2021.

3.2 Economic and social impacts of less reliability

The economy is highly dependent on electricity, and thus the reliability of electricity supply is a prerequisite for a well-functioning economy in the short- and long-run. For modern daily life and industry processes, what matters is not only the availability of electricity, but also a reliable and uninterrupted electricity supply (Heffron et al., 2020).

For companies, a key problem of insufficient flexibility is electricity supply interruptions with a slow restoration, something which could be very costly and harmful for their production process. The interruptions may cause products to deteriorate, increase waste, reduce, or destroy output, and damage machines together with a possibly increased danger for workers. Unreliable power leads companies to provide their own backup supply which is often inefficient and costly. Along the modern supply chain, interruptions in one supplier have negative effects on downstream companies. Thus, unreliable local electricity supply could spread out to a larger area due to such linkages. Such costs and uncertainty for businesses deter investment and thus economic growth.

Unreliable electricity supply could also damage non-business sectors. For instance, educational institutions and hospitals need reliable power to provide their important social services. Thus, a reliable electricity supply is not only important for economic reasons, but also contributes to social welfare.

4. Options to improve flexibility and the associated challenges

Given these undesirable consequences of unreliable power supply, meeting the flexibility needs in a cost-effective manner would be essential for achieving carbon neutrality. Flexibility can come from both supply-side resources and demand-side resources in a power system. Flexibility also arises from the design and operation of electricity markets, from transmission and distribution networks, and from the technical operation of the grid itself and storage facilities. In this section, we discuss the options to improve flexibility and the associated challenges in a Chinese context.

4.1 Supply-side flexibility

The power balance of electric systems is normally handled by the supply side, adjusting the output of conventional fossil-fuel plants. With supply-side flexibility, we mean measures or technologies through which the output of power generation units can be modified to attain power balance (Lund et al., 2015).

(a) Coal-fired plants

Given the current dominance of coal-fired power in China, retrofitting them to be more flexible is critical to provide flexibility on the supply-side. The flexibility of coal-fired plants depends on three factors: (i) their ability to cycle on and off and the lead time required (i.e., start-up time); (ii) their minimum and maximum output range while running; and (iii) the ramping speed at which they can vary their output levels. In North China, the operation of combined-heat-and-power (CHP) plants in the winter is mainly driven by heat demand, restricting their flexibility in electricity production. About 40% of China's coal capacity is CHP, and in Northeastern China it is more than 60%[7]. With rising renewable energy, it is necessary to decouple the generation of heat and power during the operation of CHPs so that heat demand could be met without hampering the flexibility of coal generators to compensate for the intermittency of renewables (DOE, 2018). One of the most effective solutions is the integration of energy storage systems – which include not only electrical energy storage (EES) but also thermal energy storage (TES). For example, large water tanks for hot water storage or regenerative electric boilers can be installed in power plants. When electricity demand drops, CHPs can still maintain the same heat output, while the extra power generated can be stored in the regenerative electric boiler, or used in the heat cycle to extract steam and heat cold

[7] The data are obtained from: https://www.china5e.com/news/news-1085168-1.html http://www.xinhuanet.com/power/2018-01/23/c_1122301319.htm (accessed at April-20, 2021)

water. This can on one hand reduce the output of power, and on the other hand, the stored heat can be released back into the heating system, and correspondingly reduces the heat output needed for meeting heating demand.

To increase the responsiveness of coal-fired plants, since 2016 China has implemented retrofitting measures with a target of 220 GW during the 13th Five-Year Plan (2016-2020) for the power sector (Li et al., 2020). The aim is to improve their ability to ramp up and down in an effective way. The typical coal-fired plant in China has a minimum output limit of 50%, that is, it cannot operate below 50% of the rated capacity. The retrofitted pure condensing plants are required to be able to operate down to 30%~40% of the rated capacity, and 40%~50% for the retrofitted CHP plants. After retrofitting, the CHP plants are able to vary the proportion of heat and electricity more flexibly, that is, adjust their electricity output in response to grid conditions and provide balancing without crowding out renewables when providing heat.

(b) Gas-fired plants

Gas-fired plants are generally considered an attractive option to increase the supply-side flexibility because of the low investment cost and high efficiency compared to other back-up technologies such as coal-fired plants (Bass et al., 2011), especially in the US and EU. Gas-fired plants in China are also usually designed to cycle on/off or ramp up/down to provide flexibility. Unlike in the US and EU, gas-fired plants are rarely employed as base load in China. An important reason is they depend on the availability of natural gas and China does not have enough natural gas resources domestically to meet the demand. ~50% of natural gas is imported at relatively high costs and the marginal cost of gas-fired electricity is much higher compared to coal-fired power. Table 1 shows that the levelized cost[8] of gas generation could be more than twice that of coal generation in China. Moreover, the costs of natural gas infrastructure including pipelines and storage mean that using gas for flexibility may not be a cost-effective approach for China. Underground natural gas storage might be a cheaper alternative in

[8] Levelized cost is the average net present cost of electricity generation for a generating plant over its lifetime or an assumed financial life. An example of calculation is given in Li and Huang (2020).

the future, but current gas storage facilities in China are very small. In 2018, working gas capacity only accounted for 3.4% of the total natural gas demand in China, compared to ~17% in the US and ~25% in the EU. By the end of 2020, the cumulative installed capacity of gas-fired plants is only 100 GW, just 4.5% of total capacity in China. Therefore, other flexibility sources are required in the near term to balance supply and demand over the various timescales.

Table 1. Levelized cost of coal- and gas-fired plants in China, 2020 (US$/MWh)

Type	Coal-fired	Gas-fired		
		CCGT	OCGT	FPGT
Cost	50~66	75~97	121~235	132~250

Notes: Data are compiled from ETC & RMI (2021) which are calculated based on auction results released by the National Energy Administration. The unit is USD/MWh. CCGT is a combined cycle gas turbine; OCGT is an open cycle gas turbine; FPGT is a free-piston gas turbine (FPGT)

(c) Nuclear plants

Nuclear plants have essentially near-zero marginal cost and are generally used as baseload in China today and are not dispatchable[9]. Nuclear plants can be designed (or modified) and operated for flexibility like in France and Germany, but it is not a current option for China to use nuclear plants as a flexibility measure because of its current small share in China's power systems (4.8% in 2019) and the virtue of having almost zero marginal operating cost. Keppler and Cometto (2012) also note that operating nuclear plants at maximum output is helpful to reduce unscheduled outages and that diligent operations with maintenance are needed for safe operation. Currently, nuclear plants are not likely to be an attractive option for providing flexibility in China. It is possible for nuclear sources to act as load-followers in the future, but the economics of this is not yet entirely clear as discussed by NEA (2011).

(d) Renewable curtailment

Another flexibility measure on the supply-side is the curtailment of centralized

[9] In 2020, the annual operating hours of nuclear plants on average in China is 7427 hours, which means nuclear plants are operated at full output over the whole year except for maintenance hours.

renewables. Renewables can be deployed in either centralized or distributed forms. The latter can generate electricity at the location of end-users and thus match spatially the demand and supply more effectively. For centralized renewables, a simple way to integrate large amounts of variable renewables into power systems in a flexible manner is to allow for restrictions on their output when necessary. This is of particular importance in the context of China given its large territory and opposite distribution of renewable resources and electricity loads. Supply and demand mismatches are frequent with high penetration of centralized renewables, and NREL (2019) shows that low levels of curtailment (e.g., less than 3%) may be a cost-effective source of flexibility since there are costs in adjusting even flexible fossil-fuel sources.

4.2 Flexibility from power grids

Given the provincial level control of dispatch, an efficient power grid with inter-provincial and inter-regional transmission capacity plays an important role as a flexibility instrument. China is large geographically, but renewable energy is not evenly distributed. In general, the northern and western regions have a lot more wind and solar resources than the other regions. Accordingly, most wind farms and centralized solar plants are concentrated in these areas which are remote from population centers in the East and South[10]. The regional mismatch between supply and demand imposes a great challenge to fully integrate renewable energy at the local level (Zeng et al., 2016). We have already noted that the combined generation of electricity and heat in North China reduces the flexibility of coal-fired plants there to act as load-followers.

Power grid companies transmit and distribute electricity and could thus provide flexibility through market coupling, i.e., forming an interconnected electricity market, which could either act as insurance for each other or address regional supply and demand mismatch on a larger scale (Antweiler, 2016). There are three important aspects of the provision of flexibility by power grids:

[10] In 2020, 76% of the wind capacity and 79% of solar capacity are installed in northern and western regions, but this growth in capacity has outpaced electricity demand in these remote areas. The electricity demand in these regions only accounts for 33% of the total demand in the entire nation.

First, matching supply and demand geographically. For the operation and planning of a power system, there is often a trade-off between more favorable low-cost or low-pollution but remote resources and the additional cost of building transmission lines for integration. This determines whether the renewable generators should be closer to load centers or closer to resources. The cross-border trade in electricity among provinces through ultra-high-voltage (UHV) transmission lines is an important element in China's power system, improving flexibility by providing access to regions of remotely located, high-concentration, renewable resources (Li and Lin, 2017). However, there are still significant institutional barriers to fully utilize these expensive UHV lines. These barriers include local protectionism for importing electricity, resistance to land acquisition for constructing UHV lines, concerns on the environmental and health impacts of electromagnetic radiation caused by UHV, etc.

Second, the large power grid reduces the flexibility needs of each province by balancing spatial fluctuations over broader areas with a cross-border exchange of renewable energy. Spreading out renewable energy on a wider area can compensate for the rapid changes in the output of a single node. Portfolio theories have shown how geographical dispersion can reduce the system variability of wind and solar power (Hu et al., 2019). Moreover, it also helps to reduce the uncertainty in forecasting renewable energy output, because forecasting the aggregate output over multiple locations is more accurate than that in a single location (Henze et al., 2020).

Third, integrating different geographical markets could create more flexibility by providing insurance through cross-border trade. As electricity demand and renewable supply is largely stochastic and only partially correlated across regions, power systems can reduce their backup capacity by sharing the dispatchable sources through importing and exporting electricity from neighboring regions (Antweiler, 2016).

4.3 Demand-side flexibility

Despite its heavy dependence on coal-fired power, China has given a clear signal to strictly control the growth of coal consumption (Xi, 2021). And in future power systems, the installed coal-fired capacity will be mainly used to ensure the stable supply of electricity and to provide regulation for renewable generation (Su, 2021). In the meanwhile, it will promote the development of high-efficiency, low-emissions technology for coal-fired power generation, including the use of carbon capture and storage (CCS) to reduce emissions from this remaining coal capacity. In the nearer term, demand-side flexibility is an important sustainable measure to add to the toolkit for matching demand with intermittent renewables. Here, demand-side flexibility refers to all measures that allow for shifting demand over time and space to address fluctuations in renewable energy generation (Fridgen et al., 2017; Heffron et al., 2020).

The massive increments in electricity demand bring new opportunities for power systems to improve the flexibility to maintain reliability. Among others, demand response (DR), which evolves from demand-side management (DSM), has emerged as a new method to help improve flexibility. DR is defined by the US Federal Energy Regulatory Commission (FERC) as "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at time of high wholesale market prices or when system reliability is jeopardized" (FERC, 2020). Compared to the conventional generation resources, DR has two major merits in providing flexibility. First, DR can be employed as a resource to decrease the peak load or as a load that follows dispatch signals to address the imbalances between demand and supply in the short-term. Second, in the long-term, a DR that is flexible geographically will help ease constraints since the locations of generation facilities are constrained by resource availability, proximity to rail, ports and pipelines, and location-specific environmental concerns. Accordingly, such advantages make DR a favorable alternative to provide flexibility of power systems both in the short-term and in the long-term.

4.4 Flexibility from energy storage

Energy storage is an important solution to the problem of variable generation. In a way parallel to transmission flexibility balancing spatial mismatch, flexibility from energy storage allows a balancing of temporal mismatches between supply and demand by shifting the supply of power through time. A major benefit of storage flexibility is that it also allows for seasonal shifting of electricity supply and demand. There is a growing interest in energy storage worldwide due to the large-scale deployment of renewable energy and rapid advances in energy storage technologies. By the middle of 2020, the cumulative installed energy storage capacity in China is 33.1 GW, which is about 18% of global installed energy storage[11].

Energy storage technologies can store energy to produce electricity or discharge it, the amount of energy depending on their storage capacities and power capacities (Lund et al., 2015). A higher storage capacity can respond better to mismatches that may occur at various cycles (e.g., daily, weekly, and seasonal), while a higher power capacity allows the storage to respond to variations of higher magnitude in loads and changes in the environment, e.g., changes in weather leading to sharp rises in demand in a short time. Different energy storage technologies can be used for different grid applications to provide flexibility. For example, technology that can offer fast response can support grid balancing intermittency; technology that with hours of available power supply can be used for daily peak shifting; while technology that has large storage capacity and slow discharge can provide seasonal storage.

While some of the technologies are flexible enough to have scalable power and storage capacities, a suitable storage technology needs to be assessed on a case-by-case basis by comparing their technical characteristics (e.g., dispatchability, interruptibility, and efficiency), cost and environmental impact (Das et al., 2018). Figure 6 illustrates the installed capacity distribution in China and worldwide, based on storage type. The most mature storage technology is pumped hydro storage, which is also the largest energy storage technology available by far, 93.7% globally in 2019. In a pumped hydro storage system, electricity is stored by pumping water to a higher gravitational potential and is later recovered by releasing the water to a lower reservoir through a hydro turbine (Lund et al., 2015). Therefore, the future development of pumped hydro storage might be limited by the lack of suitable locations with adequate elevation differences and

[11] The data is obtained from: https://www.china5e.com/news/news-1105958-1.html (accessed at April-12, 2021)

access to water flow and to an electricity transmission network. Besides pumped hydro storage, lithium-ion battery storage is the most widely-used technology, benefitting from fast-falling costs and spillovers in rapid deployment of electric vehicles.

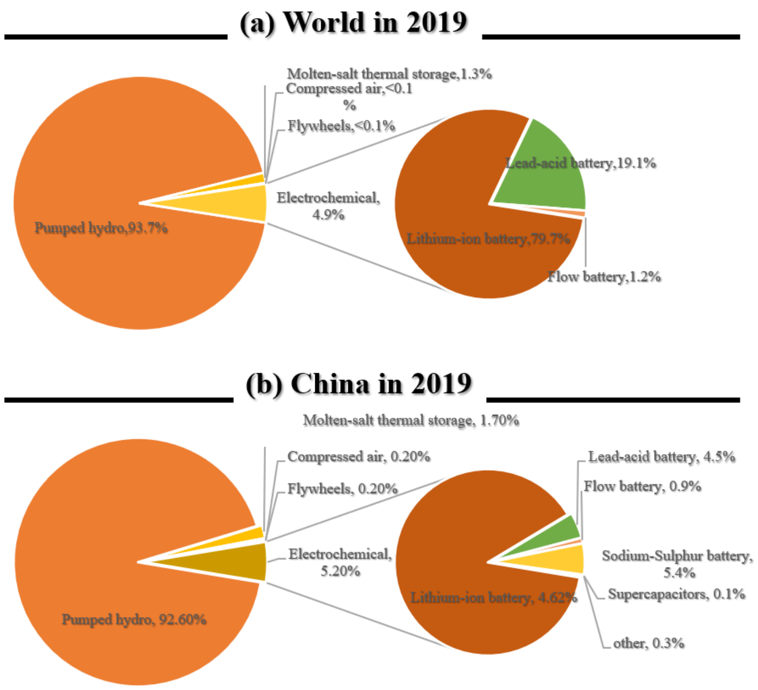


Figure 6. Share of energy storage technologies in operation for China and the world.

Note: Data are obtained from the database of China Energy Storage Alliance. The website link is: http://cnesa.org/index/data_manu.

Efficiency is a crucial benchmark for effective energy storage technologies, it measures the capacity to recover and reuse energy that is otherwise wasted. The efficiency of various technologies is provided in Figure 7. For technologies that are applied in China (shown in Figure 6), the efficiency ranges from ~70% to 99%; while the efficiency is lower for technologies that are still immature, ranging from ~20% to 80%. According to Figure 8, with higher efficiency, the supercapacitor and SMES are promising options for providing flexibility. The former allows voltage regulation, network stabilization, and end-user applications, while the latter is suitable for voltage regulation, spinning reserve, and end-user services (Das et al., 2018).

Energy storage technologies have promising prospects in helping to achieve carbon neutrality by allowing better integration of intermittent renewables. However, the large-scale application of energy storage technologies still has to overcome the challenges both in the technical and economic aspects (Yao et al., 2016).

In terms of technical challenges, no storage system can yet provide a long lifetime, low cost, high density, and high efficiency simultaneously. The future development of energy storage technology requires significant innovation and breakthroughs to encourage wider application in China and around the world. As such, the learning curve observed so far indicates that the costs could fall substantially with more application, like the cost of solar PV in the past decade (Li and Huang, 2020).

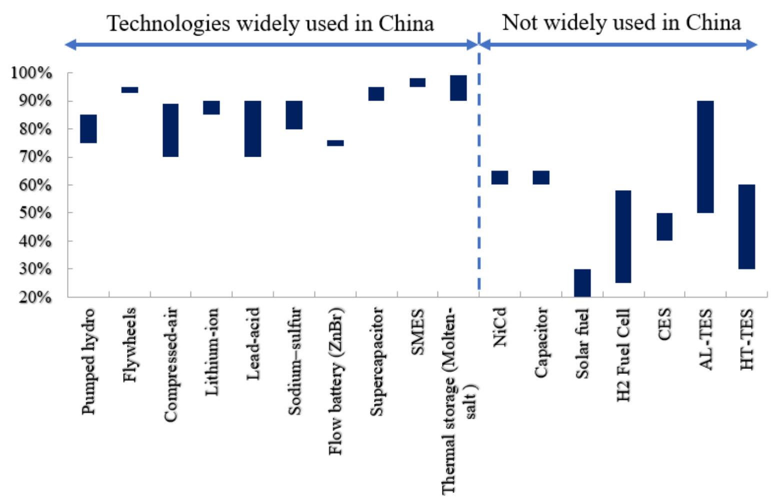


Figure 7. Efficiency of energy storage technologies

Notes: The data of this figure is obtained from Table 1 of Das et al. (2018).

5. Reforms and policies in the power market to unlock flexibility

After ongoing reforms over four decades, China's power sector is still a unique dual-track system with both plan and market elements. The current power sector in China is evolved from a vertically integrated monopoly that also maintained regulatory functions (Guo et al., 2020). The structure of China's power market is displayed in Figure 8. Grid company (GridCo) as the single buyer purchases electricity from various power generation companies (GenCo) and sells it to consumers at regulated prices. The transmission and distribution of electricity are both operated by GridCo at provincial subsidiaries. To improve trading efficiency, GeoCos are also allowed to conduct direct power purchasing with selected large industrial consumers. But the scale is limited. Different from electricity markets in the US and UK, both price and quantity of electricity trading are highly regulated or even directly determined by the government.

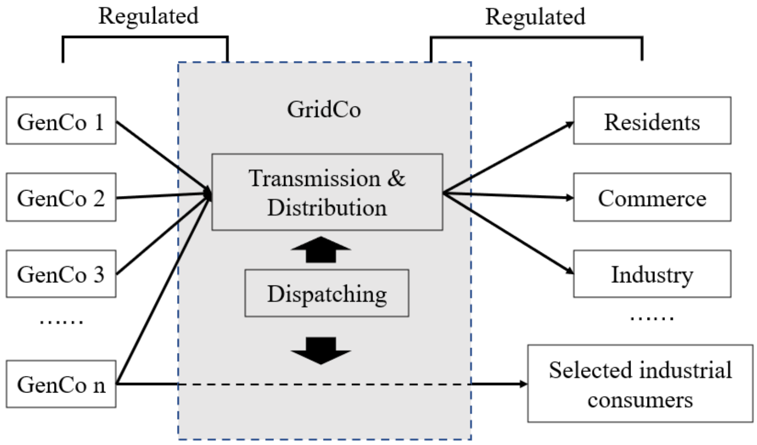


Figure 8. The structure of China's electricity market

The key information here is that the lack of market-based trading results in no incentives to provide related services other than energy. Especially, there are no appropriate rewards to the provision of flexibility for the power system because the price is mostly fixed and the revenues mainly depend on the amount of electricity they provide. To unlock the flexibility from various sources, it is necessary to conduct further reforms and polices in China's electricity market.

5.1. Policies to unlock flexibility on supply-side

On the supply-side, the current system has fixed tariffs for each type of generator determined by the government except for some spot market pilot projects. In the past decades, the rapid growth in deployment of coal-fired plants in China was supported through fixed feed-in tariffs that depend on their levelized costs. The fixed tariffs were important during the built-up phase because they provided certainty to investors. However, these fixed prices for the vast majority of coal-fired plants are now a major problem since they do not have incentives to provide flexibility, there is no compensation for such ancillary services in the current system. With the rising share of renewables, pricing reform is increasingly important otherwise there is no incentive for generators to respond to market prices.

As a first step to address this problem, China has implemented policies to support such ancillary services in several provinces whereby coal-fired plants are compensated for providing flexibility and thus they have an incentive to retrofit. For example, in

Gansu, a province with sizable wind resources, coal-fired plants could gain an extra price above the fixed tariff if they are willing to reduce their load ratio below the base-line (i.e., 50% of the rated capacity)[12]. With these policies, these installed retrofits for higher flexibility have helped to integrate wind power. Figure 9 shows the 22 retrofit pilot projects, most of which are in the North-Eastern China (Liaoning, Jilin, Hei-longjiang) and Inner-Mongolia. These are regions with the highest concentrations of wind capacity. By providing flexibility, these pilot projects succeed in reducing the cur-tailment of wind power.

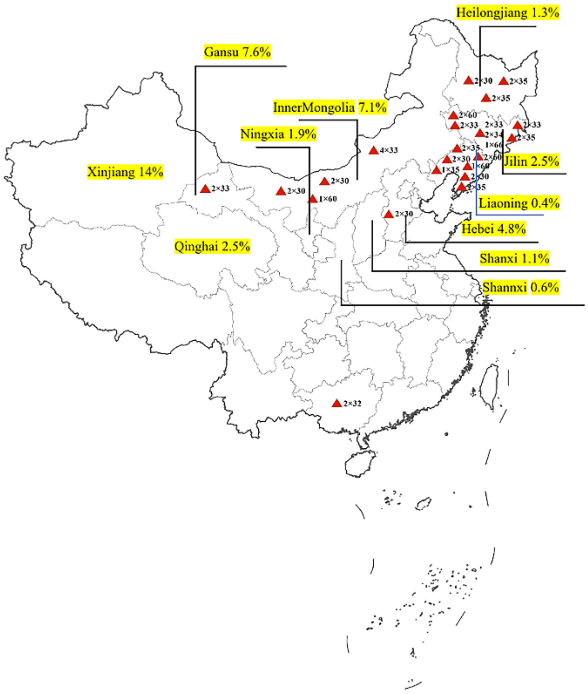


Figure 9. Retrofitting existing coal-fired plants for higher flexibility. Red triangles show the location of retrofit pilot projects, the percentages are the provincial curtail-ment rates of wind power in 2019.

However, these supporting policies have only played a limited role so far. In China's 13th Five-Year Plan (FYP), the retrofitting of coal-fired plants is expected to improve the flexibility of China's power systems by 46 GW by 2020, while less than 30% of the planned retrofits were finished by the end of 2019. As an alternative to this

[12] The ceiling of this extra price is 0.4 Yuan/kWh when the load ratio is from 40%~50%, and is 1 Yuan/kWh when the load ratio is below 40%.

fixed price support, time-varying market prices for power would offer better incentives for coal plant flexibility. Figure 10 illustrates coal-fired generation and the marginal prices in the PJM market of the US where there are spot-markets for generators. This shows that the generation of coal-fired plants could adjust quickly as a reaction to changing market prices[13]. The experience in PJM market is relevant to flexible retrofits of coal-fired plants in China, implying the important role of spot prices in incentivizing the reaction of coal-fired plants so that the flexibility of power systems could be improved.

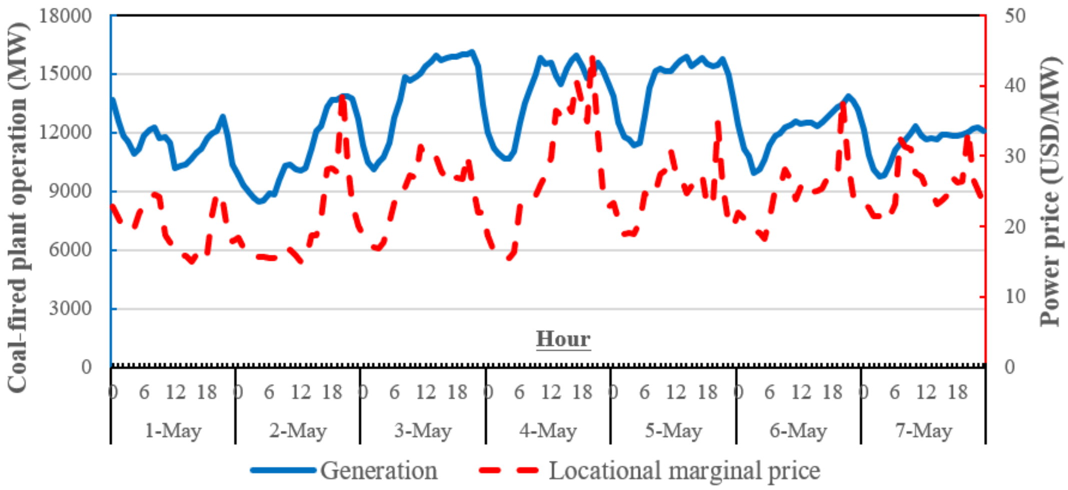


Figure 10. Operation cycle of coal-fired plants and associated prices in PJM of the US

Source: The data is accessed from the website of PJM: https://www.pjm.com.

5.2. Policies to unlock flexibility on power grids

China's power market is largely segmented by provincial subsidiaries, and it is still challenging to overcome the segmentation notwithstanding potential benefits of coupling provincial markets as discussed. China's power grids are operated by two state-owned enterprises: State Grid Corporation, and China Southern Grid Company. The provincial power grids are operated by subsidiaries of these two companies subject to

[13] Another illustration of coal-fired plants' reaction to changing spot price is provided by Agora (2017) in which they simulate the plant operation before and after flexible retrofitting. The retrofitted coal-fired plants with improved flexibility react to spot price more quickly due to higher ramp-rates and lower minimum load. Please see Figure 40 of Agora (2017).

provincial government control, a system called “province as executor”. Provincial grids are largely self-balancing with only limited interconnections. By 2019, the total interconnecting capacity among regions in China was 146 GW, accounting for only 14% of the maximum load at monthly frequency[14]. This means a big gap compared to some countries such as Germany and Denmark[15]. Moreover, the approval process for building new inter-regional transmission projects involves multiple departments in central and local governments (Zeng et al., 2016), increasing the cost and time for implementation. Besides the capacity bottleneck for transmission, local protectionism further hinders market coupling[16]. The lack of central government transfers and regional ancillary services markets means that provincial grids do not have incentives to provide back-up for other provinces.

With these obstacles in mind, China has reinforced policies to support the construction of interregional transmission capacity and to encourage cross-border trade in electricity since 2005. Table 2 summarizes the supporting policies in recent years, including speeding-up construction of transmission capacity, trading rules, pricing mechanism, short-term supporting mechanism, supervision management, etc. Based on balancing the interests of each provincial grid, these policies aim at increasing the flexibility of power systems by allocating electricity resources in a larger balancing area.

Table 2. Polices to encourage cross-border electricity transmission among provinces

Year	Policy document	Measures

[14] The monthly maximum load in China over 2019 occurred in July at 1053 GW.

[15] For example, Denmark’s transnational transmission capacity with European countries, especially Norway, accounts for more than 80% of its maximum load.

[16] An example is the transmission between Yunnan and Guangdong which are two neighboring provinces in south China. Guangdong is the richest province with the largest GDP, and Yunnan has huge hydropower resources. Usually, electricity is sold by Yunnan to Guangdong, but there are conflicts. When the economy is booming, electricity demand in both provinces is strong, and Guangdong wants to import more electricity from Yunnan, but Yunnan would like to keep more electricity for supporting its own economy. On the other hand, when the economy is depressed, Yunnan tends to export more electricity to Guangdong, but Guangdong would like to leave more electricity demand for its own power plants. This kind of local protectionism hinders market coupling among provinces.

2005	Guiding opinions on promoting IRET	Regulating transaction types and prices
2011	Opinions on strengthening the supervision of interregional electricity transactions	Regulating IRET principle, organization, transmission cost, network loss and information disclosure
2012	IRET rules (Trial)	Protecting the legitimate rights and interests of the transaction subject
2015	Notice on improving the IRET price formation mechanism	Making the request of interregional power transmission and electricity price formation mechanism
2017	Detail rules for monthly IRET in South region (trail)	Designing the detail rules on multiple short-term transaction types as well as the requirements of transaction organization, security check, transaction measurement, and settlement.
2018	Detail rules for mid- and long-term IRET in South region (trail)	Designing the detail rules on multiple mid- and long-term transaction types as well as the requirements of transaction organization and regulations.
	Measures on regulating IRET in South region (trail)	Regulating the entities in IRET that include traders, organizers, operators, and power grids.
2020	Policies on the price of electricity transmission among regions Policies on the price of electricity transmission among provinces	Approving the price formation mechanism of electricity transmission in regional/provincial grids, including that of IRET

Note: Policies from 2005-2015 are largely based on the work of Zeng et al. (2016), and we further updated the polices to 2020. *IRET* is the abbreviation of "**I**nter-**R**egional **E**lectricity **T**rade".

5.3. Policies to unlock flexibility on demand-side

The utilization of DR to provide flexibility requires appropriate market designs to send proper economic signals to incentivize the provision of DR in the short run and the investment in DR capability in the long run. In many countries such as the US and the UK, the authorities have introduced electricity market structures designed to encourage electricity users to take part in DR markets, and this may provide useful lessons for China. DR units can participate in either the wholesale electricity market or the retail market.

In the wholesale market, the DR is eligible to participate in capacity markets, energy markets, and ancillary service markets. Capacity markets are usually used to pay suppliers for being able to meet peak demand, but DR customers may also participate by being able to reduce electricity use when required, see Bowring (2013) and PJM (2019). Ancillary service markets provide services such as frequency regulation and operating reserves, both spinning reserves and non-spinning reserves. Load-serving entities (LSEs) and electric distribution companies (EDCs) are registered in the wholesale market as curtailment service providers (CSPs). CSPs are aggregators that identify curtailable load, enroll customers, and manage curtailment events[17]. Individual customers who are too small to participate on their own could provide DR through the CSPs. Examples of such customers include schools, commercial chains, or groups of residential customers. By accumulating small customers, CSPs could increase the participation of DR units in the wholesale market.

Customers can also participate individually in the DR retail markets. In the retail market, there are two categories of DR programs: price-based and incentive-based programs. In price-based programs, there is dynamic pricing where retail prices may change frequently (over hours or minutes) to provide signals for the DR resource to change consumption in order to better reflect system costs. Typical price-based programs include time-of-use pricing, real-time pricing, and critical peak pricing (FERC, 2015). Participants in such DR programs benefit by saving on their electricity bills. In incentive-based programs, DR resources usually can be controlled directly by system operators for a specified period of time, at times that are not announced beforehand. This includes direct load control of residential appliances or industrial customer equipment. In some programs DR participants are allowed a certain period of time to respond to requests to increase or decrease their power consumption. As return for participating in these programs, the owners of these DR resources receive payments that that depend on the response time and duration of response. Typical programs include direct load control and interruptible programs.

In the context of China, the current lack of power spot markets and lack of

[17] A description of CSP's participating in PJM's demand response program is given in: https://www.pjm.com/markets-and-operations/demand-response/csps (accessed at April-20, 2021).

incentives are the main barriers to the implementation of DR. First, customers that are too small to participate on their own need to sell their DR capacities in wholesale market, but the wholesale market has not been well-established in China with institutions such as Curtailment Services Providers. Second, the DR markets have not been widely set up to encourage participation due to lack of funds, and there are few incentives for DR providers. The benefits of providing DR resources often flow to multiple participants, presenting a challenge to allocating and collecting payments. For example, demand reductions from DR resources could provide benefits to intermittent generators when the wind is not blowing or the sun is not shining, and could also contribute to more efficient use of the distribution network by reducing substation congestion (Strbac, 2008). Establishing a viable business for addressing the challenge is not straightforward. The current electricity market mechanisms in China are limited (e.g., there are only some pilot spot markets) and present a significant barrier to providing flexibility through DR markets.

5.3. Policies to unlock flexibility from energy storage

Around the world, the development of energy storage in different countries is divergent, largely depending on their electricity markets and related policies. As the role of energy storage in helping to create a more flexible and reliable grid system become clear, some commercial energy storage projects have developed diverse business models, and falling storage prices spur strong growth in the still small commercial storage market.

Pumped hydro storage is still the dominant type of energy storage in China, but the installed capacity of electrochemical energy storage is growing rapidly due to the remarkable improvement in both technology and economic performance in recent years. Since July 2020, a new standard and technical guidance for China's grid system has come into force, i.e., the 'Code on Security and Stability for Power System (GB38755-2019)', replacing the old standard (DL755-2001) which the grid had been following for two decades.[18] It specifies that in order to increase the penetration of renewable energy

[18] http://www.xinhuanet.com/power/2020-01/08/c_1210429744.htm (assessed at Aug-15, 2021)

resources, in addition to fully excavating the flexibility of conventional power units (for example, thermal power, hydropower and nuclear), various flexible-regulation sources including gas-fired power stations, pumped hydro storage, and other energy storage types should be configured when necessary.

Market mechanisms are critical to the development of energy storage. However, due to the incomplete forward electricity market in China, the country's generation dispatch is primarily determined by the annual generation planning carried out by provincial governments. When electricity supplies face tight periods, regulation measures such as electricity rationing is often used to balance the power system, rather than encouraging more flexible resources such as energy storage to provide the flexibility through market measures. What is more, the prices of electricity set by the government cannot timely reflect the scarcity of available power generation units, and therefore cannot reflect the value of flexible resources such as energy storage. In addition, as power market reforms continue to develop, the ancillary services market has attracted increasing attention as it plays an important role in supporting energy storage application. However, China's ancillary services market mechanism has yet to be fully functional.

As Chinas renewable power capacity continues to increase, greater integration of flexible resources would be needed for the power system regulation. Currently with the large-scale grid integration of renewable energy, conventional power units are required to provide more ancillary services to the grid, resulting in a significant decline in their annual utilization hours. What is more, the costs of increased ancillary services are covered by the generation-side, greatly undermining the profitability of these conventional power units. In addition, as the share of installed capacity of fossil fuel to decrease further, conventional power units would not be able to provide all the ancillary services required by the grid system. Therefore, improving ancillary services market design and encouraging energy storage to participate in the ancillary services market through reasonable compensation is crucial for supporting renewable integration and grid stability.

6. Conclusion and policy implications

Climate change is arguably one of the most severe challenges of our times. As a response to this challenge, the Chinese government has announced the ambitious goals of peaking its carbon emissions before 2030 and achieving carbon neutrality by 2060. To fulfil the long-term pledge of carbon neutrality, it is essential to electrify final energy use and penetrate more renewable energy generation, both of which are associated with an increased need for flexibility in the power system to realize the real-time balancing. Our paper focuses on China's flexibility challenge in achieving carbon neutrality and discusses the options to improve power system flexibility, including power plants, power grids, demand-response measures, and storage technologies. Particular attention is paid to the associated policies and regulations, especially power market reform in China, that are considered to unlock the flexibility potentials of such sources.

In the overview, we showed that flexibility is going to be one of the serious challenges for China during the pathway of achieving carbon neutrality for two reasons: (a) the huge flexibility needs that are associated with its fast shifting to renewables as well as the large-scale electrification in final energy use; (b) the economic and social consequences if the energy system fails to provide sufficient flexibility. We therefore explored the options to improve flexibility and the challenges that have to be overcome.

The flexibility topic will likely draw even more interest in the years to come as electricity and renewable energy are expected to play central roles in addressing the global concerns on climate change. In the context of China, we observed that its unique dual-track with both plan and market in the power system makes it very challenging to operate in a flexible manner. Especially, the energy/electricity prices that are highly regulated or even directly determined by the government disincentivized the flexibility options from almost all sources, including power plants, grids, demand-response measures, and storage technologies.

Precisely because of it, we are kind of cautiously optimistic about China's ability to unlock flexibility in the near future so as to support more renewable energy penetration. With China's ongoing market-oriented reforms especially in the electricity market, the market-based measures could play a critical role in addressing the challenges of flexibility. Besides, in a country like China with a large territory, strengthening the interconnections across regions could also provide enormous potential in flexibility. This includes not only the investment in grid flexibility (e.g., smart digital infrastructure) to increase reliability and security, but also reducing political barriers of local protectionism.

Reference

[1] Agora. (2017). Flexibility in thermal power plants –With a focus on existing coal-fired power plants. Rep., Agora, Berlin, Ger.

[2] Antweiler, W. (2016). Cross-border trade in electricity. *Journal of International Economics*, 101, 42-51.

[3] Bass, R. J., Malalasekera, W., Willmot, P., & Versteeg, H. K. (2011). The impact of variable demand upon the performance of a combined cycle gas turbine (CCGT) power plant. *Energy*, 36(4), 1956-1965.

[4] Bowring, J. (2013). Capacity markets in PJM. Economics of Energy & Environmental Policy, 2(2), 47-64.

[5] British Petroleum (2020). Statistical review of world energy 2020 workbook.

[6] China National Renewable Energy Centre. (2018). China Renewable Energy Outlook 2018. Beijing.

[7] Das, C. K., Bass, O., Kothapalli, G., Mahmoud, T. S., & Habibi, D. (2018). Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. *Renewable and Sustainable Energy Reviews*, 91, 1205-1230.

[8] Energy Transitions Commission (ETC) and Rocky Mountain Institute (RMI). (2021). China zero carbon electricity growth in the 2020s: A vital step toward carbon neutrality. Available from: https://www.energy-transitions.org/publications/china-zero-carbon/ (accessed at April-20, 2021).

[9] FERC. (2015). Available from: https://www.ferc.gov/industries-data/electric/power-sales-and-markets/demand-response/reports-demand-response-and (accessed at April-4, 2021. The page was last updated on December 22, 2020).

[10] Fridgen, G., Keller, R., Thimmel, M., & Wederhake, L. (2017). Shifting load through space–The economics of spatial demand side management using distributed data centers. *Energy Policy*, 109, 400-413.

[11] Gonzalez-Salazar, M. A., Kirsten, T., & Prchlik, L. (2018). Review of the operational flexibility and emissions of gas-and coal-fired power plants in a future with growing renewables. *Renewable and Sustainable Energy Reviews*, 82, 1497-1513.

[12] Guo, H., Davidson, M. R., Chen, Q., Zhang, D., Jiang, N., Xia, Q., ... & Zhang, X. (2020). Power market reform in China: Motivations, progress, and recommendations. *Energy Policy*, 145, 111717.

[13] Heffron, R., Körner, M. F., Wagner, J., Weibelzahl, M., & Fridgen, G. (2020). Industrial

demand-side flexibility: A key element of a just energy transition and industrial development. *Applied Energy*, 269, 115026.

[14] Henze, J., Siefert, M., Bremicker-Trübelhorn, S., Asanalieva, N., & Sick, B. (2020). Probabilistic upscaling and aggregation of wind power forecasts. *Energy, Sustainability and Society*, 10(1), 1-19.

[15] Hu, J., Harmsen, R., Crijns-Graus, W., & Worrell, E. (2019). Geographical optimization of variable renewable energy capacity in China using modern portfolio theory. *Applied Energy*, 253, 113614.

[16] International Energy Agency. (2020). World Energy Outlook 2020. Paris, France.

[17] IRENA. (2018). Power system flexibility for the energy transition: Part 1, Overview for policy makers. Abu Dhabi.

[18] Keppler, J. H., & Cometto, M. (2012). Nuclear energy and renewables: system effects in low-carbon electricity systems. Nuclear Energy Agency, OECD, Paris, France.

[19] Li, J., & Lin, B. (2017). Environmental impact of electricity relocation: a quasi-natural experiment from interregional electricity transmission. *Environmental Impact Assessment Review*, 66, 151-161.

[20] Li, J., Zhou, S., Wei, W., Qi, J., Li, Y., Chen, B., ... & Liang, S. (2020). China's retrofitting measures in coal-fired power plants bring significant mercury-related health benefits. *One Earth*, 3(6), 777-787.

[21] Li, J., & Huang, J. (2020). The expansion of China's solar energy: Challenges and policy options. *Renewable and Sustainable Energy Reviews*, 132, 110002.

[22] Liu, H., & Mauzerall, D. L. (2020). Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region. *Energy Economics*, 90, 104844.

[23] Lugovoy, O., Gao, S., Gao, J., & Jiang, K. (2021). Feasibility study of China's electric power sector transition to zero emissions by 2050. *Energy Economics*, 96, 105176.

[24] Lund, P. D., Lindgren, J., Mikkola, J., & Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, 45, 785-807.

[25] Martinot, E. (2016). Grid integration of renewable energy: flexibility, innovation, and experience. *Annual Review of Environment and Resources*, 41, 223-251.

[26] NREL. (2019). Flexibility in 21st Century Power Systems.

[27] Nuclear Energy Agency. (2011). Technical and Economic Aspects of Load Following with Nuclear Power Plants. Available from: https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf (assessed at May-11, 2021).

[28] PJM. (2019). Markets at a Glance. Available from: https://learn.pjm.com/-/media/about-pjm/newsroom/fact-sheets/understanding-the-difference-between-pjms-markets-fact-sheet.ashx (assessed at April-20, 2021).

[29] Samad, H. A., & Zhang, F. (2016). Benefits of electrification and the role of reliability: evidence from India. World Bank Policy Research Working Paper, (7889).

[30] Strbac, G. (2008). Demand side management: Benefits and challenges. *Energy Policy*, 36(12), 4419-4426.

[31] Su, W. (2021). The interview with Su Wei, deputy Secretary-General of the NDRC (in Chinese). Available from: https://m.21jingji.com/article/20210423/herald/eba20048ee8c1401cb5e9e093e8aa5ee.html (accessed at July-26, 2021).

[32] U.S. Department of Energy. (2018). Flexible Combined Heat and Power (CHP) Systems. Available from: https://www.energy.gov/sites/default/files/2018/01/f47/Flexible%20CHP%20Comms_01.18.18_compliant.pdf (accessed at May-30, 2021).

[33] U.S. Department of Energy. (2019). 2018 Wind Technologies Market Report. Available from: https://www.energy.gov/sites/prod/files/2019/08/f65/2018%20Wind%20Technologies%20Market%20Report%20FINAL.pdf (accessed at July-25, 2021).

[34] Xi, J. (2021). For Man and Nature: Building a Community of Life Together. Available from: http://www.xinhuanet.com/english/2021-04/22/c_139899289.htm (accessed at July-26, 2021).

[35] Yao, L., Yang, B., Cui, H., Zhuang, J., Ye, J., & Xue, J. (2016). Challenges and progresses of energy storage technology and its application in power systems. *Journal of Modern Power Systems and Clean Energy*, 4(4), 519-528.

[36] Zeng, M., Peng, L., Fan, Q., & Zhang, Y. (2016). Trans-regional electricity transmission in China: Status, issues and strategies. *Renewable and Sustainable Energy Reviews*, 66, 572-583.