Renewable Electricity Development in China: Policies, Performance, and Challenges

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Introduction

In 2018, China consumed 3.27 billion tons of oil-equivalent primary energy, accounting for 23.6 percent of the world's total primary energy consumption. China's energy intensity (energy use per US$10,000 of GDP) has continuously decreased since the 1980s, and it had energy intensity of 2.41 tons of oil in 2018; however, this was still 2.97 times Germany's energy intensity, 2.14 times US energy intensity, and 1.49 times the world's average energy intensity.[1] Constrained by its resource endowment, China relies heavily on coal in its energy use. In fact, China consumed 1.9 billion oil-equivalent tons of coal in 2018, accounting for 50 percent of world coal consumption, and coal consumption accounted for 58 percent of China's primary energy consumption, which is much higher than the global average of 27 percent.[2] This large-scale coal consumption has led not only to the country's increasingly serious air pollution problems but also to its rapidly increasing carbon emissions. In 2018, China's CO_2 emissions were 1.83 times higher than those of the United States (formerly the world's largest emitter) and accounted for 27.8 percent of annual global CO_2 emissions. China's current and future energy development plans call for a substantial reduction of coal in its primary energy consumption as well as an increase in the efficiency of coal use.

The Renewable Energy Law, issued in January 2006, launched China's rapid expansion of wind and solar photovoltaic (PV) power generation and the growth of the sector's manufacturing industries, which supply these technologies worldwide. The law created a renewable

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[1]Unless stated otherwise, the data presented in this article on coal consumption, primary energy consumption, total power generation, wind and photovoltaic power generation capacity and generation, and CO_2 emissions are from British Petroleum (2020). The GDP data are from the World Bank's (2021) World Development Indicators.
[2]Half of China's coal consumption is for thermal power. China's total coal-fired unit-installed capacity is nearly 1 billion kilowatts, and 75 percent of total electricity comes from coal-fired power generation.

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energy development fund (funded through a renewable price surcharge on industrial and commercial electricity users) to subsidize renewable energy power generation and mandated that electric utilities procure renewable energy power generation. As a result, between 2006 and 2018, China's total installed capacity of wind power increased from 2.07 to 185 GW, and its total installed capacity of solar PV power increased from 0.16 to 175 GW.[3] In fact, China became the country with the world's largest installed wind capacity in 2011 and the world's largest installed solar PV capacity in 2015. In 2018, China accounted for 35 and 33 percent of global accumulated installed capacity of wind and solar PV power, respectively.

China's renewable energy policy has led to two major problems. First, although the surcharge has been increased five times since 2006 to finance the country's rapid renewable capacity expansion,[4] the surcharge earnings have not kept pace with the increasing demand for subsidies, and the gap between the surcharge earnings and the subsidies continues to grow. In fact, this subsidy debt (the amount the government owes renewables investors) grew from ¥19 billion (approximately US$2.9 billion) at the end of 2014 to ¥293 billion (approximately US$45 billion) by the end of 2019 (Bloomberg 2020). Given the continued rapid growth in installed wind and solar power generation capacity, this subsidy debt is likely to continue to increase unless there is a policy reform. Second, according to the National Energy Administration (NEA; NEA 2018a), the national average curtailment rate (the ratio of curtailed electricity to total electricity generation) is high for wind and solar, reaching record highs of 17 and 10.3 percent, respectively, in 2016. Although the national average rate of wind and solar curtailment decreased to 7 and 3 percent, respectively, in 2018, it was still a serious problem in China's northwestern provinces (NEA 2019a).[5] As we will discuss, these high curtailment rates have been caused by several factors, including regional economic downturns, weak demand for electricity, stagnant power transmission grid construction, local government protection of local economies, and interprovincial power market barriers.

In this article, which is part of a symposium on China and the Environment,[6] we review China's wind and solar PV development and policies, examine why and how the subsidy debt and curtailment problems have arisen, and discuss additional policy reforms that are needed to support sustainable long-term renewable electricity development in China. We divide the history of China's renewable electricity development into three stages. First, we discuss the early stage of development (before 2009 for wind and before 2011 for solar PV power), when the subsidies were limited. Then we examine the second stage, when there was large-scale development of renewables through large subsidies (2009–2017 for wind and 2011–2017 for solar PV power). Finally, we discuss the most recent stage (after May 2018) of renewables development, when the government's policies generally shifted to competitive auctions to promote wind and solar PV power generation. We conclude with a summary and brief discussion of additional policy reforms to promote the future development of renewable energy in China.

[3]See figure A1.
[4]The surcharge was increased from 0.1 to 1.9 Chinese cents per kWh between 2006 and 2018. The equivalent of ¥1 is 100 Chinese cents. At the end of 2020, the exchange rate was about ¥6.5 per US$1.
[5]For example, in 2018, the wind power curtailment rates in Gansu and Xinjiang were 19 and 23 percent, respectively, and the solar curtailment rates in Gansu and Xinjiang were 10 and 16 percent, respectively (NEA 2019a).
[6]The other articles are by Greenstone et al. (2021), who examine the literature on the impacts of China's recent policies to improve air and water quality, and Karplus, Zhang, and Zhao (2021), who discuss China's system of environmental regulation.

Early Development of Renewable Electricity in China

In the first stage of renewable electricity development in China, renewable electricity projects were promoted mainly through policy experiments such as concession bidding. Wind power development took off earlier than solar PV power development because its generation cost was much lower at the time. Although solar PV power generation was slow to develop in China during this stage, its solar PV manufacturing developed rapidly because of the country's global manufacturing competitiveness and the increasing global demand for solar PV panels.

Early Development of Wind Power

Wind power development in China started in the 1990s, when the state grid company (State Grid), which owned all power plants, used foreign aid to buy imported equipment and carried out some small-scale experimental wind power generation projects. At the time, the price of wind-powered electricity either was the same as the price of coal-fired thermal electricity or was administratively set by a local price bureau based on the generation cost.

Electricity sector reforms, 2002

In 2002, the central government implemented a set of electricity sector reforms aimed at decentralizing the electricity market. As part of these reforms, the generation side of the sector was separated from the transmission and distribution grid side, with power generation enterprises converted into independent market players. The transmission and distribution side was split into two large central state-owned grid companies, State Grid Corporation of China and China Southern Power Grid Company, and one local grid company, the Inner Mongolia Grid Company. Following the reforms, grid companies were required to buy electricity from power generators at prices set by the central government. Beginning in 2003, the Chinese government implemented a hybrid pricing scheme for wind power generation that introduced market pricing through "concession bidding" (see below) for large-scale wind power projects (100 MW or more) and maintained the original price-setting policy (i.e., tariffs were administratively set) on a case-by-case basis for smaller wind power projects. As we will discuss below, this pricing scheme encouraged the steady development of wind power during the 2003–2009 period.

Concession bidding

Concession bidding is a public bidding process convened by the government for planned renewable energy projects, with the projects' electricity tariffs included as part of the bid.[7] Between 2003 and 2007, China held five concession biddings for wind power projects with a total installed capacity of 3.3 GW, which accounted for 56 percent of cumulative installed wind power capacity at the end of 2007. The tariffs for the concession bidding projects were generally lower than the wind power tariff set by the government for other wind projects during this

[7]Once the government announced concession bidding, power generation enterprises bid for the wind projects. Generally, the enterprises submitting the lowest tariffs were awarded the wind power concessions. The awarded wind power concession was subsidized based on the bidding tariff for the first 30,000 generation hours.

period, with the lowest tariff being close to the price of thermal power. The concession bidding process helped to both reveal the power costs (thus reducing the financial subsidies required for wind power) and allocate scarce project resources to the most efficient enterprises.

Early Development of Solar PV Power

Although the levelized cost of solar PV power has declined significantly, it is still high relative to that of wind power (International Renewable Energy Agency 2020).[8] Given the higher production cost of solar PV power generation, it was more attractive and efficient to use the limited government budget to subsidize wind power generation rather than solar PV electricity during the early stages of China's renewable electricity development. Thus, as with the early development of wind power, before 2011, the government adopted a more gradual approach to solar PV power generation by developing some small experimental solar PV projects through concession bidding. China's first PV concession bidding was conducted in 2009, and concession bidding for 13 PV power station projects was conducted in 2010. However, by the end of 2010, the total installed capacity of PV power was only 1,022 MW, compared with total installed wind power capacity of 29,633 MW (British Petroleum 2020).

In contrast to the slow development of solar PV electricity generation, China's PV manufacturing industry has grown rapidly since the early 2000s because of strong global demand for PV equipment (stimulated by subsidies in major developed countries) and China's industrial manufacturing competitiveness. China's solar PV battery production reached 1.09 GW in 2007, accounting for nearly one-third of the global market, and China became the world's largest producer of PV panels in that year (Intelligence Research Group 2016). In 2009, during the global financial crisis, China's PV panel production continued to expand, reaching 4.92 GW and accounting for nearly 44 percent of global production (Intelligence Research Group 2016). In 2010, China's PV panel production doubled to 10 GW, accounting for about 50 percent of global production (Intelligence Research Group 2016).

In February 2011, Germany, which accounted for more than 40 percent of the world's new PV installed capacity (British Petroleum 2020), announced that it would lower its solar PV tariff, thus slashing its renewable subsidies. This triggered a dramatic drop in the global price for solar PV components and caused many PV manufacturers around the world to close down (Hargreaves 2011). China's solar PV producers faced a debt crisis, and some of the largest solar PV panel producers in the world at the time, such as Suntech Power, LDK Solar, and Yingli Solar, entered or approached bankruptcy a few years later.

Large-Scale Renewables Development and High Subsidies

In 2007, the central government released the "Renewable Energy Medium- and Long-Term Development Plan," which set a goal of installing 30 GW of wind power capacity and 1.8 GW of solar PV power capacity by 2020 (NEA 2007). However, in 2007, the electricity generated by wind and solar PV power was negligible (only about 3.7 and 0.1 TWh, respectively, compared

[8] Levelized cost is a measure of the average net present cost of electricity generation for a power project over its lifetime.

with China's total electricity generation of 3,282 TWh), and the main non–fossil fuel energy source—hydropower—accounted for only 5.1 percent of total energy consumption (British Petroleum 2020). Moreover, before the 2009 Copenhagen Climate Change Conference, China set a minimum target of 15 percent for its share of nonfossil energy in overall energy consumption by 2020 and a goal of reducing the amount of greenhouse gases emitted per unit of GDP by 40–45 percent. Thus, the goals set for wind power and solar PV power in 2007 were too low to meet the 2020 targets, and the government adopted more aggressive subsidy policies during the second stage.

More specifically, given the need to achieve the 2020 target for renewable energy development, China shifted its renewable pricing policy from concession bidding to a fixed feed-in tariff for wind power (in 2009) and solar PV power (in 2011).[9] This policy change led to large-scale renewable development during the second stage. Indeed, following the introduction of the fixed feed-in tariff policy, the cumulative installed capacity for both wind and solar power grew dramatically, from 8.4 GW in 2008 to 185 GW in 2018 for wind and from 1 GW in 2010 to 175 GW in 2018 for solar.

Introduction of Fixed Feed-In Tariff Subsidies for Wind and Solar

To promote more rapid growth of wind power capacity in China, in July 2009, the National Development and Reform Commission (NDRC)[10] abolished the concession bidding system and introduced fixed feed-in tariffs for onshore wind power. Under the pricing scheme, electric utilities (i.e., the state-owned grid companies) are mandated to purchase electricity from renewable electricity producers at the local coal-fired thermal electricity price, and the central government pays the renewable electricity producers the difference between the fixed feed-in tariff and the coal-fired thermal electricity price. On the basis of the abundance of wind energy resources, the NDRC set four fixed feed-in tariffs for four respective wind resource zones, with the tariffs being much higher than either the previous concession bidding price or the local (lower) coal-fired thermal electricity price.[11] The plan was for newly installed wind power projects to be subsidized under the fixed feed-in tariff for 20 years. The fixed feed-in tariffs for wind power were lowered slightly (by ¥0.02 per kWh) in both 2014 and 2015.

Partly to address the excess solar PV panel manufacturing capacity crisis, in July 2011, the NDRC introduced a fixed feed-in tariff subsidy policy for solar PV projects. The solar PV power fixed tariff was much higher than the fixed tariffs for wind-specific electricity.[12] In 2013, on the basis of China's solar radiation resources, NDRC identified three solar resource zones

[9] Fixed feed-in tariffs are fixed electricity prices paid to renewable electricity producers for each unit of renewable electricity produced and incorporated into the electricity grid.

[10] The NDRC is the most important macroeconomic management agency under the State Council, which is the Chinese government's top administrative body.

[11] In 2009, the wind power fixed tariffs were ¥0.51 per kWh, ¥0.54 per kWh, ¥0.58 per kWh, and ¥0.61 per kWh in the four respective wind resource zones. In contrast, the local thermal electricity price was between ¥0.3 and ¥0.4 per kWh.

[12] More specifically, it was stipulated that PV projects completed before the end of 2011 would receive a fixed feed-in tariff of ¥1.15 per kWh, while PV projects completed after 2011 would receive a fixed feed-in tariff of ¥1 per kWh (NDRC 2011). Both tariffs were significantly higher than the fixed feed-in tariff for wind power.

and set three different fixed feed-in tariffs for PV projects developed in the three zones. Although the solar PV tariffs were lowered in 2013, 2016, 2017, and 2018, the fixed feed-in tariffs for PV projects continued to be significantly higher than the wind tariffs, which made solar PV development more costly than wind development. Some provinces introduced additional local PV project subsidies to support the development of their provincial PV manufacturing industries.

High Renewable Energy Subsidies Led to Overinvestment and Subsidy Debt

Global progress in the development of renewable energy technologies and increased competition in wind turbine and solar PV manufacturing (supported in part by renewable subsidies) have led to a significant decrease in the cost of wind and solar PV power generation throughout the world. In fact, during the 2010–2018 period, the levelized cost of onshore wind power, which includes the lifetime cost of building, operating, and financing, was reduced, on average, by 34 percent globally, while the levelized cost of solar PV power was reduced, on average, by 77 percent globally (International Renewable Energy Agency 2019). However, China's wind power and solar PV power feed-in tariffs were not adjusted quickly enough to reflect these declining costs. For example, between 2009 and May 2018,[13] wind power fixed feed-in tariffs were adjusted only three times, resulting in reductions in the four wind resource zones that ranged from 6.6 to 21.6 percent (NDRC 2014, 2015b, 2016). Between 2011 and 2018, solar PV power fixed feed-in tariffs were adjusted only four times, resulting in reductions in the three solar resource zones that ranged from 34.8 to 52.1 percent (NDRC 2013, 2015b, 2016, 2017). The slow adjustment of these tariffs resulted in excessive subsidies for renewables, which, together with market forces and local government efforts to promote local renewable energy manufacturing industries, stimulated overinvestment in wind and solar power in China.[14]

The high subsidy also provided incentives to local municipal governments to stimulate investment in wind and solar PV power stations, especially in poorer provinces seeking to boost GDP growth. Historically, local Chinese officials have been evaluated—and their promotions and incomes determined—by the upper-level government on the basis of economic growth. Because the development of wind farms and PV stations stimulates capital investment and the development of upstream equipment and parts manufacturing, wind power and PV generation was viewed as a lucrative opportunity for local economic growth. As long as local governments could obtain a project permit from the NEA, they could stimulate investment in their jurisdiction without incurring any financial costs. Thus, local municipal governments focused more on project construction than on whether there was sufficient demand or grid connection for the power from these new installations. Several studies (e.g., Garcia 2013; Karplus, Davidson, and Kahrl 2017; Andrews-Speed and Zhang 2019; Qi et al. 2019) have analyzed this

[13] As we will discuss, the auction policy was initiated in May 2018.

[14] This overinvestment even encouraged the emergence of a black market for building permits for solar PV projects. The NEA sets an annual quota for new wind and solar PV projects for each province, and investors must apply to local governments for building permits for these projects. In our field research, we found that in 2016, a permit to build a 50-MW solar PV project could be sold on the black market for as much as ¥20 million (around US$3.1 million).

role of the political economy in renewable energy development in China. Indeed, Qi et al. (2019) showed how local municipal governments in two cities with abundant wind resources, Jiuquan (in Gansu Province) and Tongyu (in Jilin Province), aggressively pushed the development of wind power.

The overinvestment in wind and solar development, driven to a large extent by the high subsidies, also imposed tremendous financial pressures on the central government because of subsidy debt. Moreover, following the 2002 power sector reforms, the generation side of the power market was deregulated, but the transition, distribution, and retail sides continued to be regulated (and monopolized) by the two central state-owned grid companies. Thus, when wind and solar PV power generators entered the market, they faced a number of barriers that triggered significant solar and wind power curtailment. In the remainder of this section, we briefly discuss the challenge of subsidy debt and then examine the nature and causes of the high rate of curtailment of renewable electricity during the second stage of China's renewable electricity development. We also discuss the economics underlying the continued investment in renewables capacity (despite the problem of curtailment) during this period and a major reform aimed at deregulating the electricity system.

Challenge of Subsidy Debt

Annual revenues from the renewable energy fees levied on industrial and commercial customers have not met the demand for subsidies for wind and solar PV power. As noted above, this has led to a sharp rise in the subsidy debt, from ¥19 billion (approximately US$2.9 billion) at the end of 2014 to ¥293 billion (approximately US$45 billion) in 2019, and this debt continues to rise. It is also important to note that the revenue side (i.e., renewable energy fees) depends on industrial and commercial sector activity, which is vulnerable to business cycle fluctuations. Because each renewable project will be subsidized for 20 years, even by our conservative estimates, China is expected to spend more than ¥2 trillion (around US$310 billion) on subsidies for existing wind and solar PV power projects.

High Rate of Curtailment for Wind and Solar PV Power

China's high curtailment rate for wind and solar PV power during the 2009–2017 period was due to both technical barriers, particularly insufficient power transmission capacity for wind and solar PV power, and institutional barriers, particularly the country's interprovincial electricity markets.

Insufficient power transmission capacity for wind and solar PV power

As a result of the power grid being a natural monopoly, local transmission and distribution networks in China have been financed and constructed mainly by local power grid companies (which are owned by State Grid, Southern Power Grid, or Inner Mongolia Grid) that bear the corresponding costs. Provinces that are rich in wind and solar resources and have low project construction costs are generally concentrated in China's "Three North" region (the north, northwest, and northeast of China), which is thousands of miles away from the electricity demand centers in the east and south of China. This means that transmission line construction can be very expensive.[15] Moreover, because of the problem of the intermittency of wind and solar PV power, higher penetration of wind and solar PV power also increases system-wide costs, and these costs are fully borne by the grid companies.[16] However, under the fixed feed-in tariff pricing scheme, the grid companies pay the same price whether they purchase electricity that is generated from the intermittent renewable power or from the stable coal-fired thermal power. Thus, the grid companies have little incentive to build transmission channels and to purchase renewable electricity; they do so only because the Renewable Energy Law mandates that grid companies provide grid connection for all wind and solar PV facilities and purchase all of the renewable electricity that is generated. Finally, even when the grid companies have planned to build the transmission lines for wind and solar PV projects, it generally takes 2 or 3 years to complete a new transmission project, which includes project planning, feasibility studies, evaluation, approval, land acquisition and demolition, and construction.

However, developers of individual wind power and solar PV power projects do not need to consider the cost of transmission channels, and these projects can usually be completed within a few months. To develop projects in locations with good wind or solar resources, investors will complete the projects first and then try to "force" grid companies to construct transmission lines to meet the needs of these projects. Thus, the supply and demand sides of the transmission line for wind and solar PV power face opposing incentives. This has led to insufficient transmission capacity for wind and solar PV, especially because of the rapid increase in wind and solar PV capacity during this period (which resulted from the large subsidy for renewables).

The insufficient transmission capacity for wind and solar PV power is basically a technical problem that would resolve itself over time. However, the interprovincial electricity market is an institutional barrier that poses an even greater challenge to the development of renewable electricity in China.

Interprovincial electricity market barriers

Electricity production and demand need to be balanced in real time. However, because electricity storage is not yet cost competitive at scale, the only option for addressing the intermittency and instability problem is through grid system dispatching (i.e., continuously adjusting the thermal power real-time output within the power grid to meet electricity demand). This means that large-scale wind and solar PV power projects need to be supported by a large power grid and large electricity markets because the larger the radius of the grid and electricity

[15] At the end of 2019, State Grid had built 19 ultra-high-voltage (UHV) power lines, which enable long-haul transmission with little loss of power (State Grid 2021). It was widely expected that the construction of these UHV lines would help transmit wind and solar PV power from the Three North region to the demand center—the east and south of China. However, the results have been disappointing. First, because of intermittency, wind and solar PV power had to be combined with coal power to be transmitted through UHV lines, which reduces the environmental benefits of wind and solar PV power generation. Second, the UHV lines cannot address the problem of interprovincial barriers, which, as we will discuss, are a critical challenge for integrating renewables into the power grid. Thus, the share of wind and solar PV power in all-source electricity transmitted by UHV lines continues to be negligible (Downie 2018).

[16] Wind and solar PV power generation is naturally intermittent and variable and can generate electricity only when there is wind or sunshine. As such, because electricity storage technology is not yet mature, conventional and stable electricity resources, such as thermal electricity, must often be dispatched to solve the intermittency problem; this imposes an additional cost on the grid system and conventional electricity generators.

market, the more wind and PV power there is that can be dispatched and therefore consumed.[17] However, in China, electricity demand and supply are not balanced nationally; they are balanced mainly within each province, with provincial governments fully controlling the planning of power generation and allocation within their jurisdictions. Indeed, China's electricity market is separated into more than 30 independent provincial electricity markets, which means that wind and PV power must be consumed within isolated provincial electricity markets. This system means that interprovincial electricity market barriers to wind and solar PV power are inevitable.

Each year, on the basis of an annual forecast of power demand, the provincial government develops an operating plan (called an Annual Power Generation Plan) for the production of electric power within its jurisdiction. This plan determines the annual utilization hours for different power units. More specifically, when allocating generation rights, provincial governments generally follow a "fair allocation" rule, under which generators in a given class (e.g., coal-fired power plants) are allocated the same annual utilization hours per unit of generator capacity. This means that the larger a generator's capacity, the more generation rights it receives. Once the Annual Power Generation Plans have been issued by provincial governments, provincial grid companies are responsible for implementing them through monthly and daily dispatch plans. Thus, generation rights and the dispatch order of electricity (i.e., the way available sources of electricity generation are ranked) in China are determined administratively rather than on the basis of marginal cost and economic merit, as is common in most market-based systems.

The annual generation planning process ensures that demand meets supply within each province. Under the current evaluation and promotion system, local provincial governments have an incentive to protect local power generators to maintain provincial tax revenue and employment; thus, they are reluctant to import electricity from other provinces. It is only when generation in a province is not sufficient to meet electricity demand that the provincial government allows the grid companies to import electricity from other provinces. This means that if electricity supply exceeds demand in a province, there may be curtailment of wind and solar PV power unless the province is able to increase its power exports to other provinces. In 2014, total electricity trade across provinces was 679 billion kilowatt hours, accounting for only 11.7 percent of total electricity demand in China (NDRC 2015a), which indicates the limited extent of interprovincial electricity trade at the time.

In sum, China's electricity system, which is heavily administrated by local governments that are evaluated on the basis of local economic performance, encourages local municipal governments to push for investment in wind and solar PV power without considering the potential for curtailment problems. The system also encourages provincial governments to limit imports of electricity from other provinces.[18] Together, these interprovincial electricity market barriers

[17]For example, even Germany would not have been successful in its renewables integration if it were not part of the European grid.

[18]In 2015, China launched a new round of power sector reforms aimed at decentralizing the electricity market by allowing electricity producers to trade directly with electricity users. Before the 2015 reform, all electricity producers had to sell electricity to the grid companies at regulated prices, and then each grid company sold the electricity to different electricity users at regulated prices. However, even after the 2015 electricity sector market reform, interprovincial electricity transactions were still controlled by local provincial governments, and thus interprovincial power transactions remained difficult.

suggest that the political economy of China's governance is an important driver of the curtailment problem.

The curtailment problem in the Three North region

To illustrate the nature and causes of the curtailment problem, we focus here on renewable electricity trends in China's Three North region. To encourage the large-scale development of wind and solar PV power, China's renewable energy subsidies have been particularly generous to those regions with abundant wind and solar resources (i.e., the Three North region), where there has been the greatest difference between the wind and solar PV power fixed feed-in tariffs and thermal power prices. As shown in figure 1, this policy has resulted in large wind and solar PV power projects being installed in the north, northeast, and northwest provinces, where power demand is relatively small (compared with in the coastal provinces) and heavy industries account for a large share of GDP. When electricity demand from heavy industry fell because of the industrial slowdown in 2015 and 2016, excess electricity capacity became a serious challenge for these provinces. On the one hand, installed wind and solar PV capacity continued to grow, but on the other hand, electricity demand shrank in these provinces in 2016. Because of the isolated provincial electricity market system, this resulted in record-high renewable electricity curtailment rates in the Three North region in that year (NEA 2017a, 2017b). Indeed, in 2016, Gansu (northwest province), Xinjiang (northwest province), and Jilin (northeast province) had wind power curtailment rates of 43, 38, and 30 percent, respectively, and the solar PV power curtailment rate also reached record highs of 32.23 and 30.45 percent in Xinjiang and Gansu, respectively (NEA 2017a, 2017b).

To further illustrate the imbalance between installed capacity and electricity demand, we focus on the situation in Gansu Province. The total installed power generation capacity in Gansu Province was 47.22 GW at the end of June 2016; wind and solar PV power together accounted for 40 percent of that total. However, between January and June of 2016, the province's total electricity demand declined by 8.3 percent, to only 57.5 billion kilowatt hours, and the maximum real-time power capacity demand from the provincial power grid company was only

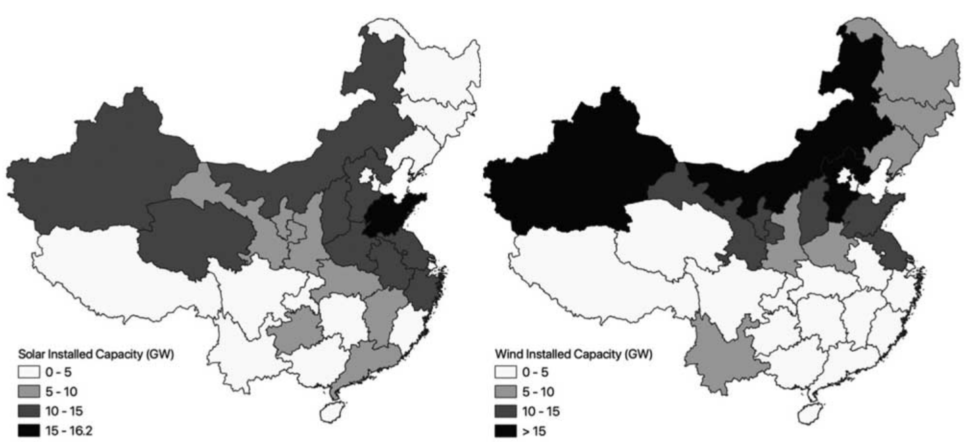

Figure 1 Installed solar PV and wind generation capacity by province (2019). Source: NEA (2020a, 2020b).

12.14 GW. Given the limited ability to export the excess electricity to other provinces, Gansu experienced a severe wind and solar PV power curtailment problem. Unfortunately, even when Gansu's curtailment rate reached 39 percent for wind and 31 percent for solar PV power in 2015, investment in renewables continued, with installed solar PV capacity increasing by 16.7 percent during the first half of 2016. This resulted in a record-high wind and solar curtailment rate in Gansu in 2016. These trends suggest that to address the wind and solar curtailment problem, the system of provincial government control of individual isolated provincial power markets needs to be reformed to create a geographically larger power market.

Economic Rationale for Renewables Curtailment and 2015 Policy Reforms

Given the market, institutional, and transmission constraints and the high curtailment rate of renewable electricity, it is puzzling that investors continued to build wind and solar plants in China's Three North region during this period. In the discussion that follows, we examine the economics underlying this behavior as well as a major reform aimed at deregulating the electricity system.

As noted above, during this stage of China's renewable electricity development, provincial economic authorities and grid companies allocated electricity production quotas (i.e., generation rights) among power generation companies based on their shares of installed capacity. Because of these proportionally distributed generation rights and the fixed feed-in tariff, power firms could not obtain generation rights through market competition; each unit of installed wind and solar PV power capacity was allocated the same number of generation rights. Such a system will eventually lead to a "tragedy of the commons" problem. More specifically, given the limited electricity demand in an individual province (which is like a "commons" for all power generators), any new installed renewable capacity will receive the same average generation rights that are allocated to the existing capacity. This means that as long as there is a high rate of return (generated by the high renewable subsidy) on investing in new installed capacity, renewable energy companies will continue to increase their investment until the economic profit from new projects shrinks to zero.

Although both power prices and production were regulated in China's electricity market during this period, market forces were still at work, but in an unexpected way. China's renewables policy during this period was a combination of a price policy (i.e., fixed feed-in tariffs) and a quantity policy (i.e., mandatory purchase of renewable electricity by grid companies), which were designed to guarantee both the price and sale of renewable electricity production and to encourage wind and solar PV power development. However, when both the price and quantity of the output are guaranteed, companies will make decisions without considering market competition and will seek only to expand their production capacity. Because renewable electricity was oversubsidized under the fixed feed-in tariff policy, it was still possible for renewables investors to earn profits even with the high curtailment rates of their electricity output. Thus, more generous subsidies made renewable investment more profitable, inducing new investment in wind and solar PV power. In addition, given the interprovincial electricity market barriers and the administrative allocation of generation hours, this overinvestment would raise the curtailment rates of wind and solar PV power until the return on newly installed projects reached the breakeven point. That is, because both the price and quantity of renewable electricity are regulated, the market cannot clear; this leads to curtailment, with the curtailment rate replacing the market price as a tool for adjusting market supply, and the more excessive the subsidy, the higher the curtailment rate.

In 2015, the central government launched another major electricity market reform. This reform sought to liberalize the sale of electricity so that grid companies could charge only transmission and distribution fees at the regulated tariff and industrial users would be allowed to purchase electricity directly from electricity producers (rather than only from grid companies at a regulated tariff) through direct bargaining or centralized auctions in the provincial wholesale electricity market. This direct electricity transaction between industry users and electricity producers meant that the price and output quantity (or generation hours) of electricity production would be determined by the competitive market. By reducing the planning power of local provincial governments, the 2015 reform improved the efficiency of electricity production (Li, Xie, and Wang 2019). However, the reform applied only to within-province electricity trading; cross-province electricity trading still had to be approved by the provincial governments.[19] Given the focus of the 2015 market reform, we expect that more provinces will push for direct trading of wind and solar PV power through long-term contracts or spot electricity trading. Then the wind and solar PV power producers will be paid a competitive market trading price plus the fixed subsidy, which means that both the price and quantity of wind and solar PV power will be deregulated.

The Recent Shift to Auction Policies and Adoption of a Renewable Portfolio Standard

The fixed feed-in tariff subsidies for wind and solar PV power have greatly stimulated renewable electricity development in China. In 2018, China's wind and solar PV electricity generation accounted for 5.1 and 2.5 percent, respectively, of the country's total electricity production and 2.5 and 1.2 percent, respectively, of total primary energy consumption (British Petroleum 2020). However, China's high fixed feed-in tariff subsidies are unsustainable. Indeed, as we have discussed, the subsidy debt has grown rapidly, and the generous subsidy has induced overinvestment in renewable generation, which has led to a high curtailment rate. In response to these challenges, as well as to a dramatic reduction in the cost of producing solar and wind power, in May 2018, the central government moved from the (administratively set) fixed feed-in tariff subsidy to a price that is set through an auction (i.e., by the market).[20] The central government still sets the fixed feed-in tariff for wind and solar power, but the tariff is used as a guidance price (i.e., the ceiling price) for the auction.[21] Thus, auctions basically became a price-setting mechanism for the subsidy program. In the remainder of this section, we briefly

[19]In 2019, about 30 percent of China's total electricity was traded through the market; most of this was within-province trading (China Electricity Council 2020). Coal-fired thermal electricity dominated direct market trading (with coal-fired thermal electricity accounting for more than 50 percent of the total trading), and the volume of wind and solar PV power traded in the market continues to be limited.

[20]As we will discuss, the Chinese government first launched an auction pilot program in 2016 and then fully implemented the auction policy in May 2018. During the auction, investors bid on the subsidy amount for each unit of electricity, and the investors proposing the lowest price win the rights to construct the wind and solar PV project.

[21]Moreover, the subsidy for new onshore wind power projects and solar PV power plants is expected to be eliminated completely in 2021 (NEA 2021).

discuss the government's policies and experience with solar PV and wind auctions. We also discuss the introduction of a renewable portfolio standard in 2019.

Solar PV Auctions

China first issued guidance for solar PV power auctions in 2016. More specifically, in May 2016, the NDRC and NEA jointly issued "Guidelines on Improving the Management of the Scale of Photovoltaic Power Generation and Implementing Competitive Mechanism of Project Allocation" (NDRC and NEA 2016), which encouraged provincial energy authorities to allocate subsidy resources through auctions and expanded the quotas of provinces that had significantly lower subsidy levels. The NDRC and NEA initially implemented a pilot program for PV power auctions, called "Top Runner," in September 2017. The electricity price of the second round of Top Runner projects dropped significantly, generally by 15–35 percent, with the lowest price reaching ¥0.45 per kWh.[22] Among the third round of Top Runner projects, the bidding prices in many regions were close to or even lower than the local benchmark price of desulfurized coal power, and grid parity of power generation has been achieved (i.e., the levelized cost of wind and solar PV is less than or equal to the average price of power from the electricity grid).

Encouraged by the success of the pilot program, on May 31, 2018, the NDRC, NEA, and Ministry of Finance jointly issued "Notification on the Construction of Photovoltaic Power Generation Projects in 2018" (also called the "531 deal"), which launched general auctions for PV power plants nationally (NDRC, NEA, and Ministry of Finance 2018). The 531 deal was aimed at improving the competitive mechanism for allocating projects that require state subsidies and reducing the dependence of the solar PV industry on state subsidies. In fact, investment in solar PV collapsed after implementation of the new auction policy, with new installed capacity of solar PV power falling from an all-time high of 53 GW in 2017 to 44 GW in 2018 and 30 GW in 2019.

In 2019, the total capacity of all planned solar PV power projects was 44 GW, with auctioned projects accounting for more than half. The auction mechanism appears to have worked well. In July 2019, the NEA announced that the average bidding price per kWh for solar PV power in 2019 was 8 Chinese cents (around US$0.0123) lower than the guidance price (or ceiling price) for the auction, which suggests that the competitive market is more efficient in revealing the cost of renewable electricity (NEA 2019b). In 2020, the capacity of auctioned projects increased to 26 GW, and the average bidding price dropped from ¥0.436 per kWh in 2019 to ¥0.372 per kWh in 2020 (NEA 2020c).

Wind Power Auctions

In June 2017, the auction of the first set of projects in the wind power pilot program was held, and in May 2018, the NEA issued "Notification of NEA's Relevant Requirements for Management of Wind Power Projects in 2018," which required that competitive price auctions be implemented for new onshore and offshore wind power projects (NEA 2018b). On December 17, 2018, the results of the wind power auctions were released. For example, the Ningxia Provincial Development and Reform Commission announced that the average electricity price

[22] Among the five auction demonstration locations in different provinces, the range of price reductions was between 10 and 44 percent (Shi 2018).

for 28 onshore wind power projects was ¥0.45 per kWh, which was significantly lower than the guidance electricity price for onshore wind power (¥0.49 per kWh). However, the lowest wind power bidding price was ¥0.35 per kWh, about 35 percent higher than the local benchmark price of coal-fired thermal power, suggesting that wind power was still not cost competitive with coal-fired thermal power.

In mid-November 2019, the Ningbo and the Wenzhou Municipal Commission of Development and Reform in Zhejiang Province announced the 2019 bidding results for their offshore wind power projects, which indicated that offshore wind power was still the most expensive renewable electricity source. The published electricity prices for the two offshore wind power project auctions in Ningbo were ¥0.76 per kWh (for the project with installed capacity of 500 MW) and ¥0.765 per kWh (for the project with installed capacity of 300 MW), almost twice the electricity price for onshore wind power (Energy Bureau of Ningbo 2019). The published electricity prices for five offshore wind power project auctions in Wenzhou (with total installed capacity of 950 MW) were ¥0.77 per kWh and ¥0.785 per kWh (Wenzhou Municipal Commission of Development and Reform 2019).

These auction prices indicate that in general, the current cost of renewable electricity in most of China's provinces is still relatively high compared with that of coal power. Coastal regions, the northeast region, and parts of central China, which are the centers of the country's electric power demand, will be the first to have competitive renewable energy costs (Wood Mackenzie 2019). Although offshore wind power remains one of the most expensive power generation technologies, its average cost is expected to be lower than the local benchmark on-grid coal electricity price by 2028 (Wood Mackenzie 2019). Since the coastal regions are the most populous and developed areas (with the largest electricity demand) and also have exceptional offshore wind resources, China's renewable energy development is likely to boom if offshore wind power becomes cost competitive in the future.

Addressing Interprovincial Barriers through a Renewable Portfolio Standard

In 2019, after many years of debate, China's central government (NDRC and NEA) released the Renewable Portfolio Standard, aimed at addressing the interprovincial barriers to renewable electricity trade that we discussed above. Minimum targets for the share of nonhydro renewable electricity (mainly wind and solar PV) in total electricity consumption for individual provinces were issued by the NDRC and NEA in June 2020, with the targets ranging from 3.5 to 20 percent by the end of 2020 (NDRC and NEA 2020). Under the policy, provincial governments are responsible for developing renewable electricity consumption plans for electricity sellers (including grid companies and independent electricity retail companies) and industrial users in their jurisdictions. The electricity sellers and industrial users that are unable to meet the minimum renewable electricity consumption requirement can either purchase green certificates or purchase renewable consumption quotas directly from companies that have met the minimum requirement and have surplus quotas. This new policy prioritizes renewable energy in electricity generation, promotes direct trading, and encourages the consumption of renewable energy across provinces. In addition, enterprises that rely on coal-fired power plants are incentivized to switch from generating power to buying power from renewable energy sources. Data for evaluating whether the policy will reach its targets are not yet available.

Summary and Conclusions

This article has reviewed China's renewable electricity development and policies from 2006 to the present. We have found that although China has made remarkable progress in its wind and solar PV power generation, fixed feed-in tariff subsidies distorted investment incentives and led to both high subsidy debt and high rates of curtailment. We have also discussed how and why the government shifted its renewable subsidy policy from fixed feed-in tariffs to auctions.

Although the new auction policy has shown promising signs of success and the subsidies for solar PV and onshore wind power are expected to end in 2021, further policy reforms are needed to stimulate the long-term development of renewable power in China. These include implementation of a pollution tax and a carbon price to enable renewable power to compete more fairly with fossil fuels. In addition, to address the challenges posed by interprovincial barriers, it is important for the current system of provincial electricity markets to be expanded into regional markets that include several provinces. Actions to address the intermittency and instability problems of wind and solar PV power, including establishing market transactions for auxiliary services to help grid operators maintain a reliable electricity supply, are also needed.

We believe that as technological progress continues and costs decline, wind and solar PV power generation will eventually no longer require subsidies and will become cost competitive in the power generation market in China, as they are in many countries around the world. Moreover, we are hopeful that if the government continues to implement reforms to the electricity sector and enacts other complementary policy reforms, China will be able to achieve renewable energy development that is sustainable in the long term.

Appendix

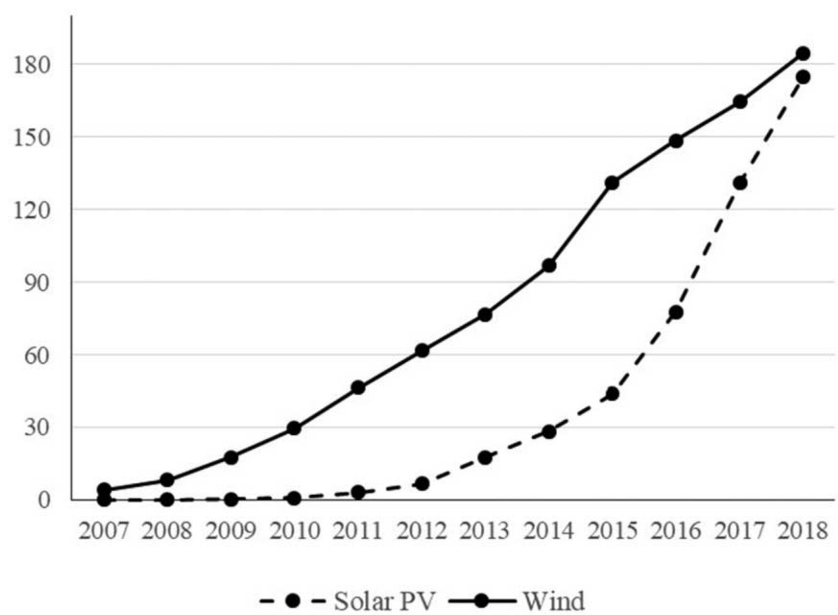

Figure A1 China's cumulative installed renewables capacity (GW). Source: British Petroleum (2020).

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