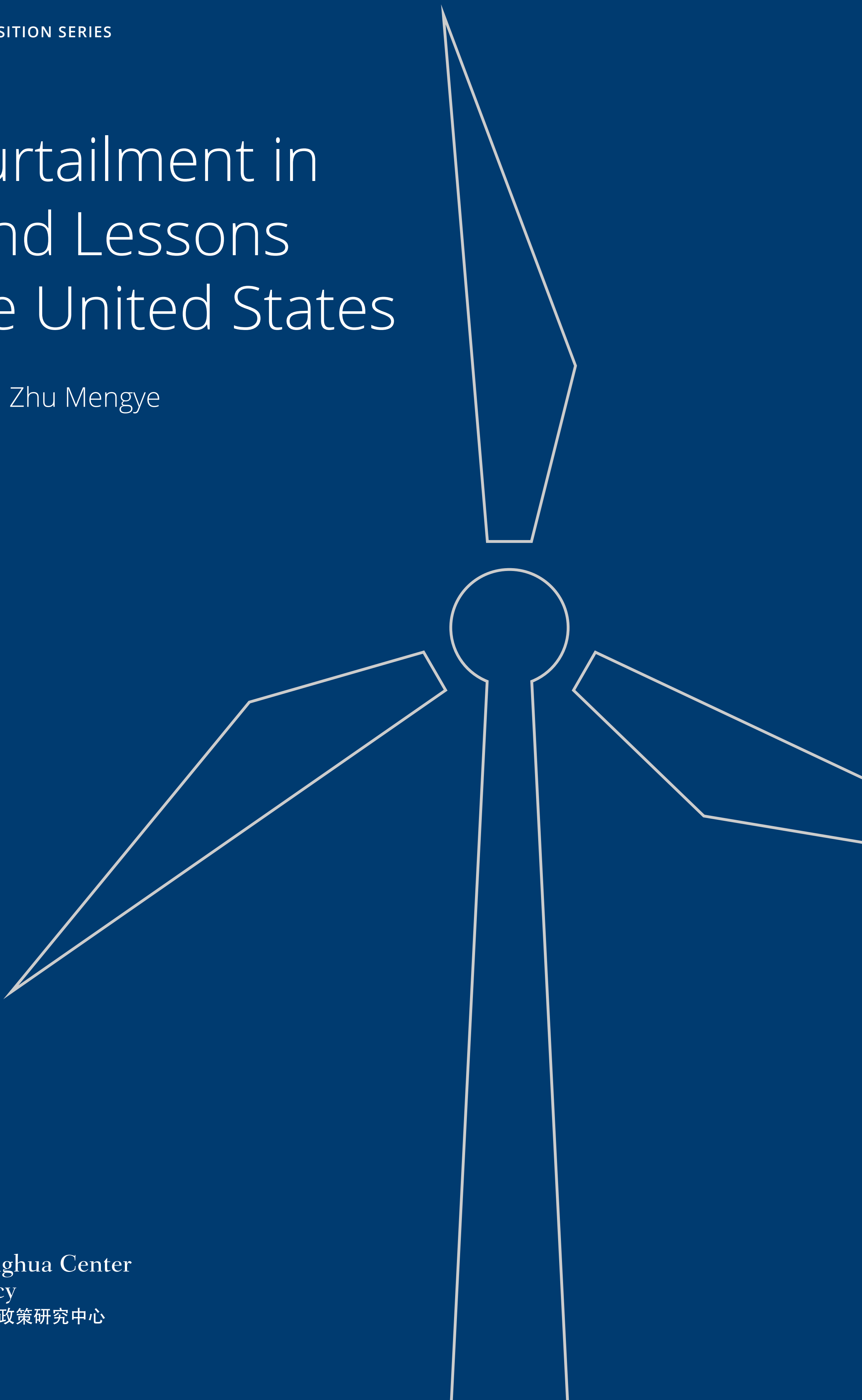
CHINA'S ENERGY IN TRANSITION SERIES

Wind Curtailment in China and Lessons from the United States

Qi Ye, Lu Jiaqi and Zhu Mengye



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Introduction

From 2004 to 2010, global renewable energy investment increased fivefold.[1,2] Europe and the United States led the surge, representing more than 60 percent of the total investment over this period.[3]

Since 2011, however, renewable energy investment has slowed down significantly due to a sharp decline in European investment and a moderate cut from the United States. Their combined investments decreased by about 50 percent from 2011 to 2015, and the share of overall investment from developed countries decreased from near 80 percent in 2004 to 44 percent in 2016.[4] Meanwhile, China has doubled its investment in the three years from 2010 to 2013, and sufficiently upheld global clean energy investment. Riding the high tide of clean energy development, China has successfully fertilized the renewables industry in terms of both installation and equipment manufacturing. Renewable energy, a key part of China's national strategy to combat climate change and air pollution, is replacing coal at an accelerating pace: China's investment in renewables grew by 100 times compared to 2005 and accounts for one-third of global investments in renewable energy today. China aims to boost its wind and solar power installation to 250 and 150 gigawatts, respectively, by 2020.[5] As a result, China's renewable energy consumption increased steadily over the past two decades, representing 11 percent of its total energy usage in 2016.[6]

China's energy is in rapid transition. Changes in the energy mix plus the economic slowdown and structural change effectively

1 Bloomberg New Energy Finance.

2 Angus McCrone, Ulf Moslener, Francoise d'Estais, and Christine Grüning, "Global Trends in Renewable Energy Investment 2017," Frankfurt School-UNEP Centre, 2017, http://fs-unep-centre.org/sites/default/files/attachments/gtr_2017_-_key_findings.pdf

3 Ibid.

4 Ibid.

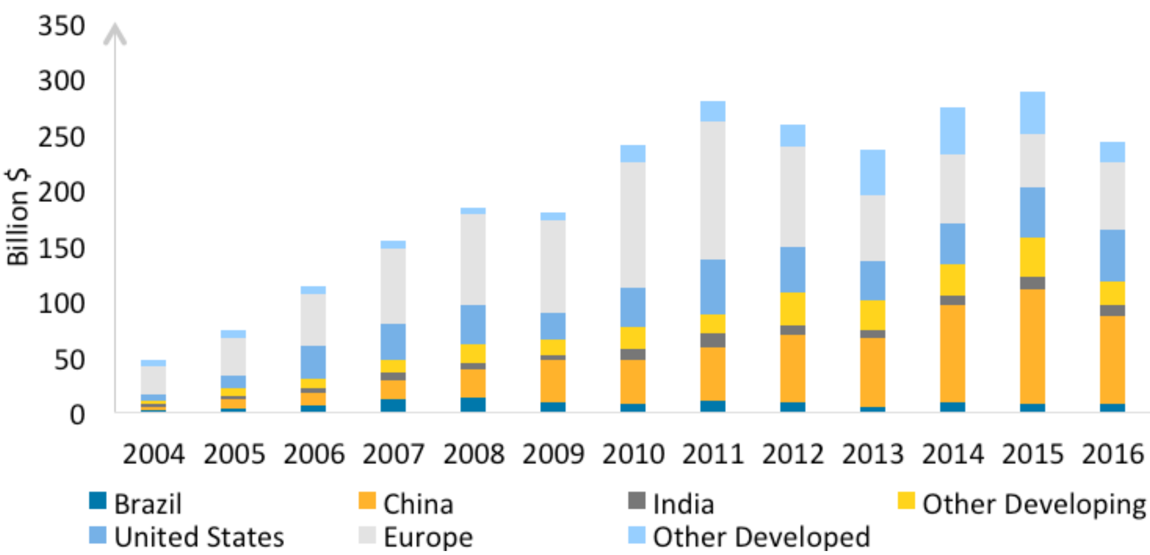
5 National Energy Administration of China, 13th Five-Year-Plan of Wind Power Development, Beijing, 2016, http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/201708/W020170809595909131668.pdf; National Energy Administration of China, 13th Five-Year-Plan of Solar Power Development, Beijing, 2016, http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/201708/t20170809_857322.html.

6 National Bureau of Statistics of People's Republic of China, 2016 National Economic and Social Development Statistical Review, 2016, http://www.stats.gov.cn/tjsj/zxfb/201702/t20170228_1467424.html

reduced coal usage and peak consumption in 2013,[7] while maintaining a 6 to 7 percent economic growth. China has entered a new stage of post-coal-fired growth due to growth of renewable energy.

However, curtailment of renewable electricity generation—i.e., the abandonment of electricity generation of effective power capacity—is becoming part of the "New Normal"[8] as wind and solar installation expand across the country. From 2010 to 2016, 150.4 million megawatt hours (MWh), or as much as 16 percent of overall wind generation, was abandoned. Over the last 6 years, the opportunity cost of wind power curtailment in China is estimated to have exceeded $1.2 billion. The total energy loss is equivalent to 48 million tons of coal consumption,[9,10] or 134 million tons of CO_2 emissions,[11] which is equivalent to about 1.5 percent of China's total emissions in 2016, equal to the total emissions of Algeria in the same year.[12] In addition, frequent curtailment would damage wind turbine, significantly shorten its lifespan for up-to five years.

Figure 1. Investment in renewable energy by source (2004-2016).



Source: Frankfurt School UNEP-Collaborating Center and BNEF

7 Qi Ye, Nicolas Stern, Tong Wu, Jiaqi Lu and Fergs Green, "China's post-coal growth," *Nature Geoscience*, vol. 9, 2016, pp. 564–566.

8 China Daily, "The 'new normal' means the Chinese economy has entered a new phase that is different from the high-speed growth pattern exhibited in the past. It is a new trend that features more sustainable, mid- to high-speed growth with higher efficiency and lower costs." http://www.chinadaily.com.cn/opinion/2014-10/10/content_18716671.htm

9 Using an economic factor 0.54 yuan per kWh from "数据 | 2011年-2015年中国风电弃风量近千亿度," Beijixing Electricity Net, April 7, 2016, http://news.bjx.com.cn/html/20160407/722711.shtml.

10 "十三五发电行业碳排放强度探讨", China Hydro-electricity Engineering Council, January 2, 2017, http://www.hydropower.org.cn/showNewsDetail.asp?nsId=20181

11 Using a converting factor of 0.89 kg CO_2 per kWh.

12 BP Statistical Review of World Energy 2017, http://www.bp.com/statisticalreview.

Renewable energy curtailment is usually explained as the underutilization of installed renewable power capacity. Technically, curtailment happens when grid operators command facilities to reduce output to maintain system balance and reduce transmission congestion. Especially for small and isolated grids, curtailment typically occurs when facilities produce excess electricity during off-peak hours that could cause baseload power plants to hit minimum generation capacity. Compared to the 1 to 4 percent average curtailment rate in the United States and Europe, China's situation is hardly a mere technical problem.

The Brookings-Tsinghua Center has launched a research project, *China's Energy in Transition*, to provide an assessment of how to transform China's energy system to a climate- and environmentally-friendly one, and to assist policymakers and the general public in understanding the complexities of the topic and challenges ahead. The following report is the first major piece in this series. In this report, we start with a brief history of wind energy curtailment in China and an overview of different provinces where the curtailment issue has been common and serious. We draw our discussion on interviews with experts, investors, grid operators, government officials, and other interested parties in Beijing and on a field trip to Gansu province in 2016 and 2017.

A brief history of wind energy curtailment in China

Wind energy curtailment has existed from the early stage of its development, and has deteriorated with the rapid growth of wind power installation.

During China's 11th Five-Year-Plan (2006-2010) period, wind energy installation surged from 1.26 GW in 2005 to 46 GW in 2011, making China the world's largest investor in wind power.[13] Echoing the 15 percent target of non-fossil energy in 2020 under the Copenhagen Accord, the National Energy Administration (NEA) proposed a renewable energy quota scheme, suggesting that large power enterprises meet a minimum of 9 percent power generation from non-hydro renewable energy in 2016. Furthermore, the *12th Five-Year-Plan of Wind Power Development* set the installation target at 100 GW with at least 190 billion kWh electricity from wind by 2015.[14] China's Ministry of Finance issued the *Temporary Rules on Fit-in-Tariff of Renewable Energy*, with financial support for renewables. As wind installation increases, the wind curtailment first worsened in the north, northeast, and northwest of China or the so-called "Three North" region where most of the national wind resource is and more than 60 percent of wind power deployment was located.[15] Wind curtailment went up to 17 percent in 2012 and then began to drop in 2013 and 2014. However, it went up again in 2015 and 2016. The severe curtailment is phenomenal and caught the attention of government, developers, and the media.

Direct causes for curtailment change over time and across different provinces. The two phases of wind curtailment are caused by different mismatches. During the first phase, from 2010 to 2012, the main causes of curtailment were the rapid growth of installation and inadequate buildup of transmission grid in the early stage of development. This curtailment phase was alleviated by the construction of more grid connection in 2013 and 2014. In the second phase, after 2014, the demand for electric power was slowed down due mainly to economic deceleration. Competition among all sources of power supply resulted in abandonment of electricity from wind and also from other sources.

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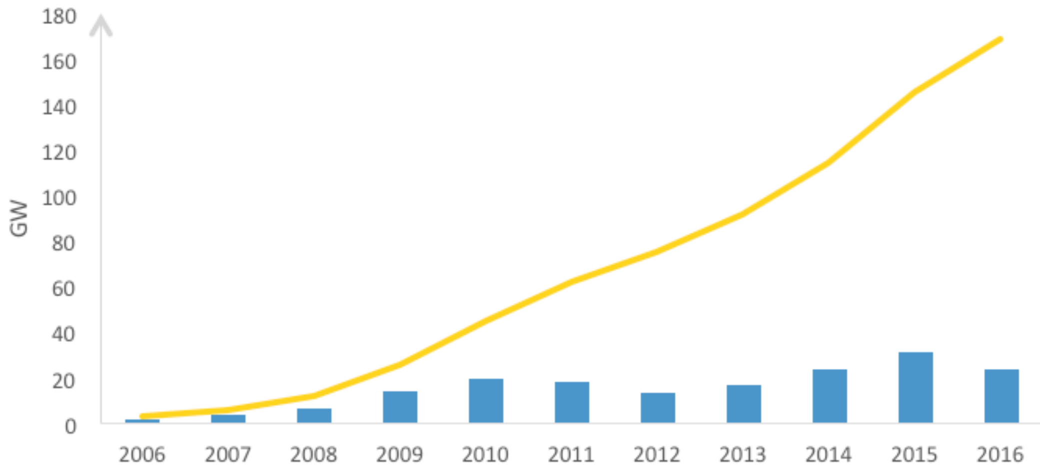
13 Wind Industry Monitoring (2011), National Energy Administration of China.

14 National Energy Administration of China, 12th Five-Year-Plan of Wind Power Development, Beijing, 2012, http://www.sxdrc.gov.cn/xxlm/xny/zhdt/201212/W020121213356692952141.pdf.

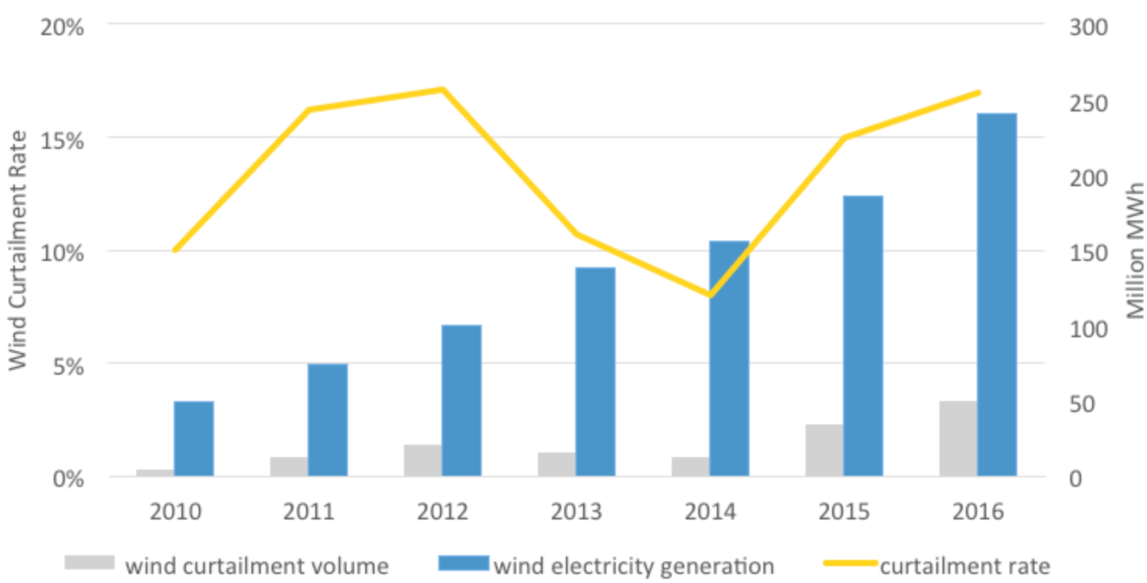
15 Northern, northeastern and northwestern China includes 8 provinces: Liaoning, Jilin, Heilongjiang, Inner Mongolia, Hebei, Gansu, Ningxia, Xinjiang.

Figure 2. Wind power installation and its annual increase in China (2006 – 2016).



Data source: Wind Industry Monitoring, National Energy Administration of China (2006-2016)

Figure 3. Wind power installation and its annual increase in China (2010 – 2016).



Data source: Wang Zhaobin, "Report on China's Wind Curtailment" July, 2014;
Wind Industry Monitoring (2011 – 2016), NEA.

Mismatch of capacity

Mismatch of wind installation and transmission capacity was a major bottleneck in the early stage of wind development.[16] Many wind farms started construction before building necessary transmission and grid up-grade. The weakness of grid capacity led to massive outages in Gansu and Hebei provinces in early 2011.[17] Under these circumstances, the NEA tightened the approval of new projects in provinces with high wind curtailment rate, and issued *Temporary Administrative Rules on Wind Power Development* in 2011, its first regulation on wind power development.[18] These regulations allowed the NEA to monitor and control the size of wind power projects.

However, NEA's regulations and controls were not enough to fix the curtailment issue. In 2012, wind curtailment went up to 17 percent. During the winter heat-supply period, the wind power abandonment in Jilin and eastern Inner Mongolia exceeded 50 percent. Some developers and policymakers deemed wind curtailment a major obstacle to wind power development in China and became reluctant to pursue further investment. Regarding the curtailment problem in the wind-rich "Three-North" area, the NEA issued *Requirements on Regulating Wind Power Development* in 2012, requiring that the new projects take the transmission capacity of the power grid and market demand into consideration.[19] Some wind developers started exploring south and southeast provinces, where the demand and grid are located.

At the beginning of 2013, the NEA urged stakeholders—including local governments, grid operators, and large wind power developers—to deal with wind curtailment. Meanwhile, the State Grid Cooperation of China (SGCC) increased investment in the grid system, building high-voltage transmission lines and strengthening local grid stability. The overall wind curtailment rate dropped significantly to 10.5 percent in 2013.

Mismatch of demand and supply

With the SGCC upgrading transmission capacity, the mismatch between wind power generation and transmission was alleviated, but a new problem emerged: the mismatch of demand and supply that arrived along with the "New Normal." Following a hike in 2011, the electricity growth rate was cut by two-thirds in 2012, from 17.6 percent to 6 percent. Although the demand rebounded to 8 percent in 2013, electricity from coal responded more quickly and grabbed a large portion of the new market (Figure 3). With lower economic growth becoming the "New Normal," the electricity consumption growth rate dropped to 4 percent in 2014, and electricity from wind suffered a deeper cut. Although in 2014 the curtailment rate decreased to the lowest point in recent years, this was due primarily to lower wind availability that year.[20]

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16 Mian Yang, Dalia Patiño-Echeverria, and Fuxia Yang. Wind Power Generation in China: Understanding the Mismatch Between Capacity and Generation. *Renewable Energy*, vol. 41, 2012, pp. 145-151.

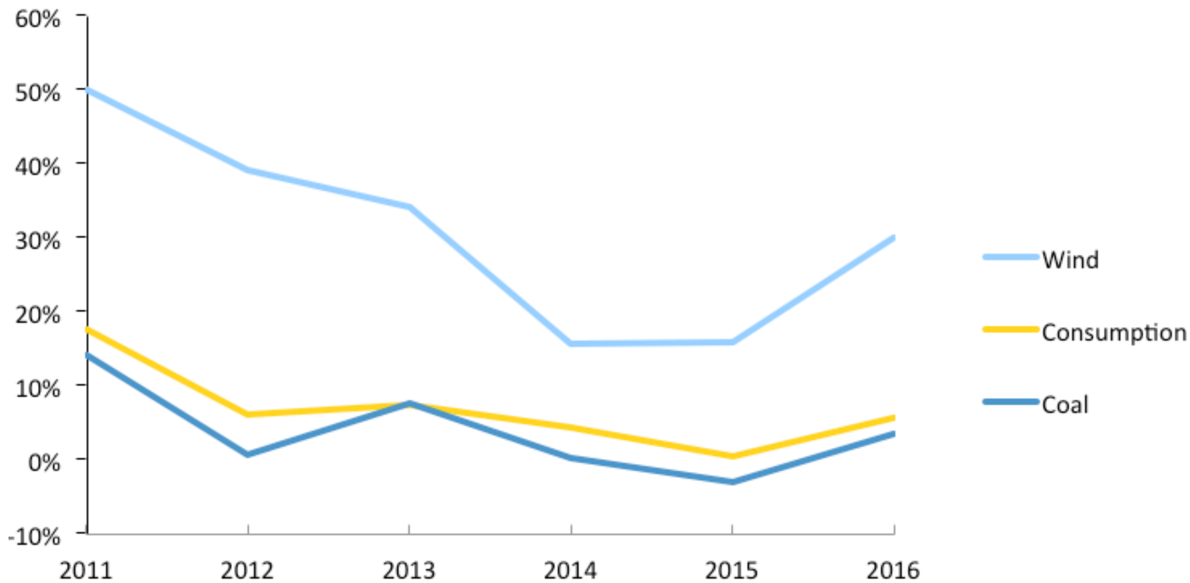
17 Rui Yang, "Massive Off-grid Incidence in Jiuquan." Caixin Net, April 4, 2011, http://companies.caixin.com/2011-04-07/100245747.html.

18 NEA, "风电开发建设管理暂行办法的通知" August 25, 2011, http://zfxxgk.nea.gov.cn/auto87/201302/t20130226_1583.htm

19 NEA, "关于规范风电开发建设管理有关要求的通知", February 16, 2012, https://wenku.baidu.com/view/d1657473a417866fb84a8e4b.html

20 NEA, "2014年风电产业监测情况", February, 12, 2015, http://www.nea.gov.cn/2015-02/12/c_133989991.htm.

Figure 4. Growth Rate of Electricity Consumption and Generation by Source.



Source: Annual Electricity Operation Review (2011-2016), China Electricity Council

With the economic slowdown in recent years, the energy intensive industry suffered greater stagnation. The overall electricity consumption growth rate dropped to a record low over 40 years in 2015.[21] The slowdown of demand also brought about protectionism that blocked inter-provincial electricity trading and dispatch cooperation. Given the fact that most wind power generation from the north has to find demand in the southeast, provinces in southeastern China had little incentive to buy power from the north when they have found outlets of their own generation to keep local power facilities in business in the economic downturn and avoid potential losses of jobs and tax revenue. Moreover, in July 2014, the State Grid imposed a new checking and reporting mechanism on inter-provincial transmission, which directly reduced the incentive for inter-provincial dispatch and balancing cooperation.[22] Many wind farms in the Northwest Grid experienced serious curtailment afterward. In 2015, inter-provincial transmission and trade reduced by 0.34 percent, and trading in the Northwest Grid dropped more than a quarter. Consequently, wind farms in the "Three North" region have found it more difficult to reach the market.

Despite the slowed growth in power demand, the supply was increasing. The

21 "去年全社会用电量同比增长0.5% 增速再创新低", 和讯网, January, 27, 2016, http://news.hexun.com/2016-01-27/182043128.html.

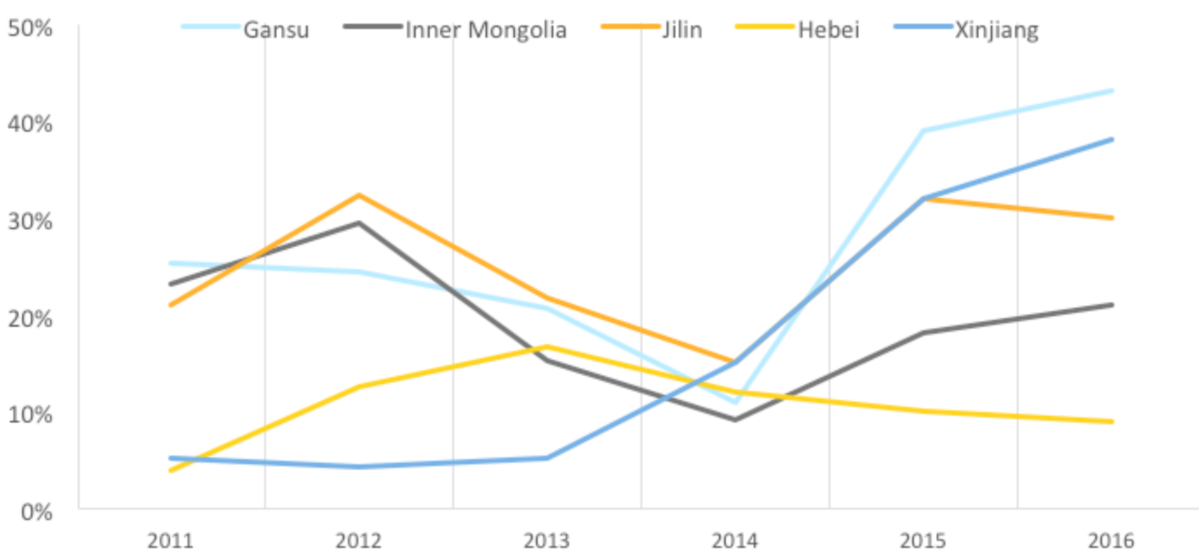
22 Brookings Institution interview with Liu Wenlong from China Resources Power Holdings Company of Northwestern Region in August 7, 2016. Also see "最高限电60%!甘肃弃风困局为何持续恶化?" *China Energy Newspaper*, September 2, 2015, http://www.ce.cn/cysc/ny/xny/33/201509/02/t20150902_6387612.shtml.

expectation of adjustment of wind power's benchmark price caused an "installation boom" as project developers geared up to complete wind installation before the price cut. The boom resulted in an increase of installed capacity in the "Three North" region, widening the gap between demand and supply. Total installation of wind power surged to 129 GW in 2015, exceeding the 12th Five-Year-Plan target by 30 percent. At the same time, wind curtailment kept worsening. The national average of the wind curtailment rate was 15 percent in 2015, and reached 21 percent in the first half of 2016. Wind curtailment in Xinjiang hit a new record. Ningxia, as well, reached a curtailment rate of 13 percent in 2015 from almost zero in 2014. In response, the NEA issued additional regulations. *Administrative Rules on Guaranteed Purchase of Renewable Energy Power* (2016) further emphasized the priority of renewable energy power utilization and required power grids to take all planned renewable energy.[23] The NEA also released guidance to promote renewable energy quotas and green certificate schemes. In July 2016, the NEA implemented an alert on wind investment, banning new investment in provinces with more than 20 percent curtailment rate. Due to the complexity and controversy of this issue, the effectiveness of these policies remains to be seen.

Case studies:

As of 2017, 11 provinces in China have been suffering wind curtailment. Six provinces experienced a curtailment rate greater than 20 percent in 2016. We chose two provinces, Gansu and Jilin, for a closer look. The two provinces represented 84 percent of all curtailed wind power nationwide in 2016 and more than a quarter of overall curtailment since 2011.

Figure 5. Curtailment Rate in Different Provinces.



Source: China Electricity Council and NEA (2011-2016)

23 NEA, "可再生能源发电全额保障性收购管理办法", March, 28, 2016, http://www.nea.gov.cn/2016-03/28/c_135230445.htm.

Gansu

Gansu (especially west Gansu) is blessed with abundant wind resource with low development costs due to its geography. It was also one of the few places for wind-power development pioneers in China to build wind farms since the 1990s. The massive development of wind farms started in 2008 when the NEA approved the Ten-GW Class National Wind Energy Base in Jiuquan, Gansu, a wind-rich north-western part of the province, 1,000 km (625 miles) away from the provincial capital Lanzhou and its load center. It is the first wind power base of its class in China with a total 11.8 GW planned installation. Thus far, 6.8 GW installation has been completed. And there are other wind farms beside the base. By the end of 2016, wind power installation in Jiuquan reached 9.15GW, accounting for 71.6 percent of the total in Gansu. Wind curtailment in Gansu appeared as early as 2008. However, it did not significantly impede wind power generation until 2012. The wind energy base in Jiuquan was originally designed for inter-provincial transmission under the idea of "build the massive wind power base and connect it to the integrated power grid."[24]

In the early stage of wind development in Gansu, curtailment was due mostly to transmission constraints. Local officials admitted facilitating a wind manufacturing industry was the priority.[25] By 2010, the wind power base in Jiuquan was only connected to 330KV transmission lines. Transmission was obviously limited while the wind power installation surged. In response, the SGCC built 750 KV transmission lines to deliver electricity from planned wind installations to the provincial capital and power demand pool in the east. However, the overall capacity in Jiuquan soon exceeded the transmission capacity. When the 750 KV transmission line could take 2.5 to 3 GW wind generation capacity, the overall installations in Jiuquan had achieved 5.6 GW by the end of 2010.[26] Moreover, the power grid of Xinjiang province was connected to the 750 KV line in 2013.[27] Gansu had to share the transmission capacity with Xinjiang where it also confronted a severe curtailment issue. From 2013 to 2016, Gansu had to abandon about one quarter of overall wind production. The local government took actions to strengthen line capacity and integrate more wind. In July 2014, the SGCC constructed another 750 KV transmission line, doubling the transmission capacity in Gansu. Additional transmission capacity combined with low wind availability has successfully lowered the curtailment rate to 11 percent in 2014.

Nonetheless, the curtailment rate jumped to 39 percent in 2015 and to 43 percent in 2016. This was partially a result of the installation boom in 2015 as developers surged to qualify for the electricity tariffs before the cut, and also due to the

24 Gansu Provincial Sci. & Tech. Department, "酒泉市扎实推进新能源基地建设", http://www.gsstc.gov.cn/News_Notice/detail.php?n_no=286032.

25 Shi Jingli, Brookings Roundtable on Wind Curtailment, Beijing, September 2017.

26 Brookings Institution interview with Wang Ningbo, Director of Wind Energy Technology Center, National Grid Company of Gansu, August 8, 2016.

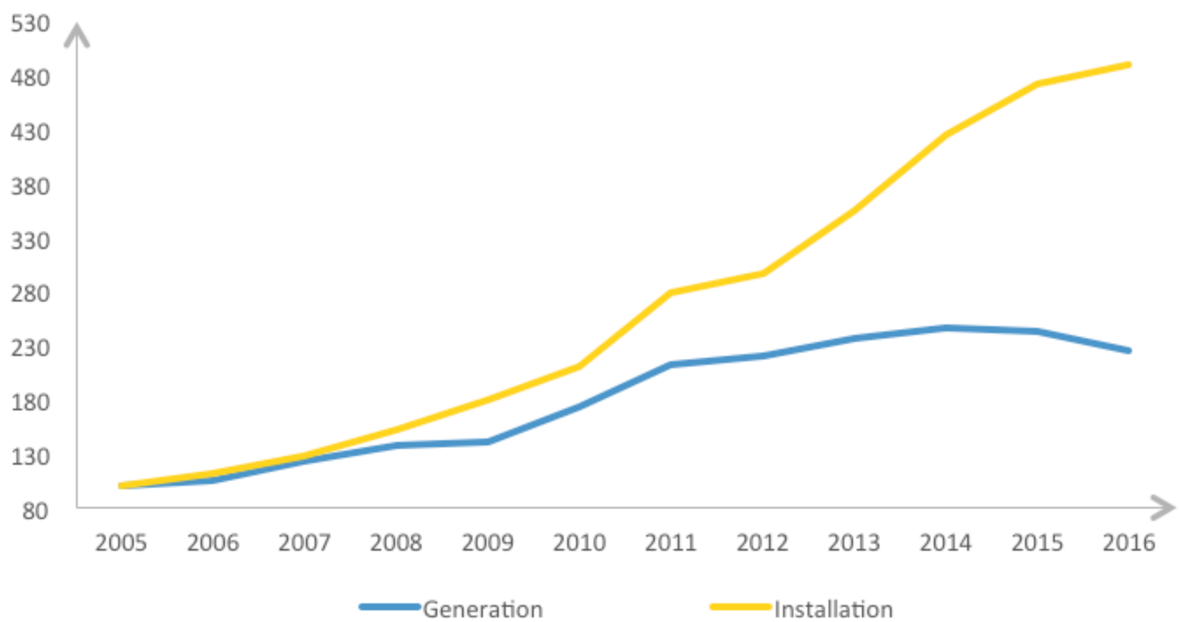
27 Ibid.

reduced electricity demand. Gansu's peak demand decreased by 6 percent to 13 GW in 2015 and its overall electricity consumption was less than 110 million MWh in recent years, and decreased by another 10 percent in 2016. As of 2016, Gansu had a total of 47.5 GW power generation capacity, including 12.8 GW wind, 19.3 GW coal, 6.8 GW solar, and 8.6 GW hydro power. In other words, its coal generation capacity alone is sufficient for the baseload and electricity demand. Therefore, Gansu had to count on exporting its electricity to neighboring provinces and Shandong where the demand was high. But China's overall electricity demand grew by half a percentage point in 2015, the lowest annual growth rate in nearly 40 years. Electricity exports from Gansu dropped by 60 percent in 2014 and by another 7 percent in 2015. The slowed demand and oversupply of wind-electricity generation resulted in new wave curtailment.

In response, Gansu has implemented two approaches to mitigate curtailment. First, Gansu provincial government has implemented a Power Purchase Agreement (PPA) mechanism that allows large electricity consumers to purchase electricity directly from wind farms with a lower price than from the grid. For the energy-intensive industry, lowering the electricity price could significantly reduce its cost of production. However, the effect of PPA is insufficient given the condition of the economy. Electricity consumption from manufacturing and heavy industry in Gansu remained constant in 2015 comparing to 2014, and decreased by more than 7 percent from 2016.

Second, Gansu has promoted building a high-voltage transmission line to export

Figure 6. Installation vs. Generation in Gansu (2005-2016, normalized[28]).



Data Source: China Electricity Council (2005-2016)

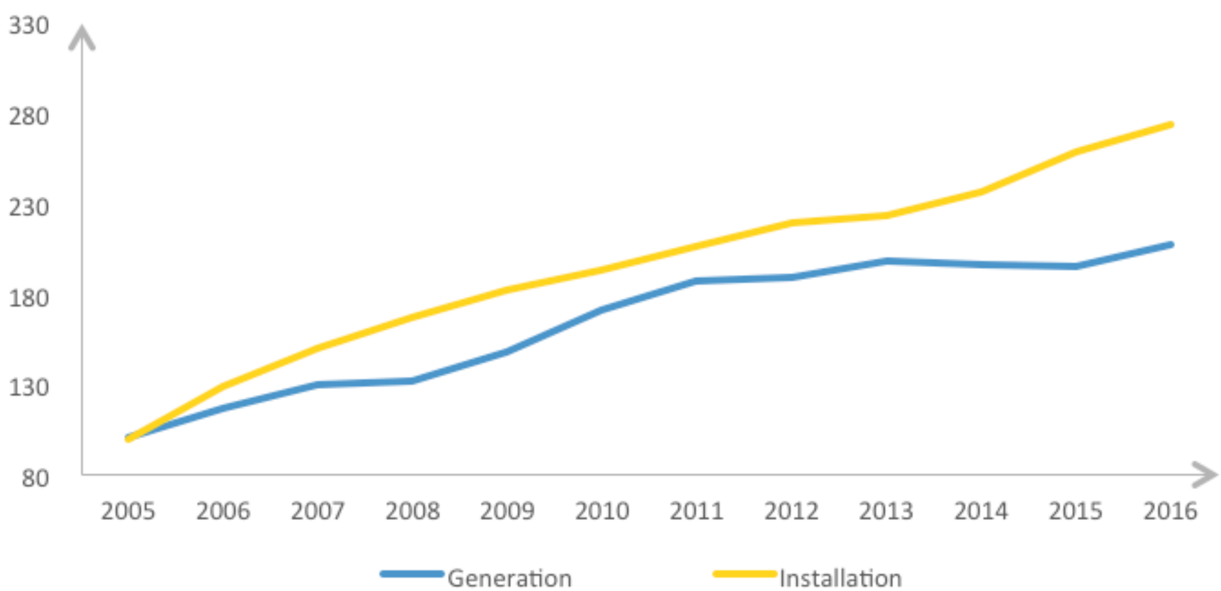
28 Making installation and electricity generation in year 2005 100.

excess electricity from Jiuquan to Hunan province to power the manufacturing industry there. The high-voltage transmission line as planned is capable of transmitting 40 million MWh of electricity. However, Hunan may not feel the same urge. While Hunan's peak load and electricity consumption growth was weak, its own generation capacity increased. Consequently, Hunan's capacity factor of coal-fired units dropped to 39 percent in 2015 and to 37 percent in 2016. Importing electricity from Gansu would continue to squeeze out its coal units. The planned power transmitted through the Jiuquan-Hunan high-voltage line is 8 billion KWh in 2017. By the end of June, only 0.5 billion KWh, or 6 percent of the total, was completed. Meanwhile, the NEA approved another 5 GW wind installation, 1.5 GW solar, and coal and gas power plants as the sources of the high-voltage transmission in Jiuquan. The Gansu government chose to push for these installation projects despite developers' concern over the curtailment issues. This seems to have violated the NEA alert system mechanism. But the Gansu government argued that as the source of the high-voltage transmission project, these installations were not regulated by the alert mechanism.

Jilin

By 2016, Jilin had about 5.05 GW wind capacity, an increase of 61 MW from 2015. Jilin has experienced high curtailment rates of 15-32 percent in recent years, even surging up to 53 percent in winter. Two major bottlenecks define Jilin's wind curtailment: transmission constraints and lack of system flexibility during winter when the grid prioritized power from CHP plants to ensure heat supply for buildings. Similar to the spatial pattern of the country, Jilin's wind capacity concentrates in the western part of the province where grid access is insufficient for the amount of generation online. As

Figure 7. Installation vs. Generation in Hunan (2005-2016, normalized).

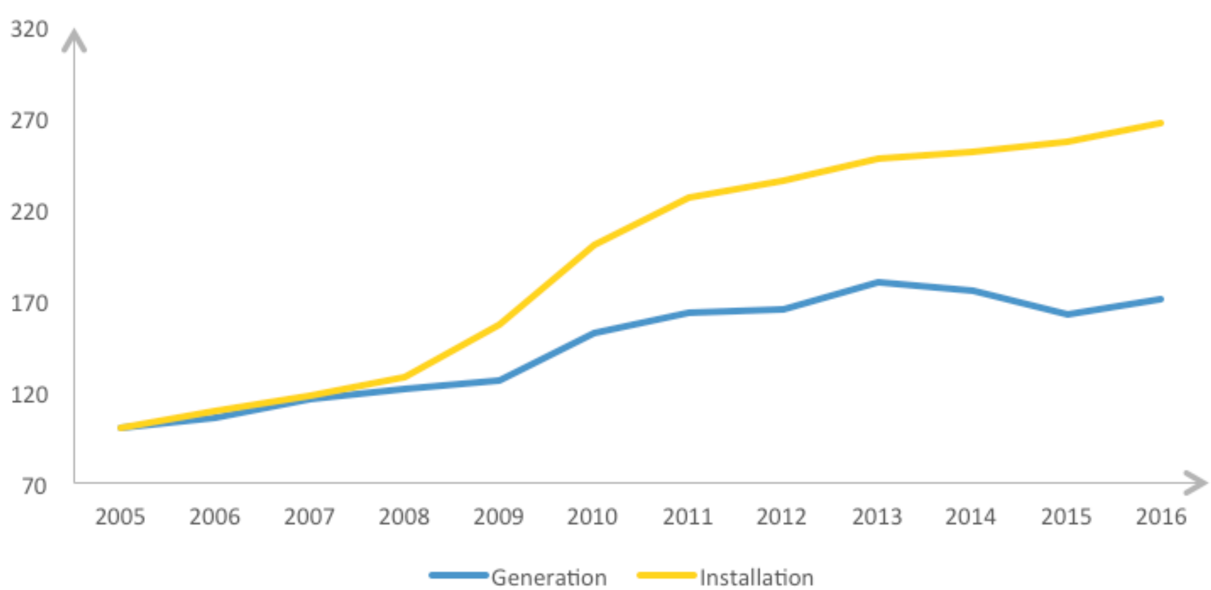


Data source: China Electricity Council (2005-2016) early as 2005, several franchising projects were brought online before building the necessary transmission and thus led to curtailment. Those wind facilities had experienced significant levels of curtailment even before wind construction surged in 2009. Although the provincial government recognized the transmission constraints, the process of strengthening the transmission system was slow. The new 500 KV transmission project did not start until late 2013 and has not been completed as of today.

Second, about 60 to 75% of overall curtailment happens in winter. CHP units have to produce minimum electricity while providing heating services, and grid operators would have to curtail wind in order to maintain system balance. Jilin has about 13 GW of CHP units, greater than the peak load. When the CHPs fully operate during winter, Jilin needs to access neighboring provinces in the northeast grid to maintain system balance. Thus, very little room is left for wind.

Slowed down electricity demand further worsens wind curtailment. Jilin's electricity demand has been weak and overall generation started declining in 2013. Jilin's economy relies heavily on state-owned heavy industry. Energy-intensive chemical and manufacturing activities contribute more than 50 percent of the provincial GDP. As a result, Jilin's peak load and electricity consumption growth have been slowing down over the past few years and declined in 2015. Meanwhile, Jilin's wind capacity is still increasing. The declining demand overlapping with increasing generation capacity will likely further intensify existing problems and raise the curtailment rate. Although Jilin's curtailment rate has been decreasing in the last two years, to what extent the improvement can be attributed to governance or system improvement is still unknown.

Figure 8. Installation vs. Generation in Jilin (2005-2016, normalized).



Data source: China Electricity Council (2005-2016)

Mismatch of new technology and the old electricity governance system

The causes for curtailment change over time and across provinces. Improving grid connection and building long-distance transmission capacity solve only part of the problem, but the potential of this approach has been undermined by the economic slowdown and structural change of the economy.

Although many provinces can still maintain medium high growth, construction and manufacturing sectors are stumbling, and so does their electricity demand.

Power demand slowdown has opened up a window opportunity for renewable power substitution. “Green dispatch” and “priority dispatch” are prioritizing distribution of renewable sources and phasing out carbon and pollution-intensive power plants. Recent demand slowdown has only exposed and intensified existing system drawbacks. In the following section, we argue that the foundation of wind curtailment lies on China’s energy governance which is defined by its fragmentation and lack of operational integration.

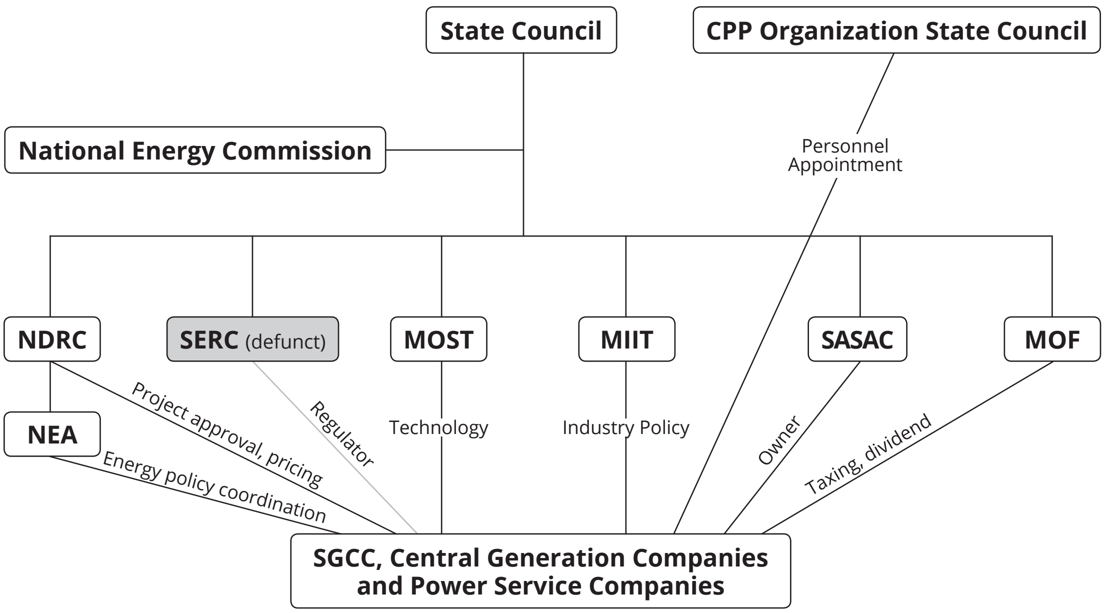
Governing the electricity sector: SERC and the NEA

An effective and efficient electrical power sector requires effective regulation. In the electricity structural reform in 2002, the State Council established the State Electricity Regulatory Commission (SERC), a ministerial level agency, to oversee electricity development and to act as an independent regulator of the electricity sector. A key responsibility of SERC is to “establish and oversee market rules, including competitive bidding rules and protecting fair competition, market tariff adjustment proposals, monitor operational quality standards, issue and monitor licenses, settle disputes, and oversee implementation of the universal service reform.”[29] However, during the electricity structural reform SERC was never granted adequate authority to be an effective regulator.[30] For instance, setting market rules and standard practices for electricity market pilot programs was taken by SGCC; project approval was issued by the NDRC; the authority for monitoring and setting transmission and distribution costs, and setting electricity wholesale and retail prices was placed in the hands of the Price Department of the NDRC.

29 The State Council of China, Plan for Electric System Reform,2012.

30 Xu Yi-Chong, *Sinews of Power: The politics of the State Grid Corporation of China*, Oxford Press, 2017.

Figure 9. Government Structure over the Electricity Sector.



Source: modified based on figure 4.1 in Sinews of Power (2017), P83, by Xu Yi-Chong

More importantly, SERC is unable to regulate the SGCC. As early as 2002, SERC proposed to carry out the electricity reform by further dividing the SGCC by region and calling for the separation of generation, construction, maintenance, finance, and other services from SGCC, leaving transmission and distribution its only core services. Yet these were never the authority of SERC. As the most profitable enterprise of the Fortune Global 500 and national flagship SOE, any major change in operation, merger, and acquisition are supervised by State-owned Assets Supervision and Administration Commission of the State Council (SASAC), which has a very different agenda and policy preference. In fact, the SGCC does not need approval from SERC to get things done. SGCC would approach NDRC for project approval and price setting, SASAC for major business decisions, such as divestiture and acquisition.[31]

In 2006, the State Council set up a task force involving various stakeholders and experts, including those from the NDRC, SGCC, and international experts from the World Bank Group, to study the role and responsibility of SERC. They concluded that lack of exclusive authority and fragmented responsibilities between SERC and other government agencies inhibited its ability to exercise effective governance.[32] However, the issue was not properly addressed. Later that year, SERC announced that "the electricity reform has failed."[33]

The ambiguity of SERC ended with its merger into the NEA in 2013, yet the issues embedded in the nation's energy

31 Ibid.
32 World Bank, 'Study of Capacity Building of the State Electricity Regulatory Agency, P.R. China' 2007.Washington, DC. http://documents.worldbank.org/curated/en/276241468213282253/pdf/453020ENGLISH01PUBLIC10Aug021102007.pdf
33 Xu, 2017.

governance endure. First and foremost, the NEA is not empowered with adequate authority from the NDRC. Energy related pricing, project approval, and long-term and national-level planning are still under the control of the NDRC. As a vice-ministry level department supervised by the NDRC, its responsibilities are to participate in energy related development, to suggest energy price adjustment, to suggest electricity reform, and so on. In other words, the NEA still does not have exclusive authority over energy and electricity related decision-making. "We lack necessary resources and measures to regulate the energy sector," said Zhang Guobao, the first administrator of the NEA. "For example, none of the five licenses regarding coal industry is issued by the NEA."[34] In addition, like the old SERC, the NEA also faces obstructions and challenges coming from outside of the NDRC.[35] At a national energy conference in 2011, when being blamed for allowing the SGCC to enlarge its market monopoly, Zhang Guobao replied: "NEA wouldn't take the blame, it was approved by some other department."[36]

Without an agency with authority to conduct integrated planning, system inefficiency and costs could rise significantly. This is particularly important with the volatility of renewables. Fragmentation in electricity and energy governance has seriously backfired in electricity system planning. With the local DRC, NDRC, SASAC having different agendas and priorities, it is difficult for the NEA to coordinate without exclusive authority in decision-making. Thus, there is very little stakeholder engagement prior to plant construction and no public participation in system planning. The coal and CHP intensive power structure in the "Three-North" region reflects the lack of planning and system flexibility. CHP units must generate some electricity to provide heating in winter. This causes serious grid conjunction especially when electricity demand is low, leaving limited space for wind. For instance, in response to demand slowdown, many coal facilities in Gansu switched to CHP in order to secure their generation quota in winter, without consulting and cooperating with other stakeholders. Although the provincial government has authority to block these changes, it tends not to do so. As a result, almost all applications were approved in recent years. Switching to CHP units have been making the generation resources even less flexible.

Provincial-based electricity operation

At the national level, multi-agency regulation makes comprehensive cooperation and integrated planning difficult. Provincial interests and protectionism define the boundary of electricity operation. The intention of electricity reform in 2002 was to create a trans-provincial and trans-regional transmission grid to help adjust resources distribution and to address unbalanced electricity demand and supply. The SGCC thus was sub-divided into five regional grids, each covering four to six provinces. Following the central

34 Hu Senlin, "张保国身退", *New Finance Economics*, March 2011, http://finance.ifeng.com/news/people/20110310/3622148.shtml.

35 Xu, 2017.

36 Ibid.

government guidelines, in 2003, the SERC first initiated the integrated regional electricity market in the Northeast and East region. However, as the result of rising coal prices and failures in market design, the Northeast Grid ended up with a net loss of 3.2 billion yuan in 16 days. The SGCC had no choice but to propose ending all trading.[37] More importantly, the trading scheme triggered political disputes among provincial governments.[38] In Heilongjiang and Jilin, the majority of generation capacity belonged to the national generation companies, but in Liaoning, 21 percent was left to the provincial government and 70 percent belonged local independent power producer.[39] Following the SOE reform, all three provinces were struggling for jobs and economic growth.[40] Heilongjiang and Jilin complained that their cheaper power could not reach the load center in Liaoning. The political disputes and opposition from provincial governments put an end to the regional electricity market.[41] Later, Zhang Guobao admitted that there was no choice but to abandon the trading program when provincial governments and the gird company were all against it.

Leaving the provincial interests untouched has consequences and implications for electricity operation. Although there are regional grid companies, grid operation is provincial-based. This means the operators can only access the baseload reserves within provincial boundaries and thus dispatch electricity accordingly unless otherwise planned. The divided operating areas and lack of inter-provincial dispatch reduces grid operators' access to capacity reserve and demand, thus limiting the system's ability to absorb wind volatility, hindering system reliability, and increasing operational costs. Restricting regional cooperation has been an important cause of wind curtailment. Also, had Gansu been allowed to share reserves with neighbors, it would have reduced the baseload (provided mainly by coal-fried units) by a third and left greater market share for wind.[42] One study indicates that, by expanding the provincial operation area to regional-based—i.e., allowing the provinces to share baseload reserves and exercise full transmission across the region—the Northeast grid could successfully integrate wind power and reduce the wind curtailment substantially.[43]

37 Shen Xiaobo, "电监会高层曝内地第一个区域电力市场改革试点失败内幕", *Energy*, October 2014, http://finance.ifeng.com/a/20141008/13167972_0.shtml.
38 Xu, 2017.
39 ibid.
40 ibid.
41 ibid.
42 Brookings Institution interview with Wang Ningbo.
43 Michael R. Davidson, "Brining China's Wind to Market: Can Power Sector Reforms Help Integrate Renewables?" conference presentation, Beijing, June 2017.

Lessons from the United States

Electricity is a local industry by nature. Power generation capacity is built locally, connected with low voltage wire to support local demand. The conflicts between local and larger regions are not unique to China.

International experience has shown that with good operations and flexible system design, modern electricity systems can integrate renewable energy sufficiently. For instance, in the United States, Iowa is a wind and coal heavy state with wind representing nearly 40 percent and coal and nuclear representing more than 60 percent of total electricity capacity installation. Iowa is hundreds of miles from any major demand center, yet it manages to arrange 37 percent of its electricity consumption from wind while keeping its wind curtailment negligible.[44]

This achievement does not come easy. Many regions—situated in different geographies, market rules, power structures, regulations, and system operations—have been experimenting and implementing various approaches to improving renewable penetration. These practices and accumulated experiences can provide insights for Chinese policy-makers to fix wind curtailment. In a report published by National Renewable Energy Laboratory (NREL), Cochran et al. highlight strategies for better integrating renewable energy: coordinated and integrated planning; flexibility requirements; market design that enables system flexibility; expanded operational accessibility; and operational improvement such as forecasting and increased automation of signaling.[45] On top of those, Bird et al. added that reserve management, demand response, and flexible generation were helpful elements in addressing integration challenges.[46] In the following section, we explore further details of the successful approaches in the United States.

Strategy 1:
Coordinated and integrated planning

In the electricity sector, planning is essential to minimizing system costs and optimizing system security. In the United States, transmission constraint is the most common reason for renewable curtailment. Among 18 utilities and grid operators that

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44 EIA, "Iowa: State profile and energy estimates", https://www.eia.gov/state/?sid=IA.

45 Jaquelin Cochran, Lori Bird, Jenny Heeter, and Douglas J. Arent. Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience, 2012, Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy12osti/53732.pdf.

46 Bird, L; Milligan, M; and Lew D, "Integrating Variable Renewable Energy: Challenges and Solutions," National Renewable Energy Laboratory, September 2013, https://www.nrel.gov/docs/fy13osti/60451.pdf.

have experienced significant wind curtailment, 11 of them cited transmission constraint as one of the major causes.[47] In Texas, for instance, much wind generation capacity was deployed before building new transmission capacity and, as a result, wind curtailment in Texas gushed to 17 percent in 2009. Building and upgrading grid capacity can be difficult, and it can take up to ten years before new construction is completed because of various jurisdictional, regulatory, financial, and private property concerns and disputes.

Regarding the complexity, the Texas state legislature passed Senate Bill 20 to grant the Public Utility Commission of Texas (PUCT) clear authority to integrate planning of generation, transmission, and system performance, and to establish Competitive Renewable Energy Zones (CREZs) in the Electric Reliability Council of Texas (ERCOT) area. The PUCT stepped in to select transmission providers and initiating construction.[48] To maximize public support, the PUCT organized public hearings that involved stakeholders such as landowners, county commissioners, utilities, and federal agencies to address public concerns and facilitate public engagement.[49] Once the construction plan is set, generators and regulated utilities (transmission owners) would negotiate and split the cost. To further encourage transmission investment, Texas abolished an old rule that required newly constructed lines be utilized above a certain level. Instead, it demanded the PUCT plan a transmission system that could keep the curtailment level below 3 percent.[50] After transmission building, Texas successfully reduced its wind curtailment to 1.6 percent in 2013 and to less than 0.5 percent in 2014.[51]

Strategy 2:
Emphasis on system flexibility

System flexibility is particularly important for renewable energy, because intermittency requires the electricity system to address quick and unexpected changes in demand and supply. Flexibility can reduce the need for new controllable capacity, such as coal and gas fired units, and thus is valuable to the system. Flexibility can be achieved through building transmission capacity and adding flexible resources, such as more flexible generating units and energy storage. To better accommodate renewable energy, electricity system planning put emphasis on flexibility by diversifying generation sources and diversifying renewable energy locations, and optimizing generation and transmission resources across the grid. In practice, some regulators set up flexibility requirements for evaluating construction of new generation resources, and others provide financial incentives to encourage coal and CHP facilities to improve flexibility. These practices have ensured the flexibility of newly constructed generation and have improved

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47 Ibid.
48 Ibid.
49 Ibid.
50 Anders Hove and Kevin Mo, "Going for Gold: Championing Renewable Integration in Jing-Jin-Ji: Best Practices from Germany and Texas," The Paulson Institute, 2016, http://www.paulsoninstitute.org/wp-content/uploads/2016/07/Renewable-Energy-Integration-EN.pdf.
51 Ibid.

flexibility of the old resources to increase renewable energy penetration.

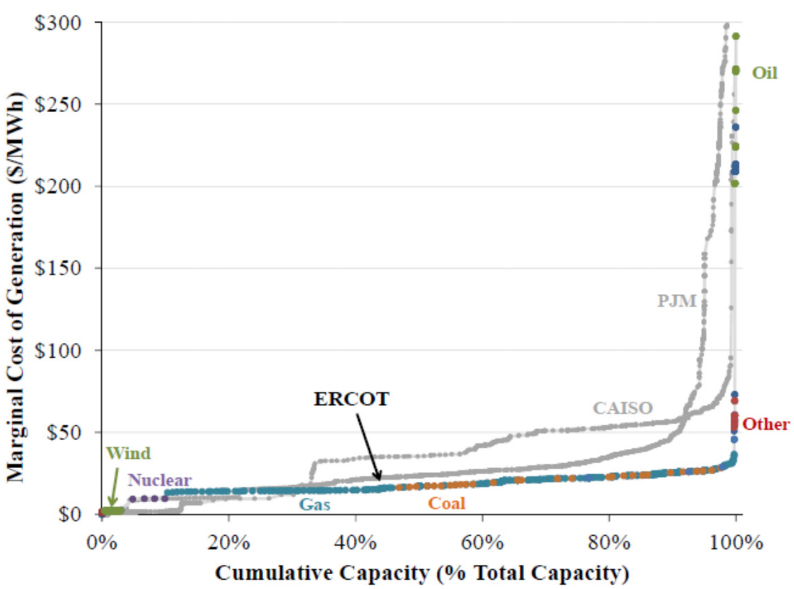
Demand-side response is another important way to reduce load. Demand response is a mechanism that allows and compensates electricity customers for reducing their load when requested. Demand response can provide important support to the grid flexibility that helps integrating renewables, especially during ramping or extreme events. In Texas, for example, demand response supports half of its spinning reserves for the ERCOT.[52] For the high wind penetration case, when a large drop in capacity or significant undersupply occurs, demand response can save up to $450,000 per MW annually rather than maintaining increased spinning reserves.[53]

In addition, the market plays an essential role in finding the most cost-effective way to improve the system's physical flexibility. In dealing with a decline in wholesale price, some operators offer capacity payment for flexible generation and financial incentives to compensate the cost of equipment and technology upgrade that improve flexibility.[54]

Strategy 3: Wholesale market and market design

A competitive wholesale market can help reduce curtailment. Electricity wholesale markets in the United States are controlled and operated by non-profit organizations called Regional Transmission Operator or Independent System Operator (RTO/ISO). The RTO/ISO is also responsible for grid operation, such as transmission operation, dispatching generation, and balancing demand with supply. Power generation is operated and dispatched based on market

Figure 10. Actual Economic Supply Stacks for Three RTOs (ERCOT, PJM, and CAISO).



Source: Phillip Brown. "U.S. Renewable Electricity: How Does Wind Generation Impact Competitive Power Markets?" (Cite: S. Newall, et al., "ERCOT Investment Incentives and Resource Adequacy" The Brattle Group, June 1, 2012.)

52 Bird, et al.
53 Ibid.
54 Cochran et al.

rules—to provide reliable power at the lowest possible cost. Therefore, wholesale electricity is typically dispatched to match load based on the lowest marginal cost of electricity available at the time.[55] In this competitive market, the RTO/ISO requests all generators within the operational area to participate in price bidding for a certain period of time, and then the RTO will arrange bids from the lowest to the highest to meet the forecasted demand.[56] Renewable power with zero marginal cost could bid with the lower price and would be purchased and dispatched first. In a period of oversupply, wind energy can offer zero or even negative bidding that discourages other generators from entering the market to reduce supply and encourages flexible load to increase consumption. Figure 10 demonstrates the actual economic supply and dispatch curves for three RTOs in the United States. The wholesale electricity market is comprised of day-ahead and real-time market. Box 1 demonstrates the practice of each market in California.[57]

In addition, the market mechanism has to be well designed to balance the market

Box 1. Operation of Wholesale Market in CAISO

Day-ahead market

The day-ahead market is made up of three market processes that run sequentially. First, the ISO runs a market power mitigation test. Bids that fail the test are revised to predetermined limits. Then the integrated forward market establishes the generation needed to meet forecast demand. And last, the residual unit commitment process designates additional power plants that will be needed for the next day and must be ready to generate electricity. Market prices set are based on bids.

A major component of the market is the full network model, which analyzes the active transmission and generation resources to find the least cost energy to serve demand. The model produces prices that show the cost of producing and delivering energy from individual nodes, or locations on the grid where transmission lines and generation interconnect.

Scheduling coordinators (SCs) are pre-qualified entities authorized to transact in the ISO market. The day-ahead market opens for bids and schedules seven days before and closes the day prior to the trade date. Results are published at 1:00 p.m.

Real-time market

The real-time market is a spot market in which utilities can buy power to meet the last few increments of demand not covered in their day-ahead schedules. It is also the market that secures energy reserves, held ready and available for ISO use if needed, and the energy needed to regulate transmission line stability.

The market opens at 1:00 p.m. prior to the trading day and closes 75 minutes before the start of the trading hour. The results are published about 45 minutes prior to the start of the trading hour. The real-time market system dispatches power plants every 15 and 5 minutes, although under certain grid conditions the ISO can dispatch for a single 1-minute interval.

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55 Phillip Brown, "U.S. Renewable Electricity: How Does Wind Generation Impact Competitive Power Markets?" Congressional Research Service, November 7, 2012, https://fas.org/sgp/crs/misc/R42818.pdf.

56 Ibid.

57 California ISO, https://www.caiso.com/market/Pages/MarketProcesses.aspx.

power of generators, system operators, and consumers. In the process of electricity market liberalization, some states have experienced a price surge due to the imbalance of the market. From 2000 to 2001, California underwent an extreme high electricity price which eventually bankrupted many utilities across the state. This event, known as the California Energy Crisis, demonstrated that market restructuring without careful design can be very risky. Since then, market reform in different ISOs/RTOs uses more controllable and diversified market mechanisms, such as long-term contracts, auctions, and other financial mechanisms to balance the market power of different players in the electricity market.

Strategy 4: Expand operational accessibility

Creating larger operating/balancing areas is essential as penetration of renewable energy continues to grow. It enables grid operators to access diverse generation resources and demand centers, and reduces baseload reserve requirements as well as wind curtailment accordingly.

In the western United States, for example, regulators and the Department of Energy have encouraged interconnecting different balancing authorities to join the Energy Imbalance Market (EIM) launched in 2014.[58] The EIM covers balancing areas in California, Oregon, Nevada, Washington, Utah, Idaho, and Wyoming. By expanding the balancing area, the EIM can reduce the variability of wind generation, managing and dispatching renewable output across different states. The California Independent System Operator (CAISO) estimates that the EIM has gained $3.8 million per month since 2014, and the total avoided renewable curtailment was 112,948 MWh in the first quarter of 2016 alone.[59]

Texas electricity reform is another successful experience. In order to reduce the cost of transmissions congestion and base load, Texas merged nine separate dispatch areas into one balancing area of ERCOT in 2001 and 2002.[60] In 2010, the state further combined four balancing zones with different pricing mechanisms to a unified electricity market. According to Hove et al., state grid planners claimed that these changes were as valuable as the transmissions investment in under CREZ.[61]

Strategy 5: Faster response and better forecasting

Encouraging faster balancing market and dispatch intervals from hourly to five minutes can improve system flexibility and reliability. Shorter dispatch intervals allow grid operators to adjust electricity generation to accommodate unscheduled fluctuations in supply and demand. Dispatching the system in a shorter time interval would reduce scheduling deviation and reduce system balancing requirements.

Also, adopting various wind forecasting techniques is deemed by grid operators from 18 countries as "the most important prerequisite for successfully integrating

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58 John P. Banks, "Renewables Get the Job Done Despite Skepticism," The Brookings Institution, September 11, 2016, https://www.brookings.edu/opinions/renewables-get-the-job-done-despite-skepticism/.

59 Lin Liu, "Benefits for Participating in EIM," California ISO, 2016 Q1 Report Quantifying EIM Benefits, April 2016, http://www.caiso.com/Documents/ISO_EIM_BenefitsReportQ1_2016.pdf.

60 Hove, et al.

61 Ibid.

wind energy into power systems."[62] NERL estimated that each 10 percent improvement in wind forecasts could result in 4 percent reduction in curtailment and significant operation cost.[63] Widiss and Porter summarize how forecasting can benefit renewable integration in at least three ways. First, it can help reduce the amount of system flexibility required for integrating variable generation; second, better forecasting provides information about current weather condition and helps better prepare for output ramping; and third, it enables more efficient scheduling and dispatch, reducing fossil fuel consumption, plant damage, and additional O&M cost associated with frequent plant operational changes.[64] In practice, system operators and wind generators adopt multiple forecasts to improve accuracy, and share information for better cooperation.[65] PSCO improves its forecasting model using resources from the National Center for Atmospheric Research. These practices have helped generators and grid operators reduce their cost of forecasting and reduced curtailment.

62 Lawrence E. Jones, "Strategies and Decision Support Systems for Integrating Variable Energy Resources in Control Centers for Reliable Grid Operations." U.S. Department of Energy and Alstom Grid, 2011, http://www1.eere.energy.gov/wind/pdfs/doe_wind_integration_report.pdf.

63 Debra Lew, Michael Milligan, Gary Jordan and Richard Piwko, "The Value of Wind Power Forecasting," National Renewable Energy Laboratory, April 2011, https://www.nrel.gov/docs/fy11osti/50814.pdf.

64 K. Porter and J. Rogers, "Survey of Variable Generation Forecasting in the West: 2013 Update," National Renewable Energy Laboratory, April 2014, https://www.nrel.gov/docs/fy12osti/54457.pdf.

65 Bird et al., 2014.

Policy implications

Despite various difficulties and constraints, the United States has successfully reduced wind curtailment.

Banks summarized that expanded grid operation areas, fast markets, improved forecasting, and flexible generation are among the key factors for the success of renewable energy. Banks particularly emphasizes flexibility and argues that "flexibility is the new paradigm" under modern electricity systems.[66]

However, China's power sector exhibits few of these characteristics. Since the electricity structural reform from 1997-1998, China has successfully encouraged generation-capacity building to fuel the fast-growing economy. Yet the reform is far from complete. In contrast to the success of the United States, China has a long way to go in improving system flexibility. Lagged grid construction, absence of market elements, and provincial-based operations represent weaknesses of energy governance in the era of low-carbon transition. Table 1 summarized five areas of the power sector that facilitate different levels of system flexibility in China and the United States.

In this section, we propose three policy recommendations to increase penetration of renewable energy in China.

First, **establish regional electricity market pilot program to break the inter-provincial barriers**. Expanded operating areas would allow grid operators to access to a larger pool of balancing resources including diverse generation resources, transmissions, and demands, thus increasing resource variability, improving system reliability, enhancing grid tolerance, lowering baseload, and reducing costs. In spite of various "prioritize dispatch" policies and limited pilot programs, the current power dispatch is dominated by quota setting which allows the provincial grid operator to set generation plans for different sources based on demand and export assessment. In current annual electricity planning, the grid operators schedule hydro power and coal-fired sources first, and leave the remaining share to wind and solar. Creating a day-ahead market and real-time market to replace the old allocation mechanism is a pressing task. China has initiated some provincial pilot market programs in 2017. The emphasis now should be on breaking the inter-provincial barriers to build an effective market. The

66 Banks, 2016.

Table 1. Comparison of the power sector governance between the U.S. and China

	U.S.	China
Integrated Planning	Substantive cooperation and emphasis on diversification	Limited cooperation, little emphasis on diversification
Flexibility Requirements	Flexible generation, demand response	Emphasis on flexibility in 13th FYP, some pilot coal fire flexibility improvement programs
Operating Areas	Large, aggregated operating areas	Fragmented, provincial-based
Market Element	Active, fast, wholesale market with designs to balance market power; retail deregulation	No wholesale market, executes government benchmark price, limited bi-literal contract and pilot market programs
Wind Forecasting	Multiple advanced forecasting	Weak or no forecasting

government should consider taking a step further to enhance the pilot program to the regional level.

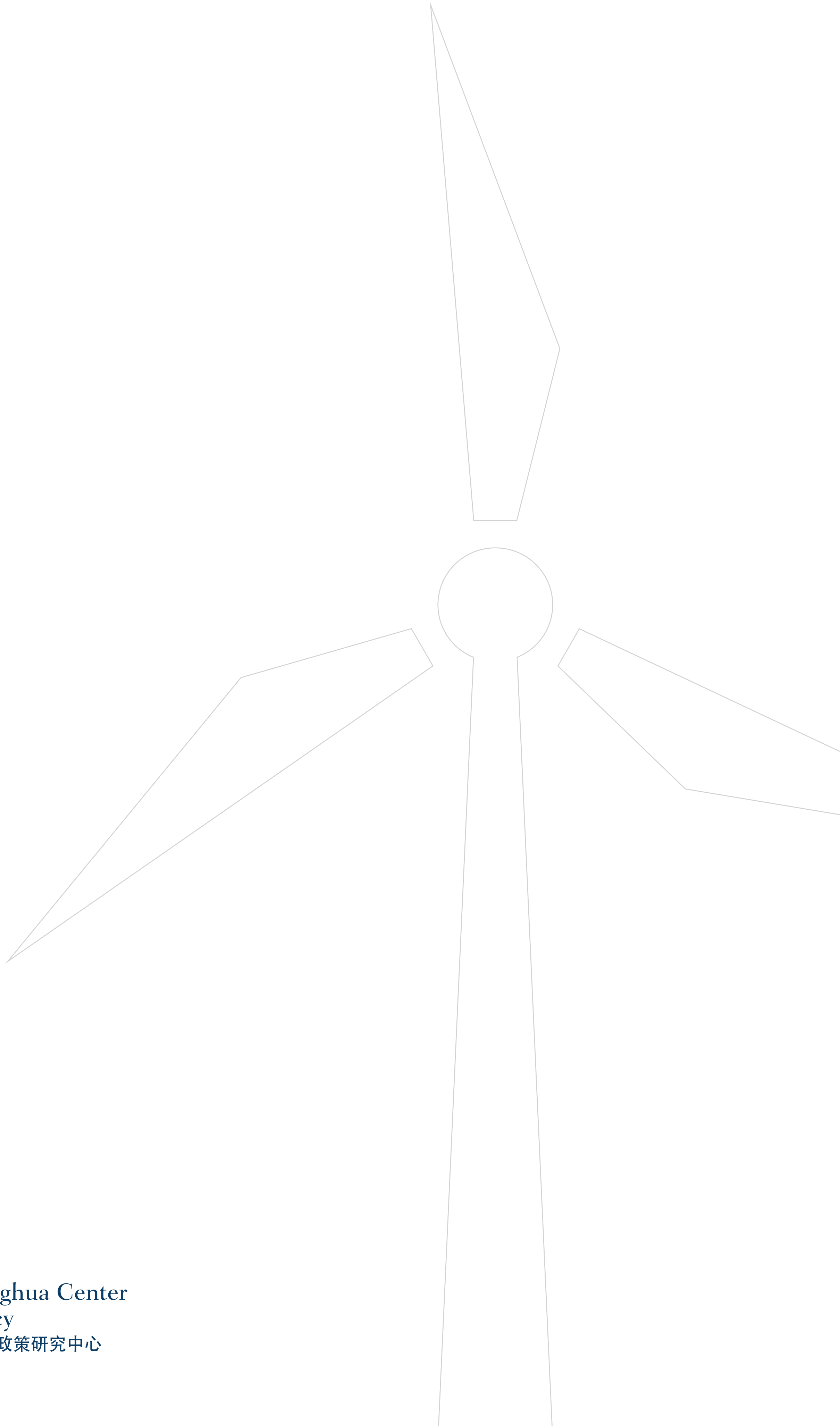
Second, **carefully design a regional market that balances market power of different players**. As we learned from the Northeast Market Pilot Program in 2003, the unbalanced market power leads to political dispute which eventually cost the program. During the experiment, generators soon lost their market power due to a rapid increase of the price of coal, eventually invoking political disputes among stakeholders and the provincial government. As U.S. electricity reform experiences show, the asymmetry of market power can be managed with more sophisticated and careful market design. Some market mechanisms, such as long-term/short-term contract and futures, can help to mitigate market fluctuations and imbalances. We suggest placing balance of market power at the center of market design to minimize potential conflict and political disputes among players, and to ensure the sustainability of electricity market reform.

Third, **improve wind forecasting and operate based on the forecast**. International experiences have shown that accurate and fast forecasting can yield significant economic benefit to both wind power generators and grid operators. As of 2017, fast, advanced weather and wind forecasting is rarely used in wind power operation in China. In Gansu, for instance, wind farms tend not to have forecasting equipment, and wind farms and grid companies are in dispute about who should bear the cost. The poor wind forecasting limits the capacity to manage uncertainty, thus enlarging the burden on the grid system. Wind generators may cooperate with the grid operators and researchers to advance their forecasting technology, and each should adopt multiple forecasting measures to improve accuracy. System operators should integrate advanced forecasting techniques into market operations, the control room, and other standard operating practices.

Conclusion

The curtailment issue is a syndrome of the ineffective energy regulation and absence of basic market elements. It signifies deep political economic challenges underlying China's energy governance and regulation system during the energy transition. The on-going reforms of the power sector is an opportunity to address these challenges.

Energy transition is a global phenomenon. It is happening in Germany and the United States as renewable shares grow, but the stakes are higher in developing countries. Nations face challenges of renewable integration, and will break the limit of renewable penetration sooner or later to address climate change and sustainable development. Given the magnitude of its potential impacts on climate change, China's energy transition is an important milestone in the Anthropocene. Research on this subject can help facilitate the transitions and consolidate international efforts combating climate change.



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