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Review

China's clean power transition: Current status and future prospect

Gang He[a,*], Hongliang Zhang[b,*], Yuan Xu[c,*], Xi Lu[d,*]

[a] Department of Technology and Society, College of Engineering and Applied Sciences, Stony Brook University, Stony Brook, NY 11794, USA
[b] Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA
[c] Department of Geography and Resource Management & Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Hong Kong, China
[d] School of Environment and State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 10084, China

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A B S T R A C T

In this paper, we reviewed four key themes in the study of clean power transition in China, the resources potential, the technology advancement, the air pollution control, and the policy and reform of the power sector. In each theme, we summarized the ongoing research development and highlighted some key areas for further study. Given that China's power sector transition is a huge task, we hope this review will add some discussions into the ongoing conversation.

Contents

* Corresponding authors.
E-mail addresses: Gang.He@stonybrook.edu (G. He), hlzhang@lsu.edu (H. Zhang), yuanxu@cuhk.edu.hk (Y. Xu), xilu@tsinghua.edu.cn (X. Lu).

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1. Background

Before the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (United Nations, 2015) in Paris in December of 2015, China submitted a plan to the United Nations committing to reduce China's carbon intensity (carbon emissions per unit of GDP) by 60–65% in 2030 compared to that of 2005. According to the plan, China also committed to peak its carbon emissions around 2030 and to increase the share of non-fossil energy in primary energy consumption to around 20%. China cannot fulfill these strategic objectives without the development of non-fossil energy resources, including nuclear power, hydropower, wind power, and solar power.

China now has the world largest power capacity and electricity generation, reaching 1507 GW and 5550 TWh respectively in 2015. In addition, China has achieved electricity access for its all population by end of 2015, providing electricity for the last 2.73 million people who lives in remote areas in three years since 2012 (NEA, 2015). At the same time, power sector contributed to 33% of NOx, 23% of SO_2, and 8% of particulate matter (PM), and 50% of the energy related carbon emission in China. Power sector plays a unique role in achieving national targets and international commitment, and more importantly, to supply clean energy, air, and water to its people.

In this paper, we reviewed four key themes in the study of clean power transition in China, the resources potential, the technology advancement, the air pollution control, and the policy and reform of the power sector. In each theme, we summarized the ongoing research development and highlighted some key areas for further study. Given that China's power sector transition is a huge task, we hope this review will add some discussions into the ongoing conversation.

2. Key research themes

2.1. Resources potential

Fossil-fuel resources in China are featured as "rich in coal, poor in oil and short of gas". According to the BP statistical review of world energy (BP, 2015), the coal reserve in China ranks NO. 3 in the world. China has become the largest producer and consumer of coal in the world, and China itself accounts for more than half of the global coal consumption. The ratio of reserve to production (R/P) of coal in China is only about 30 years. If production of coal in China were to grow at an annual rate of 3.5%, this implies that China could run out of domestic supplies of coal by as early as 2032, if no major new reserves are added. In addition, China's coal reserves and production are concentrated in the North and West of the country (particularly in Shanxi, Shaanxi and Inner Mongolia). To meet the increasing demand for energy in southeastern coastal provinces, where over 40% of the population is located (NBS, 2010), coal is first transported by rail east to the coast and shipped subsequently to the high demand centers in southeast, incurring inevitably additional costs and energy consumption.

Oil represents about 20% of total energy consumption in China. China holds around 25 billion barrels of proved oil reserves, and the highest in the Asia-Pacific region (excluding Russia) (U.S. EIA, 2015). China's total oil production ranks No. 4 in the world (about 4.6 million barrels per day), has risen approximately 50% since 1993 and serves only its domestic market. Despite the increase in production, oil consumption has outstripped production in China, growing at an annual average rate of 6.7%. Imports accounted for 60.7% of total consumption in 2012 (McElroy, 2016). China is the world's second-largest consumer of oil and moved from second-largest net importer of oil to the largest in 2014 (U.S. EIA, 2015).

In contrast to situation of its fossil-fuels, China has abundant renewable resources, namely hydro, wind, solar etc. The potential of hydropower ranks number one in the world, accounting for 1/6 of the global total. According to the river flow rate and water head, the potential of hydropower in China is estimated at 694.4 GW, with economical viable reserve of 541.6 GW (Huang and Yan, 2009). With its vast territory and long coastline, China has also exceptional wind power resources, with onshore potential estimated ranging from 800 GW to 3.4 TW (Archer and Jacobson, 2005; CMA Wind and Solar Energy Resources Center, 2009; He and Kammen, 2014; Lu et al., 2009), and offshore potential from 297 GW to 1007 GW (He and Kammen, 2014; Hong and Moller, 2011; Lu et al., 2009; Lu et al., 2013). McElroy et al. developed a GIS-based spatial economical model to simulate the economical feasible potential for onshore wind power in China. Assuming a guaranteed price of 0.516 RMB (7.6 U.S. cents) per kilowatt-hour for delivery of electricity to the grid over an agreed initial average period of 10 years, their analysis concluded that wind could accommodate approximately all of the demand for electricity projected for 2020 (approximately 7.4 PWh). A study by Davidson et al. (2016) indicated a potential production of 2.6 PWh per year by 2030 (Davidson et al., 2016). This represents 26% of total projected electricity demand, and only 10% of the total estimated physical potential of wind resources in China. Hong and Møller, analyzing the costs of electricity generated from offshore wind in China, suggested that offshore wind energy in China could contribute economically to 56%, 46%, and 42% of the coastal region's total electricity demands by 2010, 2020, and 2030, respectively (Hong and Moller, 2011). As to solar power, He and Kammen using 10-year hourly solar irradiation data from 2001 to 2010 from 200 representative locations in China, found that China has a potential stationary solar capacity from 4.7 TW to 39.3 TW, distributed solar about 200 GW, and the annual solar output could reach 6.9 PWh to 70.1 PWh (He and Kammen, 2016). Resources of solar power are most concentrated in northwest provinces, topped by Inner Mongolia, Xinjiang and Gansu.

China initiated development of hydro, wind, and solar power at different times. Judged by current installed capacity and future development plans, China now leads the world in all three sectors. With the completion of the Three Gorges Dam by the China Three Gorges Corporation (CTGC) in 2012, China's installed hydropower capacity reached a record of 249 GW. By the end of 2015, it reached 297 GW and it is expected to increase further to 360 GW by 2020 (State Council of China, 2014). Current development of China's hydropower resources involves construction of a series of major new dams, including on the Jinsha River, the upper reaches of the Yangtze River. The existing installed hydro capacity is expected to increase by at least 75 GW.

In the past decade, China's wind power has also been developing rapidly. In 2010, China's installed wind power capacity surpassed that of the US to become the world's largest. By the end of 2015 it had increased to 145.1 GW, equivalent to the total capacity of six Three Gorges Hydropower Stations (GWEC, 2016). China is in the process of building nine wind power bases (each with a total capacity larger than 10 GW), including Xinjiang Hami, Gansu Jiuquan, Hebei, Jilin, Jiangsu Coast, Eastern and Western Inner Mongolia, and Shandong, and an offshore one in Jiangsu. Accordingly, China plans to increase its installed wind power capacity to 250 GW in 2020.

China's solar power industry began with export-oriented production of PV cells and panels. In recent years, the domestic PV market has gained more attention and developed rapidly. China's installed PV capacity increased 54-fold from 2010 to 2015, from 0.8 GW to 43.2 GW. According to the current development plan, it is expected that China's PV installed capacity will reach as high as 70 GW in 2017 and 100 GW in 2020 (State Council of China, 2014). In addition, about 10 GW capacity of concentrated solar power (CSP) are planned to be deployed by 2020.

As the three foremost types of renewable energy, wind, solar, and hydro power share two major challenges in China. The first is that the generation capacity is limited by the scale of resources and that the outputs are inherently variable in time. The second is that China's richest areas of wind, solar, and hydro resources are in relatively remote locations. The power grids in these regions are relatively weakly developed and far from the demand centers on the southeast coast. The capacity to consume power locally is often limited, resulting in curtailment – intentional waste of free, clean energy – of all three types of renewable power. Their benefits in terms of fossil fuel substitution, especially the reduction of air pollutants and GHG emissions, have not been fully realized. The strategic plan is needed to optimize the utilization of these renewable sources by taking advantage of their complementary effects in temporal variations.

2.2. Technology advancement

Technology innovation is the key to fulfill the transition to a cleaner power supply in China. Due to the large consumption of coal in total energy and power sector, coal is the major source of air pollutants and carbon emissions (Hu et al., 2015; Huang et al., 2017; Zhang et al., 2012a,b). Thus, cleaning coal through the processes of chemically washing coal of its minerals and impurities, removing sulfur dioxide, and making CO_2 in flue gas economically recoverable is one of the key strategies to clean power (Chen and Xu, 2010). Improving the efficiency of energy distribution and storage and increasing the share of renewable energy are also important technologies. In this section, we summarize the status quo and future prospective of key technologies.

2.2.1. Clean coal technologies

Improving the combustion efficiency using advanced power generation technologies is straightforward in clean coal energy. Replacement of inefficient small units with large units is the fundament for advanced technologies, such as supercritical and ultra-supercritical (USC) technologies, and fluidized beds combustion (FBC). The research on supercritical and ultra-supercritical systems in China started late but develops rapidly. By 2015, there are more than 500 units with capacities of 600 MW or more have been in operation or under construction.

Transformation that converts coal to other forms before combustion is another means to improve efficiency and/or reduce emissions. One major technology of transformation is gasification, which converts carbonaceous materials into carbon monoxide and hydrogen at high temperatures with controlled amounts of oxygen and/or steam. It has the capability to achieve extremely low emissions of SO_2, NOx and PM from burning coal-derived gases.

Liquefaction creates synthetic liquid fuels as substitutes for various petroleum products. It also helps meet the increasing demand for oil in transportation sector in China. Direct liquefaction dismantles coal structure partially and converts coal directly into liquids without intermediate step while indirect liquefaction coverts coal to form a synthesis gas before being converted to liquids (Liu et al., 2010). China has made great progress on coal liquefaction from the late 1990s to 2006 due to the enthusiastic investment and promotion of the central government (Qi et al., 2012). It is important though to evaluate the net energy and life-cycle greenhouse gas emissions in this case.

Integrated gasification combined cycle (IGCC) technology has been improved greatly after the first demonstration power plants in 1980s. It uses coal gasification system to convert solid coal into a synthesis gas containing CO and H_2, so that pollutants such as sulfur components, mercury and PM can be removed from gas before being burned in turbine generator for generating electricity. It also has higher energy efficiency than traditional coal burning since the heat in exhaust gases can be recovered to generate additional steam. China accelerates the development of IGCC after which was selected as a key technology in the National Program for Medium-to-Long-Term Scientific and Technological Development (2006–2010) (Na et al., 2015). Domestic IGCC plants are developed by the combination of importing and using foreign technologies while increasing localization. Units with 300 and 400 MW capacities are preferred. Huaneng Group is the leader of IGCC project in China, it has the first near-zero-carbon-emission IGCC power plant in Tianjin. While USC power plants have lower costs, IGCC offers lower carbon emissions, water demand and solid waste, the possibility for poly-generation, and lower costs to capture CO_2 (Chen and Xu, 2010).

Controlling emissions is also critical, which demands increasing of energy-intensive activities. For example, China increased thermal power generation by 63% from 2005 to 2010 (Zhang et al., 2012a,b). Technologies such as flue gas desulphurization (FGD), selective catalytic reduction (SCR) and electrostatic precipitators have been used to reduce emissions of SO_2, NOx and fine particles. The major technical barrier of using these technologies is the reduction in energy efficiency (Zhai and Rubin, 2013). Future studies should improve the efficiency of pollutants removal by introducing better solvents, process design, and reuse of products. More discussion can be found in Section 2.3.

Although use of emission control devices is required and expected to reduce air pollutants efficiently, it cannot reduce CO_2 emissions. Increasing efficiency of power generation processes is the key means for CO_2 reduction, but it is not enough. Carbon capture, utilization, and storage (CCUS) is the process that requires different technologies to capture CO_2 emissions from large source including power plants and large industrial plants, and then either reuse or store underground. China is currently aggressively pursuing research and demonstration of CCUS. In April 2013, the National Development and Reform Commission (NDRC) adopted a new policy to promote CCUS, trying to pave the way for "large-scale application and commercialization". However, necessary breakthroughs in a series of critical technologies need to be made to achieve the goals of China's CCUS development.

CO_2 capture needs large energy consumption and high cost, which makes reducing energy consumption and cost an important target. The chemical absorbents used in post-combustion capture have the largest effects (Yu et al., 2013). Membrane separation and solid adsorption have great potential to reduce energy consumption (Zhang et al., 2013). For pre-combustion capture, advanced water-gas shift catalyst is a key direction and developing low-energy consumption and large-scale oxygen generation is key for Oxy-combustion (Lai et al., 2012). Low-cost, security and reliable transportation of captured CO_2 to storage location is also important. Leakage detection and security technologies are critical for large-scale transportation using pipelines. Location selection, long-term safety, and cost reductions are the key factors for CO_2 storage (Jafari et al., 2017).

2.2.2. Renewable energy

Development of renewable energies such as solar energy, wind, and hydro power will reduce the increase rate of thermal-power generation. With the support of favorable policies, the industry is experiencing a rapid development in China especially for wind and solar power (Lo, 2014). By the end of 2015, non-fossil fuel energy accounted for 12% of the total primary energy consumption in China, with the aim of 15% in 2020 (Chen, 2015). With rapid development of renewable energy in China, the integration becomes an increasingly serious challenge due to large uncertainties caused by meteorological and geographic factors (Li et al., 2015a,b). Researches should be conducted for several aspects to improve the integration. Enhanced transmission as a precondition for renewables, stochastic forecasting, cluster connection and control, forecasting the demand side, and an increased flexibility on the supply side are important measures for China (Lu et al., 2016). Another essential contribution can be provided by distributed energy supply, storage technologies, micro and smart grids, and smart meters.

2.2.3. Smart grids

Dealing with renewable energy requires complex planning and operation scheduling supported by technologies. Smart grid, which refers to a class of technologies to deliver utility electricity using computer-based remote control and automation, is made possible by two-way communication technology and computer processing (Aghaei and Alizadeh, 2013). Smart grid can enhance energy efficiency by improving operation of traditional power plants and grids, facilitate the integration of renewable energy in large-scale concentrated and/or small-scale distributed ways, and boost innovations and applications in demand response and promote energy efficiency in demand side. In China, smart grid deployment is estimated to effectively avoid 63 GW of coal power installation in 2020, which is 220 billion RMB reduction in coal power plant investment. Increase in efficiency of power plants also decreases coal consumption and overall line loss. By increasing renewable energy installation by 25–30 GW in 2020 and promoting electric vehicles (EV), it also significantly reduces emissions of air pollutants and CO_2 (Yuan et al., 2014b).

Developing smart grid is not just an engineering or technical problem. Multiple challenges should be dealt with for the transition to smart and low carbon power systems. China has made encouraging progress with an expanding ultra-high voltage transmission system. Since 2004, fundamental research was conducted to improve large interconnected power system and real-time simulation. In 2007, the East China Power Grid (ECPN) carried out the first feasibility study on smart grid focusing on power system deployment, digital substations, and unified data platform. From 2010 to 2012, the State Grid Corporation of China (SGCC) lunched a total of 228 pilot projects across the country and breakthroughs that have been made include smart substation, automatic power distribution, collection of power consumption, EV charging infrastructure, and smart grid deployment (Tuballa and Abundo, 2016; Yu et al., 2012).

Despite tremendous success, several problems exist like slow progress in distributed generation, micro-grid and intelligent demand management, integration of medium/small scale renewable generation, lack of clear national strategy, monopoly position of grid companies and their incentive structure (Yuan et al., 2014b). In particular, technology immaturity is crucial as the smart grid is still emerging, standards are not in place, and features are not fully proved (Luthra et al., 2014). Also, ancillary facilities have problems in coping with the requirements of smart grids (Armaroli and Balzani, 2007). For example, most current equipment do not satisfy the requests of informationizenation, interoperability and automation; equipment specifications and standards are inconsistent and not interchangeable in different areas (Yu et al., 2012). The difficulties are not specific to China, but China may need more efforts to overcome them due to large differences in economic developments, industrial types, residential activities and reality among regions.

2.2.4. Energy storage

Energy storage unit is energy buffer or backup to counteract power imbalance between supply and demand. Energy storage is believed to be a flexible resource that can significantly offset carbon emissions, enhance system reliability and increase system efficiency and resiliency. Energy storage can facilitate increased penetration of renewable energy by storing excess solar and wind energy and using it in times of peak demand (Luo et al., 2015). However, the promising technology cannot be fully utilized in China due to the present status (Li et al., 2015a,b).

Material cost is key for advancement of energy storage technology. Performance, lifetime, reliability, and specification of the materials affect requirements and standards, leading to high cost constraints. In short time, it is tough to overcome cell efficiency and cost, so cost of battery critical materials should be the focus for reducing total storage cost. High cost of battery for China is the lack of self-developed technologies (Huang et al., 2008). Maturity is another factor that limits energy storage. Decision makers tend to avoid energy storage products due to the technological maturity level, reliability and environmental impacts caused by toxic chemical materials used (Mahlia et al., 2014). Difficulties in large-scale industrial application and lack of industrial policies are also limiting the development of energy storage in China (Yuan et al., 2016a,b).

2.3. Environmental impacts and pollution control

Power generation poses serious impacts on the environment, while addressing these impacts generally also requires energy consumption. This section discusses about the two-directional relationships for various energy resources that are playing or planned to play significant roles in China's power generation.

2.3.1. Air pollution and power generation

Energy consumption is closely linked with the emissions of major air pollutants, such as SO_2, NO_x and PM (IEA, 2016). In comparison with other fuels, coal often has the highest emission rate for one kWh of electricity. Coal contains a certain proportion of sulfur and when burned, it will be converted into SO_2. Different coals have different sulfur contents to result in different SO_2 emission factors. One direct solution is to burn lower-sulfur coal to reduce the generation of SO_2 (Lu et al., 2011). NO_x emissions have two major sources. On one hand, nitrogen in coal could be converted into NO_x in combustion. On the other hand, the high-temperature combustion with air could turn nitrogen gas in the air into NO_x. Coal contains ash to emit primary PM when burned. SO_2 and NO_x in the air could be converted into secondary PM through atmospheric chemical processes, whose aero-dynamic diameter is often smaller than 2.5 micro meters to fall into the category of $PM_{2.5}$ with major health impacts (Chan and Yao, 2008; Zhang et al., 2012a,b).

Pollutant removal technologies are available to prevent emissions, but generally have to consume significant amounts of energy. For example, the most commonly adopted technology for SO_2 removal uses limestone slurry to react with SO_2 in flue gas and emit CO_2. Energy is consumed for pumping the limestone slurry and driving fans. Depending on the sulfur content of coal, usually about 1%–2.5% of electricity that is generated in a coal-fired power plant could be consumed for the purpose and accordingly more CO_2 would be emitted (Xu, 2011). The large-scale deployment and normal operation of Flue Gas Desulfurization facilities in China's coal-fired power plants resulted in more than 50 million tons of additional CO_2 emissions in 2010 (Xu et al., 2013).

2.3.2. The energy-water nexus

Energy supply requires much water, for cooling and processing, while the transport and treatment of water are one of the largest sectors for energy consumption (Qin et al., 2015). Power generation that involves steam turbines demands a substantial amount of water for cooling, mainly including coal and natural gas-fired power plants and nuclear power plants. Water use, or water withdrawal from original water bodies, may be significantly different from water consumption, generally evaporated or entering into final products. Three cooling technologies with different water consumption and use rates could be applied corresponding to the local availability of water resources (Macknick et al., 2011; Yuan et al., 2014a; Zhang et al. 2016). For two water-based cooling technologies, the once-through technology has a much higher water use rate, but the circulated cooling technology has a much higher water consumption rate. In an arid region, dry cooling technologies are often used with little water consumption and water use, but the thermal efficiency is lower. Hydropower generation converts potential energy into electric energy. Although water is just a carrier of potential energy and it is not consumed in the process, reservoirs behind hydropower dams often create much greater water surface to enhance water evaporation especially in dry areas and make hydroelectricity in China not necessarily low-water-intensive (Liu et al., 2015). The actual consumption of water for one kWh of hydroelectricity depends on the surface area of the reservoir, evaporation and the amount of electricity generated. One big advantage of renewable energy, other than their much-reduced lifetime emissions of CO_2 and other air pollutants, is that their conversion from mechanical energy (wind) or photonic energy (solar) to electricity does not require water consumption directly and the lifecycle water consumption in China is still much lower than that for fossil-fuel-fired electricity (Li et al., 2012a,b).

2.3.3. Climate change and power generation

Different power generation technologies correspond to a wide spectrum of greenhouse gas emissions per kWh, while fossil fuels-fired electricity has high emission factors (IEA, 2008). Coal dominates power generation in China and has the highest CO_2 emission rate. Because the carbon-hydrogen ratio is much lower and the energy efficiency is higher, natural gas-fired electricity generally emits less than half of CO_2 than coal for one kWh of electricity. China has been actively increasing the supply of natural gas from domestic and international sources, while non-power sectors had been prioritized for replacing coal with natural gas, largely due to the greater environmental benefits and more expensive end-of-the-pipe pollution removal processes (NDRC, 2012). Although hydropower does not directly cause CO_2 emissions, CH_4 could be emitted when vegetation is inundated into the reservoir due to rising water levels (Raadal et al., 2011). Renewable energy such as wind and solar does not emit CO_2 when generating electricity, although a certain amount of CO_2 are emitted during the manufacturing of wind turbines and solar panels. Because of the energy-intensive process of making polysilicon materials, solar energy often corresponds to relatively higher lifetime CO_2 emissions than wind energy for generating one kWh of electricity (IEA, 2008).

In order to reduce CO_2 emissions from power generation, there are generally three major approaches. First, electricity demand could be reduced with higher energy efficiency and better conservation. The average thermal efficiency of China's coal-fired power plants has significantly surpassed that of the United States (Xu et al., 2013). Second, more carbon-intensive fuels could be replaced with lower carbon-intensive ones. China has been aiming for a higher share of non-fossil fuels in its Five-Year Plans (National People's Congress, 2011; National People's Congress, 2016). As a result, the utilization of wind and solar energy has been rapidly increased over the past decade to make China the world largest market (BP, 2016; Xu, 2013), while China's overall coal consumption might have peaked in 2013 (Qi et al., 2016) and coal consumption for power generation could peak in as early as 2020 (Yuan et al., 2016a,b). Third, CO_2 capture, utilization and storage could remove most of CO_2 emissions before their emissions and China is active in its development (Global CCS Institute, 2015; Xu and Liu, 2015; Zhang et al., 2013). However, CCS is highly energy-intensive to consume about 20%–25% of electricity that is generated in a coal-fired power plant, or about 15% in a natural-gas-fired plants (IEA, 2013).

2.3.4. Environmental impacts of renewables and unconventional natural gas

Renewable energy could significantly alleviate the environmental impacts of fossil fuels. However, they have their own challenges. Large-scale wind and solar farms often require significant amounts of land and the consequent land use change could negatively affect original ecosystems (Denholm et al., 2009; Ong et al., 2013). Wind turbines, when rotating, generate noise pollution and light flicking to cause nuance for people who live nearby (Saidur et al., 2011). The revolving blades and tall towers of wind turbines could also lead to casualties for migrating birds, although the impacts are regarded low in comparison to modern skyscrapers and kittens (Erickson et al., 2014).

Inspired by the success in the United States, China has been keen in developing its own unconventional natural gas resources. In conventional comparison, coal is cheaper while natural gas is cleaner. However, because of the application of hydraulic fracturing technology, the exploration of unconventional natural gas, especially shale gas, demand a reassessment of the lifetime environmental impacts. The technology often consumes much more water, discharges heavily polluted water, leaks more methane and probably is linked with small induced earthquakes (Caulton et al., 2014; Ellsworth, 2013; Guo et al., 2016, 2017; VanBriesen and Boufadel, 2014). In addition to the related technological challenges in dealing with the potential environmental impacts, China may not have established a capable regulatory system to ensure environmental compliance (Guo et al., 2016, 2017, 2014).

2.4. Reform and policy

The development of China's power sector is driven by technology advancement and policy intervention. China's power sector has experienced four main stages of reform and is still under ongoing reform from a vertical integrated planned sector to a more liberalized market (Kahrl et al., 2013; Zhang, 2007). Those reforms and policies have been swinging between promoting generation capacity to satisfy soaring electricity demand and restricting expansion to improve the efficiency, safety and environmental performance of the power sector. The evolving of China's power sector will be greatly shaped by the following pillar policies.

2.4.1. Coal control policy: cap first and then phasing out

China's power sector is still dominated by coal, which accounts about 65% of the total capacity, and about 75% of the total generation in 2015 (CEC, 2015). China has to peak its coal consumption before it can peak its carbon emission around 2030, as announced in China's Intended Nationally Determined Contributions (INDC) before Paris climate talk. However, 195 planned coal-fired power plants up to 159 GW were issued permits in 2015 to build in the coming years (Myllyvirta et al., 2015). The recent economic rebalancing in China has created a plateaued effect in electricity consumption in some of the economic advanced provinces, and coal for electricity generation might already plateaued in those provinces (Lin et al., 2016). This presented a series of challenges on air pollution, climate change, in addition to the investments by potentially stranded assets.

Controlling and capping coal consumption can be achieved through two main approaches: by administrative regions (province), or by coal consuming sectors, including power industry, iron and steel, cement, coal chemical, coking, building material, and non-ferrous metal industry (Coal Cap Research, 2016). Both need careful coordination between central government and local governments, and sophisticated definition of the targets and elaborate implementation of policy instruments. In this sense, the coal cap and coal replacement initiatives have to be integrated into China overall social and economic development and its grand energy transition.

To quantitatively capture the benefits of reducing coal in concept and make strong arguments for coal controlling policy, there are emerging literature and policy debates on the "external cost of coal", which includes the life-cycle environmental cost of the coal value chain (CAEP, 2014; Epstein et al., 2011; Mao et al., 2008). The external cost of coal in China is reported to range between 204.76 RMB/t (~$30 $/t) and 260 RMB/t (~$40 $/t) (CAEP, 2014; Epstein et al., 2011; Mao et al., 2008; Teng, 2014). The concept of external cost of coal needs more research and discussion. More importantly, how to implement the concept into policy instruments such as resources tax and energy pricing mechanism is a key policy question.

2.4.2. Renewable energy development policy: from quantity to quality

China's renewable energy policy has been focusing on encouraging capacity expansion, and needs to shift to improve the quality so to facilitate systems integration. China's renewable energy development has been a global success story (Qiu and Anadon, 2012). Benefit from strong government support and manufactural capability, China has become the world largest solar and wind installer, with 43.18 GW and 125 GW total installed capacity by 2015, respectively. However, as more variable renewable energy is connected online, the integration presents a practical challenge to the grid. On average, 15% of the wind was curtailed nationally in 2015 (NEA, 2016).

This challenge presents two highlighted areas for policy research. First, the policy evaluation of China's renewable energy industrial policy. China has created feed-in-tariff (FIT) for wind and solar (He and Morse, 2013; Li et al., 2013; Li et al., 2012a,b) and is believed to be a driving force for the booming of wind and solar installation. However, there is not much research on the real impact, and benefits and costs analysis of such policies. Second, policies to facilitate the integration of soaring renewables without hurting system reliability and stability. Research is highly demanded on innovations and strategies on flexible resources, including storage, distributed generation, demand response, and the use of price signal to incentivize and coordinate multiple resources to facilitate the integration of variable renewable energy.

2.4.3. Air pollution control and climate change policy: leveraging the co-benefits

China's power sector will also be shaped by the environmental regulation and climate governance, as power sector is the main source of SO_2, NOx, soot, $PM_{2.5}$, and carbon emission. In 2012, power sector contributed to 33% of NOx, 23% of SO_2, and 8% of PM. Air pollution has presented real challenges to human health, and has become a source of social unrest. Between 350,000 and 500,000 Chinese die prematurely each year because of the disastrous air pollution (Chen et al., 2013; World Bank, 2007).

In September 2013, China's State Council released the National Action Plan on Air Pollution Prevention and Control, which requires that, by 2017, PM_{10} in cities at or above the prefecture level be reduced by over 10% compared with the 2012 level (State Council, 2013). This plan also requires that annual $PM_{2.5}$ in the three metropolitan areas, including Beijing-Tianjin-Hebei Area, Yangtze River Delta, and Pearl River Delta, should be reduced by over 25%, 20%, and 15%, respectively, by 2017 compared with 2012. The Plan also unveiled $277.5 billion to be invested from 2013 to 2017 in the prevention and control of air pollution. Air pollution is a regional problem, the coordination of regional economic development and air pollution prevention and control involves long-lasting efforts.

China's power sector contributes about half of its energy related carbon emissions, which makes it the center arena for carbon mitigation (He et al., 2016). In addition to the command and control policies, a meaningful carbon price would be critical to achieve carbon mitigation at lower cost. China has already launched several cap-and-trade pilot programs in Beijing, Shanghai, Tianjin, Guangdong, Shenzhen, Wuhan and Chongqing, with a price range of RMB20-130 ($3-$20). Chinese government has committed that a national cap-and-trade program will be set up as early as 2017. If the true cost of coal and the social cost of carbon are incorporated, the co-benefits of deep decarbonization would offset the increased electricity costs in dealing with air pollution and climate change at the same time (He et al., 2016; Hu et al., 2017).

2.4.4. Power sector reform: the unfulfilled endeavor

A long overdue reform since the major reform attempt in 2002, State Council unlashed a series documents in 2015 on deepening the reform in the power sector (State Council, 2015), followed by a series of implementation details issued by National Energy Administration (NEA) and National Development and Reform Commission (NDRC), including the mechanisms on transmission and distribution pricing, power market and electricity trade, wholesale market and power exchange.

The reform targets to transform its electricity market aiming at gradually loosening the state monopoly and spurring competitive electricity pricing. As part of the reform package, China will also strengthen governmental supervision and electric-power planning to ensure the system operates at high efficiency and reliability. China will encourage mid- and long-term electricity trading from regions with excess power to those experiencing shortages. The nation will also increase the share of renewable and distributed energy generation in its power supply.

At the core of this market-oriented reform is the power tariff pricing reform, which will fundamentally transform how the electricity is generated, transmitted, distributed and consumed. Electricity is so important to its economic development and maintaining social stability, the long-lasting impact of the power sector reform will need close observation and is an active area for research. Since the electricity system is a complicated physical and economic system that is sensitive to market manipulation, the reform process also requires deliberated regulation and balance of market penetration and regulator's intervention.

3. Concluding remarks

China's power sector consumes about a quarter of global annual coal and emits about 13% of world annual energy related carbon emission, and it is also a major source of air pollutants and PM. The transition to a clean power sector will not just shape the future of China's energy system, but also have large impact on both the local air quality improvement and international climate governance.

China has the resource potential to power its grid largely by renewable energy, and needs to overcome the challenge of system integration posed by the power grid currently dominated by coal fired capacities. China invests heavily on technology development and now hosts the world's highest efficiency advanced coal power units, while the development of big data, energy internet, and energy business model innovation have brought new opportunities for the integration of growing variable renewable resources.

While conventional air pollutants are still the focus of environmental performance in China's power plants, the future installation will be increasingly constrained by PM, carbon emission and water resources. As China builds more solar panels and wind turbines and connects them online, it will have to manage the environmental and societal impact of renewable deployment appropriately.

China's power sector is undergoing major reforms to more market oriented operation, however, articulated regulations are needed to phase out coal consumption, at the same time, boost high quality renewable generation to address the over investment and curtailment of variable renewables.

The transition of China's power sector is backed by its vast potential, however, spatially imbalance and temporally variable renewable resources. The scale, scope, and speed of such a transition is not seen in the history. The effective technological, environmental, and policy instruments are required to be implemented in a coordinative way to make it happen. The success of China's clean power transition will be key to global and China's energy revolution and sustainable development.

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