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Patterns of Innovation in China's Energy System:

A Comparison of Advanced Electricity Generation Technologies

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Patterns of innovation in China's energy sector vary by industry and can be related to China's pre-reform institutional legacy. Focusing on examples of technologies that reduce CO_2 emissions from electric power generation through efficiency and alternatives to fossil fuels (advanced coal, solar, wind, and nuclear), this analysis discusses the roots and extent of currently-observed "cost innovation." First, patterns of innovation in each of these industries are characterized in terms of cost reductions and other measures of innovations achieved. Second, features of each low carbon solution are discussed in terms of historical and institutional context, factor and demand conditions in each industry, enabling government policies or plans, and support for advanced research and development (R&D) activity, among other factors. Third, this descriptive analysis concludes by placing China's situation in a broader context by, when possible, drawing comparisons with patterns of innovation in each of these industries in other parts of the world. The analysis suggests that "cost innovation" is likely to dominate in China's electricity sector for the foreseeable future, even as a transition to knowledge innovation emerges in other parts of the economy. Factors favoring cost innovation include continued large, government-supported domestic market demand for low-cost, reliable renewable energy and nuclear power, as well as persistent constraints and weak incentives related to accessing and/or developing first-of-a-kind applications of electricity technologies. Implications for future fuel choices, as well as the potential and timing of a shift in China from "cost innovation" to technological leadership in the industries considered are proposed.

1. Introduction

Much has been made of China's recent emergence as a source of low-cost environmental technologies of comparable quality, and the potential of these technologies to offset the expected environmental impact associated with ongoing economic development at national and global scales. A subset of a broader trend observed across many industries in China known as "cost innovation" (Williamson and Zeng, 2008), the proliferation of low-cost environmental technologies has been received both positively (e.g. by the global sustainable development community) and negatively (by established industries who see a threat from large-scale influx of China's low-cost products). Nevertheless, the emergence of China as a source of cost innovation is now well established and prompting strategic responses across the global business community (Immelt et al., 2009).

While the emergence of China's cost innovation advantage has been widely recognized, fewer studies have placed this success in the context of the development of the country's broader innovation system. When it comes to knowledge-based innovation that leads to fundamental breakthroughs in product or process design, China's record is weaker. Is the observed weakness just a function of the country's short history of broader investment in advanced research and development capabilities? Or does it reflect systematic weaknesses in incentives facing would-be innovators that are unlikely to disappear without institutional redesign? Given that the government has played a central role in creating conditions for cost innovation in China, will these conditions help or hinder the long-term development of breakthrough innovative capabilities?

This paper provides a foundation for exploring these questions by focusing on advanced electricity generation technologies in China, specifically the cases of solar, wind, coal, and nuclear power. Cases are chosen for diversity in the past importance of generation types (incumbents as well as new entrants), factor and demand conditions (including the role of domestic and international markets in driving adoption at scale and associated cost reductions), and policy drivers. All technologies produce the same commodity product (electrons), controlling for an otherwise important source of heterogeneity in a broader survey of energy system innovation. The paper begins by describing the setting for innovation in China, discusses each of the cases, and draws lessons from cross-case comparisons.

Explaining observed innovation performance in China's energy (as well as other) sector(s) is important for several reasons. Fundamental breakthroughs are widely thought to hold great potential for substantially reducing greenhouse gas emissions and other development-related environmental impacts. China's contribution will be decisive in any path to a low carbon world. How China innovates therefore will affect the mix of solutions that will be applied globally—and whether these solutions will be more low-cost versions of currently-available technologies or something radically new remains an open question. Beyond clean energy, the relative role of cost innovation will have implications in a wide range of sectors. Looking ahead, China's leaders are eager to see the nation operate at the leading edge of new high technology product development—and reap the economic as well as environmental and other rewards associated with this global leadership.

2. Background: Innovation in China's energy system

Explaining patterns in China's present-day energy innovation requires historical context. Starting from the late 1970s, China's leaders embarked on a broad program of economic reforms and opening to the global economy. Efforts to develop homegrown science and technology leadership were launched in parallel, with increasing funds devoted to technology acquisition and to a lesser extent, domestic fundamental research. This context is important because it clarifies the origin of China's cost innovation advantages, as well as its persistent shortcomings in delivering breakthroughs.

2.1 Revitalizing China's innovation system

From 1949 to the late 1970s, science and technology in China were largely organized according to the Soviet Union's central planning model, which defined separate research and production units under the leadership of each industrial ministry. Some basic research remained in the Chinese Academy of Sciences, which was isolated from the industrial sectors altogether; very little research was done in universities (IDRC, 1997). During the Cultural Revolution (1966-76), universities were dispersed to the countryside, researchers and professors were downgraded to the lowest classes, and industry received little to no infusion of fresh ideas. Despite the isolated achievements of a few focused initiatives, such as the synthesis of insulin, the 1970 satellite launch, and the detonation of the hydrogen bomb, innovation capabilities in China languished and proved ill-equipped to contribute substantially to economic activity.

Mao's death and the end of the Cultural Revolution prompted a sober look at the shortcomings of China's innovation system. Led by Deng Xiaoping, the government embarked on a broad reform program that included rehabilitation of academics, limited ownership and market reforms in China's state-owned enterprises (SOEs), and strong emphasis on science and technology development. Both the 1978 National Science Conference and the Sixth to Eighth Five Year Plans (1981-1995) included commitments to revitalizing science and technology as economic drivers. To modernize capital stock and seed domestic innovation, the government spent an estimated U.S. $40-70 billion on imported technology purchases between 1979 and 1993 (Suttmeier and Cao, 1999). Despite poor or redundant technology choices, this effort did result in the widespread upgrading of product quality, savings in energy use, and productivity gains. China also sent many students overseas for further study and upgraded its own laboratory facilities with the help of international loans. **Figure 1** shows the number of students from the mainland studying abroad and returnees since 1978. Much of the emphasis of science and technology policy during this period focused on creating a domestic workforce capable of developing useful products and services that would aid in the country's development.

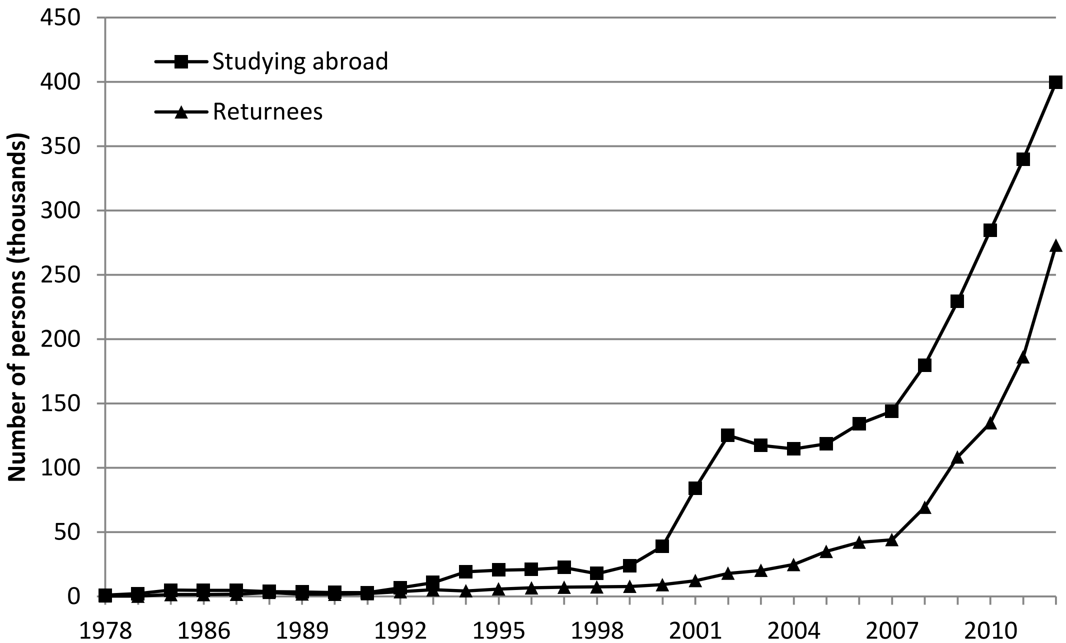
How to make research more responsive to industry needs has remained a persistent challenge. The 1985 "Decision on Reform of the S&T Management System" included reducing government funding to research institutes and providing them with more management autonomy to foster relationships with enterprises (Liu and White, 2001). The survival of research institutes depended increasingly on their ability to meet the needs of industry, while stronger market competition led industries to seek the latest technologies that would confer a competitive advantage. The government also began to provide competitive grants to researchers to focus on industrial problems, the most prominent of which was the "863" Program (so named because it was launched in March of 1986), which awarded competitive grants for applied research in several key sectors, including energy, aerospace, and biotechnology.

Departure from the old system at the very least sensitized many institutions to their bottom lines and at most induced drastic overhauls of mission and identity. Research institutes facing tight budgets struggled to redefine themselves as universities, consultancies, businesses or basic research facilities, and some still fill the roles of all four. Some research institutes were completely restructured into enterprises or became the in-house R&D department of their industrial counterpart, while others engaged in a mixture of consulting activities, enterprise spin-offs, or basic research. Outcomes varied widely by location and industry, but overall responsiveness of institutes to economic realities increased. Though the number of spin-offs was high (CAS spun off more than 900 enterprises during the reform period), the number failed attempts was also significant (60-70 percent), placing an added burden on parent institutions and the social welfare system (IDRC, 1997). Despite a steady rise in the R&D intensity of GDP since the reforms began, a persistent observation of China's innovation system is that it does not emphasize fundamental research enough.

The reforms also targeted state-owned enterprises (SOEs) with the goal of increasing their responsiveness to international and domestic competition by reducing state ownership, increasing R&D spending and technology acquisition, and encouraging formation of domestic or international joint ventures. SOEs that had for years passively accepted government-mandated technology investment decisions had seriously weak or nonexistent R&D departments. The university system also experienced considerable restructuring during the reforms. In 1998, many research institutes were decoupled from industrial ministries, given full-fledged university status, and oversight was reassigned to the Ministry of Education. Suddenly, formerly technical institutes were charged with a broader mission of training and basic research, with faculty status determined by student throughput and academic publications in internationally recognized journals. Many began to raise tuition and began to market their services and inventions. Both traditional comprehensive universities and those derived from research institutes began to spin-off enterprises, creating a rich class of new high technology businesses. On the other hand, in the more traditional industries, such as mining and petrochemicals, universities and research institutes increasingly performed contracted R&D activities for the latter. Often partnerships were dictated by former institutional ties carried over from the association of production and research units under the same ministerial leadership; outside of these historical links, novel horizontal partnerships were otherwise slow to form (CUP, 2006).

In addition to extensive purchases of foreign technology, the government encouraged overseas firms to invest in China and set up manufacturing bases, reflected in high levels of foreign direct investment (FDI) and a large number of joint ventures across a variety of industries. Chinese-made versions of imported technologies are often developed quickly and in some cases are up to eight times cheaper than their foreign counterparts, which may carry heavy royalty payments and technical fees. Although in many cases the quality and technical support associated with imported technology has been noted as superior, price is often the deciding factor for local firms lacking an established financial position and fighting to survive in competitive industries.

Figure 1 Number of Chinese students studying abroad and students returning to the Chinese mainland.



Source: China Statistical Yearbook, 2013.

2.2 Origins of China's advantage in cost innovation

In many respects, China's early efforts at seeding a modern science and technology enterprise against a backdrop of rapid, export-driven economic growth created conditions ripe for the emergence of cost innovation. Relatively low labor and capital costs, a growing overseas and domestic market for low cost products of comparable quality (especially true in China for staples such as electric power), promotional export policies, and a strong application-oriented engineering workforce provided a winning formula, as will be discussed in the specific cases of electric power technologies. The government's role in fostering market certainty for specific technologies—for instance, through setting national capacity targets by fuel type or naming and mandating the application of specific technologies at scale—has also played an important role in incentivizing manufacturers to move quickly to large scale production and to deploy resources in ways that keep costs low. These targeted policies and technology development programs have served the immediate goals of enlisting large domestic production capacity (e.g. industrial policy) and delivering low cost market solutions deemed necessary given the rapidly expanding need for reliable, affordable power in China during the early 2000s.

By contrast, the conditions and incentives needed to develop the deep knowledge and know how needed to produce breakthrough innovations have remained weak. Collaboration partners have hesitated to transfer knowhow along with blueprints; tacit knowledge and related managements practices are in any case difficult to transfer. Uncertainty surrounding potential applications and marketability of any new technology also discourages private sector investment, while public R&D funding to enterprises and institutes is easily repurposed to serve more immediate goals. While it is possible that achieving breakthrough product innovations is just a matter of time, it is also important to understand whether incentives are aligned in ways that would allow these breakthroughs to emerge over the longer term.

3. China's electric power sector

3.1 Institutional organization of China's electric power industry

China's electric power industry has remained among the targets of reforms since the mid-1980s. In 1986 as part of the government's broader reform agenda, efforts to attract greater investment by opening the sector to non-state investors were introduced. Reforms went another step forward in 1997 by creating the State Electric Power Corporation from the former production arm of the Ministry of Electric Power, which in 2002 was parsed into five generating companies (each less than 20% of market share), two grid administration companies, and several consulting companies to further encourage improvements in management and allocation efficiency by fostering competition. However, since 2002, reforms in China's electricity sector significantly slowed.

In March 2003, a regulatory body, the State Electricity Regulatory Commission (SERC) was created under the State Council to supervise and regulate competition in the industry. As the first government-sponsored regulatory agency in the primary industry sector, the SERC is charged with issuing licenses to operators, monitoring operations, and holding operators accountable for violations of pricing and competition rules, as well as setting up an electricity supply trading market. Although intended as a major step towards allowing more competition and independence among various players in the power sector, the role of the SERC remained unclear for two years and was often overshadowed by the powerful NDRC. New guidelines issued in 2005 helped to clarify the situation, but allocated the key task of approving power investments to the NDRC instead of the SERC as originally envisioned. The need to retain government control until the power shortages can be resolved was the reason given for the failure to delegate greater responsibility to the SERC, which rendered the organization weak and ineffective (Metha, 2005). The SERC was folded into the National Energy Bureau in late 2013.

With the transition of national leadership in 2012, attention has once again focused on the potential for further electric power sector reform. Potential reforms include moving to market-determined electricity prices, the creation of wholesale markets for electricity, and breaking up the state grid monopoly as well as privatizing or adjusting incentives within state-owned enterprises more broadly. In the case of new power projects, project developers negotiate an electricity tariff that ensures cost recovery (broadly consistent with band set by the government by generation type), calculated as a function of technology cost, efficiency, and location. Operating hours by generating type are largely determined by the grid company, which can in principle factor cheaper generation options, although it has been instructed to facilitate grid connections for more costly renewable electricity. A surcharge is factored into the electricity price charged to consumers, which is divided between the renewable developers and the grid company in order to create an incentive to deploy renewable energy. This system has not been uniformly effective in incentivizing renewable utilization. During the 2000s, policy set mandatory capacity targets but not generation targets, with the result that by 2010 much of China's large new renewable capacity was not connected or well-integrated into the generation mix. In renewable deployments plans for 2020 and beyond, generation targets are now included alongside capacity targets.

3.2 Energy use trends in China's electric power sector

China's electric power sector has historically been dominated by coal, while installed capacity for hydropower, and more recently nuclear, solar, and wind, has increased as a share of the total. China's coal-dominated energy mix underpins its large and growing contribution to total global CO_2 emissions. The electricity sector accounts for around half of China's coal use, and until very recently, the share of coal in China's electricity generation exceeded 90%. By contrast, wind, solar PV, and nuclear have been developed more recently, with nuclear development starting earliest from the mid-1990s. Electricity use demand growth accelerated during the early part of the 2000s and has continued apace, with coal use continuing to increase along with growing shares of nuclear, wind, and to a lesser extent, solar PV. Installed capacity by generation type in China's power sector is shown in Figure 2, while rapid demand growth observed since 1985 in China relative to the rest of Asia is shown in Figure 3.

Figure 2 Installed capacity by primary energy type of China's electricity system through 2013.

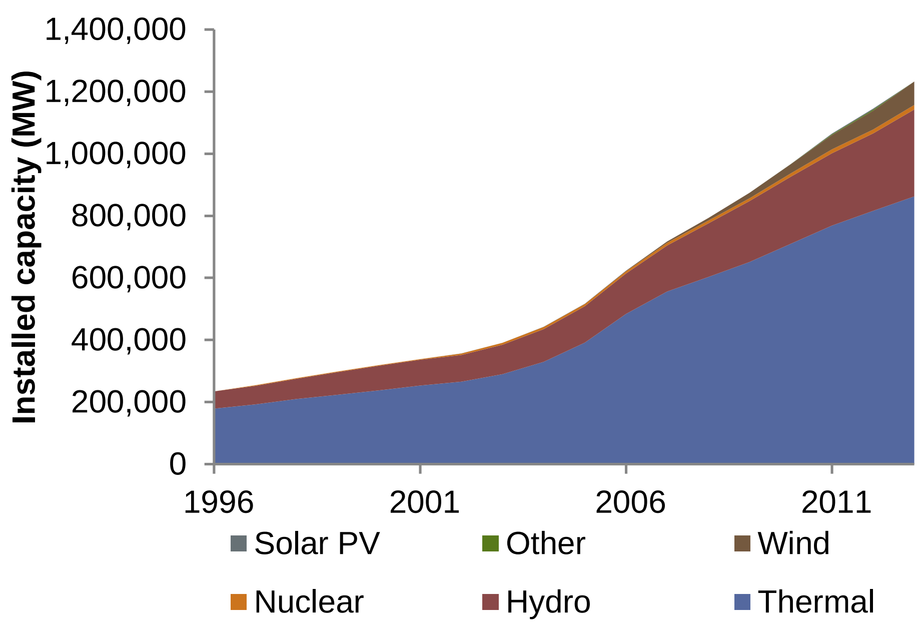
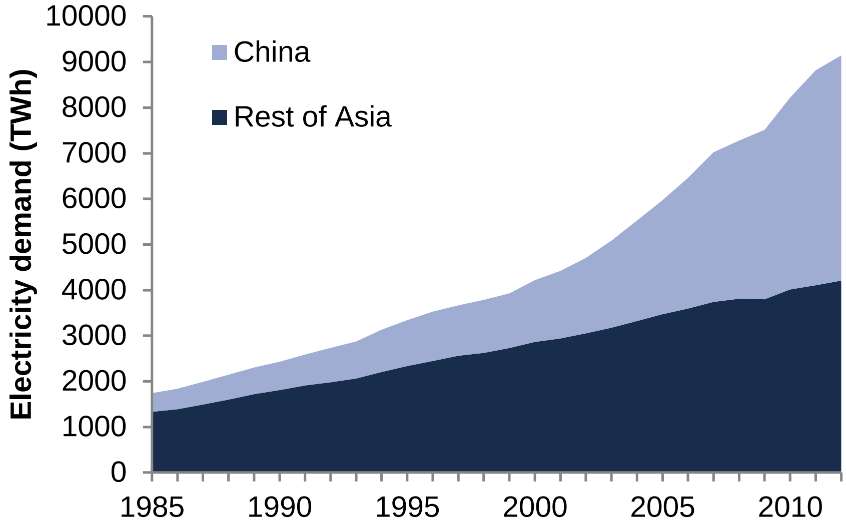


Figure 3 China's rising share of Asian electricity demand, 1985-2013.



4. Case studies of advanced low carbon electricity technologies

Table 1 summarizes several drivers and general patterns of innovation for several electricity technologies in China, focusing on the case of coal, nuclear, solar, and wind. The following sections start with a description of patterns of innovation for each, with a focus on cost reductions achieved in China (or attributed to developments in China). Second, each low carbon electricity solution is discussed in terms of historical and institutional context, factor and demand conditions in each industry, enabling government policies or plans, and support for advanced research and development (R&D) activity, among other factors. The conclusions place China's situation in a broader context by, when possible, drawing comparisons with patterns of innovation in each of these industries in other parts of the world.

4.1 Efficient coal generation

Given the central role of coal in the electric power system since its inception, it is no surprise that the country has focused on ways of improving usage efficiency and reducing its impact on the environment. However, it is important to note that innovation improving the efficiency of coal use is different in important ways from the low carbon technologies that would displace it—it is the incumbent (with strong backing from established interests), its scale is massive, and innovation is mainly about improving efficiency, rather than driving the adoption of an alternative.

Development in China's coal power industry reflect the dual need to provide reliable, inexpensive power with an interest in more efficient advanced designs. China clearly designated the supercritical (SC)/ultrasupercritical (USC) technology as its preferred option for scaling up coal generation at the end of 1990s to meet rapidly growing domestic electricity needs (Yue, 2012). The domestically-produced 1000 MW USC Yuhuan Power Plant came online at the end of 2006, signaling that the USC technology had been indigenized successfully. At the same time, China's cost advantage in installations of USC technology became widely recognized, even relative to sub-critical units, with a 1000 MW USC unit costing 550-700 $/kW, while by comparison a sub-critical unit cost 650-800 $/kW (Yue, 2012). These designs were also significantly cheaper than estimates for new sub-critical projects in the United States. These investments and rapid deployment of SC and later USC technology led to a reduction in energy intensity of electric power generation—the average grams of coal equivalent per kWh across China's coal fleet declined from 370 in 2005 to 340 in 2009.

The rapid rise of USC technology in China benefitted from explicit government support on multiple fronts. In 2000, a Plan for the Development Complete Sets of 600 MW SC Coal-Fired Power Unit Equipment was included in the National Key Technology R&D Program under the Tenth Five-Year Plan (FYP) (Yue, 2012). Over time, USC has remained the favored technology, leaving alternatives such as integrated gasification combined cycle (IGCC) as targets for advanced research but with few clear policy signals about future potential market size. Similarly, carbon capture and storage remains in China's R&D pipeline, but has not achieved the scale or breakthroughs that many had expected, and projects have been subject to delays (Sims Gallagher, 2013). The difference in the fates of USC and IGCC thus far suggests that the policy and institutional environment is far better suited to cost innovation at present, a situation that is further complicated by conditions under which China can access the intellectual property and develop indigenous designs.

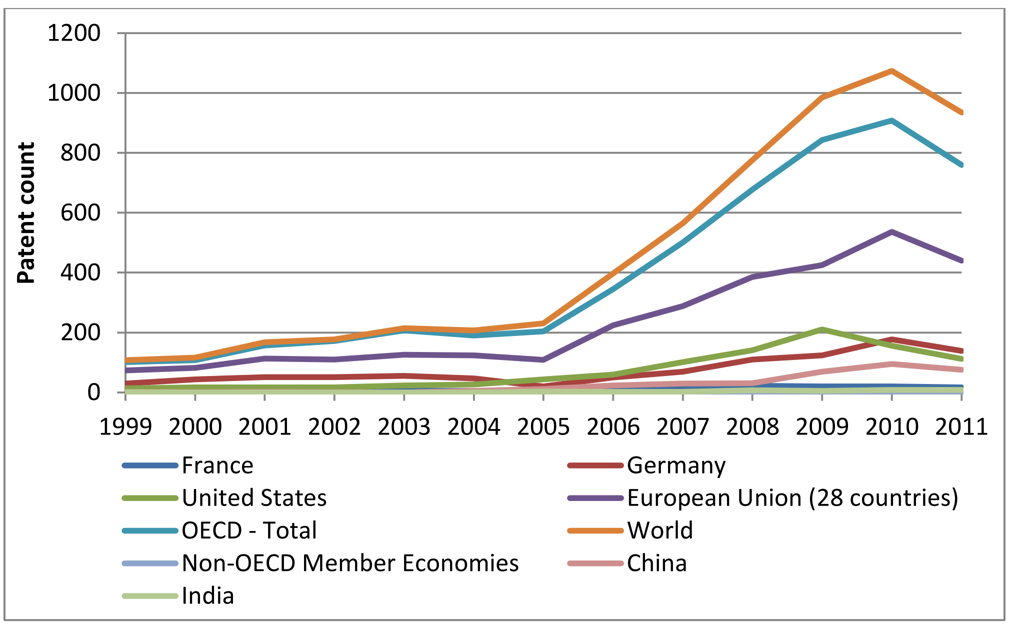
4.2 Wind

With over 30 years of development in mainland China, wind has recently been growing rapidly as a share of installed capacity, and is beginning to make a substantial contribution to total electricity generated, especially in regions endowed with rich wind resources. By the end of 2013, China's wind installations expanded to 77.6 GW (from only 25 MW at the end of 1996) and wind generated reached 137 Terawatt-hours (TWh), a scale exceeded only by wind deployment in the United States (CNREC, 2014). By 2020, officials target 200 Gigawatts (GW) of installations and 390 TWh of annual wind generation. Long-term projections reach as high as 400 GW by 2030 and 1000 GW by 2050, possibly accounting for 17% of total electricity demand (ERI, 2011).

Innovation in China's wind technology industry has also largely followed the cost innovation path, adopting and localizing designs from overseas manufacturers. The drop in wind turbine price to about one third of what the prevailing cost overseas was in 2007 has been attributed to the competition posed by Chinese products, while in the Chinese market domestic manufacturers tended to beat costs of foreign entrants by around 20% (Zhang et al., 2009). Much of the cost reduction in wind turbines occurred in the course of domestic market expansion and the prominent role that homegrown companies quickly achieved in new market share. Over time, the share of new wind farms constructed by domestic manufacturers and their joint ventures increased to 75% in 2008, as a result of the improved equipment quality and favorable local industrial policy. In 2003, the introduction of bidding for wind farm concessions (as opposed to the earlier practice of direct government contracts) signaled the beginning of China's large-scale wind development. While in the early years all wind projects required central government approval (which proved time-consuming and costly), rules were later changed such that only wind projects larger than 50 MW required central approval (Han et al., 2009). (This helps to explain why most of China's wind projects are 49.5 MW.) Starting with the second round of bidding for wind farm concessions, a process coordinated by the National Development and Reform Commission, a 70% local content requirement has been imposed. In the early bidding rounds, domestic manufacturers offered unrealistically low prices in order to win, leading to later cost overruns and compromising quality.

Patent data also support the dominant role of cost innovation in China's wind industry in recent years. Overall, China's international patenting activity has remained limited relative to other countries (**Figure 4**). Domestic patenting activity also began to increase rapidly starting from around 2002, and grew exponentially through 2008. The total number of patents issued to domestic developers in 2008 was close to 1,000, which exceeded the total number of patents issued globally in that same year. However, a closer examination of these domestic patents is necessary to distinguish them from international patenting trends—anecdotally these patents represent developments needed to protect local adaptive innovations. Filing for a domestic patent was also far less costly and time consuming, served the needs of manufacturers who were primarily targeting the domestic market, and avoided language barriers, compared to filing for a global patent.

Figure 4 Number of wind equipment patents filed by inventor country of residence under the Patent Cooperation Treaty.



Several policies have underpinned China's acquisition of wind technology and its expansion, including the wind power concession program, power price surcharge to support renewable developers and grid companies, and a range of forms of tax relief for developers (Zhang et al., 2009). China's technology developers have become adapt fast followers of global product development, as measured by the rapid catch up of developers in terms of turbine size (Ru et al., 2012). However, in the area of wind technology, investment support for manufacturing has remained largely disconnected from incentives to innovate in turbine design (Grau et al., 2010). This observation is perhaps not surprising, given the very short time horizon over which China's wind industry has emerged (Ru et al., 2012). Zhou et al. (2012) find that what is often termed R&D in China's wind joint ventures is an extension of technology licensing arrangements, given the persistent knowledge gap between the Chinese and overseas developers engaged.

4.3 Solar PV

In contrast to wind, cost innovation in solar PV technology has been achieved largely through scale deployment overseas rather than in China's domestic market. When China's Renewable Energy Law was passed in 2006, solar PV was still relatively expensive by domestic market standards. However, the existence of favorable policies outside of China—most notably feed-in tariffs in Europe—created an opportunity for domestic manufacturers of PV systems, enhanced by a range of policies aimed at promoting China's export industries. Production capacity expanded rapidly from the mid-2000s, with the number of individual domestic manufacturers also increasing dramatically. The number of domestic PV manufacturers doubled between 1998 and 2004, although at the time most subsisted on far smaller sales volumes and older versions of the technology.

The growth of the international market has been complemented by domestic efforts to scale up the technology through subsidized government purchases—examples include the Golden Sun Demonstration Program, announced in July of 2009 by the Ministry of Finance, the Ministry of Science and Technology (MOST), and the National Energy Administration (NEA), which supported more than 500MW PV projects in two or three years (Huo et al., 2012). In the same year, investment subsidies were announced for on-grid (50% capital cost subsidy) and off-grid PV systems in remote rural areas (70% capital cost subsidy). Starting from March 2009, the Solar Roofs Program also provided a domestic installation incentive—the Ministry of Finance (MOF) and the Ministry of Housing, Urban and Rural Development (MOHURD) provided additional per-watt subsidies for new installations (Huo et al., 2012).

Technology acquisition and localization was accompanied by efforts to seed basic R&D in the development of advanced materials and other technologies with applications in the solar equipment industry. Most basic R&D funds for solar PV were provided by the Ministry of Science and Technology, and public spending totaled 4.54 million Euros, ranking China twelfth out of 17 countries engaged significantly in solar PV R&D (Huo et al., 2012). China's ranking in terms of public R&D spending on PV stands in contrast to its status as a major center of PV manufacturing. Interestingly, China did not have specific targets for cost reduction as were characteristics of R&D programs in other parts of the world, perhaps because ways cost reduction were achieved in China differed from the expected sources of cost reductions targeted by the rest of the world.

4.4 Nuclear

Nuclear power factors strongly into the government's energy development plans, especially for the coastal provinces far from coal reserves. China began developing nuclear power in the mid-1980s. Efforts to localize the technology at low cost have been the central goal of China's nuclear technology acquisition and development programs. The first plants included one at Hong Kong's Daya Bay designed by Framatome with turbines supplied by GE, while one at Qinshan (south of Shanghai) employed technology that was almost entirely indigenously designed based on earlier imported models. Two later plants relied on similar Framatome or indigenous designs, though one employed CANDU technology developed by Atomic Energy of Canada. The country's nuclear capacity has grown from 8350 MWe in 2006 to 14610 MWe in 2013. China's National Nuclear Corporation (CNNC) is constructing eight new large reactors, which are localized versions of Westinghouse's AP1000 (the CAP1000 and soon the CAP1400), while as of spring 2014 a consortium of companies had signaled interest in buying eight new Westinghouse reactors. Closest to completion is the Sanmen 1 reactor (Westinghouse AP1000), which is expected to come online in 2015. Simultaneously, nuclear construction using Areva technology (Taishan 1 and 2, Guangdong province) is also underway, with the verdict still out on which will be the dominant design for China's planned nuclear scale up. Despite a two-year setback due to the Fukushima incident, regulatory approvals for nuclear plants have restarted and nuclear is expected to play a significant role in the country's future energy supply.

Cost innovation is an important part of China's nuclear program. Based on the AP1000 experience, costs for building a new nuclear plant in China are one-third to one-half of the cost of building a new plant in the United States. Cost advantages are not solely due to lower labor and capital costs. They often stem from the co-location of plants with a wide range of suppliers with variation in the quality and capabilities, which allows for competitive sourcing of parts that meet specified tolerances for different applications. Many in China have also signaled that the country is keen to become a global source of nuclear plant designs and components (WNA, 2014).

While R&D in the nuclear field has been underway for several decades, the main focus on these efforts has been the first construction of designs originating overseas. One such example is the high-temperature gas cooled reactor (HTR), while fast breeder (under development at the China Institute for Atomic Energy) and molten salt (under development in Shanghai) reactors are also candidates. Tsinghua's Institute for Nuclear Engineering Technology (INET) developed a 10 MWe HTR reactor funded by the "863" Program and National Key Special Projects Program. Justification for the project focused on the need to improve efficiency and safety over conventional reactor designs. The HTR's signature pebble-bed technology—so-named for the spherical packing of fuel—was originally developed in Germany. Building on the German platform with the help of Siemens and Interatom, China has developed a version of the pebble-bed reactor design. Chinergy, a 50/50 joint venture between Tsinghua University's Holding Company and China's State Nuclear Power Corporation, attracted investment from a consortium led by the Huaneng Energy Group to build a 210 MWe pilot reactor in Shandong Province. As of 2013, Chinergy had started to build the 210 MWe HTR which consists of twin HTRs. Although some suggest that the HTR could become the dominant design for future nuclear deployment estimated to be in the 350-450 GWe range by 2050, many are concerned that the design is too costly for large-scale deployment in China. Research has also been underway since the mid-1960s to develop a fast breeder reactor with Russian support and a 65 MW pilot near Beijing was scheduled to be completed by 2008. Even though these technologies are expected to be important by mid-century, innovation in the case of nuclear mainly takes the form of demonstrating concepts that have originated elsewhere, in large part because of the long time horizons required.

5. Conclusions

A survey of innovation patterns across China's electricity generation technologies suggests that cost innovation is likely to remain important in the coal, nuclear, wind and solar industries, while stronger incentives are needed to incentivize deployment of advanced options. At present, given the cost and design complexity, these technologies are likely to remain experimental rather than mainstream for at least the next ten years, despite high hopes.

It is worth considering how redoubled efforts to address air pollution and carbon emissions in China might affect prospects for the various electricity technologies, as well as incentives to invest in research that could produce fundamental breakthroughs. At present, after a massive build out, China seems more prepared to shift away from coal, based on central policy announcements that coal use in China may peak by 2020 and begin to decline, while peaks are expected earlier in some eastern coastal areas. The remaining coal use is expected to take place at large coal bases located far from major cities, using large, efficient USC designs fitted with air pollution control technology and real-time monitoring equipment. Central energy planners have also signaled that natural gas will play a growing role in the country's future electricity mix. However, China possesses few of the cost innovation advantages in natural gas that it has for other renewable energy types, advanced USC coal, and nuclear power. Natural gas is also a relatively expensive fuel. These conditions favor a more limited role for natural gas in the future in the absence of a significant change in domestic fuel cost conditions or technology cost advantages.

The factors supporting cost innovation in China's energy system are strong and likely to persist for some time. Even as China considers market-based climate and energy policies, strong elements of the planning and "market creation" efforts that have helped create certainty for technology developers are likely to remain. An open question concerns whether market-based approaches to environmental regulation (such as a national-scale version of the cap-and-trade systems the country is currently piloting) would to an extent level the playing field for existing and advanced technologies, perhaps providing an incentive for developers to experiment with high-risk, high-reward technologies of their own accord in the absence of incumbents hand-picked by policymakers. Abandoning government-coordinated plans and direct, technology-focused could create greater uncertainty around the future of proven technologies, potentially undermining investments of the size needed to realize scale advantages and associated cost innovation. To some extent, policymakers may view facility in producing on par with today's market leaders as a precondition for breakthroughs later on, recognizing that some degree of catch-up investment is necessary and desirable. Cost innovation, by contrast, is desirable from the perspective of consumer benefits, but as overcapacity in China's renewable energy production industries suggests, cost innovation under competitive market conditions may prove a challenging environment for producers to survive and thrive in China over the longer term.

This short analysis leaves a number of questions unanswered. Based on the cases discussed above, cost innovation—while important and successful in China—seems to be neither necessary nor sufficient for a transition to breakthrough innovative capabilities. The origins of this gap can be connected to developments in China's evolving innovation system. An open question remains whether or not conditions explicitly promoting cost innovation may be at odds with the conditions needed to promote more fundamental breakthroughs and novel solutions. The absence of technological breakthroughs in China's electricity technologies is consistent with—but by no means proves—this proposition. This situation can also be explained by the country's still limited experience with advanced clean energy technology development, and the often-articulated need for stronger exposure and access to knowhow in addition to blueprints from overseas. China's institutions supporting R&D are still evolving along with the countries reform and modernization efforts. However, a better understanding the conditions that lead to cost innovation, and how they support or undermine more fundamental forms of product and process innovation, could provide valuable insights on the levers that could be most useful to China's innovation policymakers going forward.

Table 1 Patterns of innovation in coal, nuclear, wind, and solar technologies in China.

Energy source	History	Factor conditions	Demand conditions (domestic/ international)	R&D policies and resources	State-sponsored commercialization policies and programs	Potential gains from further innovation	Innovation performance
Coal	Mainstay of the power generation mix	Favorable: Fuel cost low Capital cost advantage	Strong domestic; Moderate international	Torch Program; 863, 973 funding programs, localization	Deployment of USC according to government plans/support	Without a price on carbon, market opportunity limited	Cost: Strong; Knowledge: Weak/Medium
Nuclear	Stop-start on deployment, but relatively long history	Favorable via suppliers in particular, labor & capital costs, co-location	Large market domestically; Strong but risky potential international	863 Program; Special Key Project Funds	Significant uncertainty, but target was recently increased	Advanced safe designs at low cost have potential	Cost: Strong; Knowledge: Weak/Medium
Wind	Recent, cost reduced through domestic deployment	Favorable: Capital/land cost advantage	Strong domestic and more recently overseas	863, 973 programs, Key Technologies Program	FITs, targets, tax breaks, concessions, local content reqs., CDM	Reduce costs of offshore wind, be able to provide turkey solutions	Cost: Strong; Knowledge: Weak
Solar	Recent, used market abroad to reduce costs	Initial low materials costs in China	Limited domestic; strong overseas	863, 973 programs, Key Technologies Program	Deployment targets, Golden Sun program, FITs, tax breaks	Limited gains from relying solely on manufacturing	Cost: Strong; Knowledge: Weak

References Cited

China National Renewable Energy Centre (CNREC). 2013 National Wind Construction Outlook. (2014).

China Statistical Yearbook 2013. Chapter 8: Energy. China Statistics Press.

CUP. [Conversation with Deputy Director of Overseas Oil and Gas Engineering Center, China University of Petroleum], Jan. 2006.

Energy Research Institute (ERI). *China Wind Energy Development Roadmap 2050*. (2011).

Grau, T., Huo, M., and Neuhoff, K. (2011). *Survey of Photovoltaic Industry and Policy in Germany and China*. Discussion Paper 1132. German Institute for Economic Research.

Han, J., Mol, A.P.J., Lu, Y., Zhang, L. (2009). Onshore wind power development in China: Challenges behind a successful story. *Energy Policy*, 37, 2941-2951.

Huo, M., Zhang, X., and Wang, S. (2013). Lessons from photovoltaic policies in China for future development. Unpublished manuscript, used with permission.

IDRC [International Development Research Center]. *A Decade of Reform: Science and Technology Policy in China*. IDRC Canada, www.idrc.ca, 1997.

Liu X. and S. White. (2001). "Comparing innovation systems: A framework and application to China's transitional context." *Research Policy*, 30:1092.

Metha, A. (2005). "Establishing the National Electricity Regulatory Commission," Technical Assistance Completion Report, Asia Development Bank.

Ru, P., Zhi, Q., Zhang, F., Zhong, X., Li, J., Su, J. (2012). Behind the development of technology: The transition of innovation modes in China's wind turbine manufacturing industry. *Energy Policy*, 43, 58-69.

Sims Gallagher, K. (2013). *The United States and China: Moving Forward on Coal and Climate Change*. Washington, DC: Brookings Institution.

Suttmeier, P. and Cao, C. (1999) China Faces the New Industrial Revolution. *Asian Perspective*, *23*(3).

Zhang, X., Chang, S., Huo, M., and Wang, R. (2009). China's wind industry: Policy lessons for domestic government interventions and international support. *Climate Policy*, 9(5), 553-564.

Zhou, Y., Zhang, B., Zou, J., Bi, J., and Wang, K. (2012). Joint R&D in low-carbon technology development in China: A case study of the wind-turbine manufacturing industry. *Energy Policy*, *46*, 100-108.

Watson, J., Byrne, R., Stua, M., and Ockwell, D. (2012 *UK-China Collaborative Study on Low Carbon Technology Transfer*.

World Nuclear Association. (2014). Nuclear Power in China. (www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Power/)

Yue, L. (2012) Dynamics of clean coal-fired power generation development in China. *Energy Policy*, 138-142.