Developing Super Smart Grids in China: Perspective of Socio-technical Systems Transition

Yuan Jia-Hai

Abstract This chapter adopts the framework of socio-technical systems transition to discuss the development of smart grid (SG) in China. Multi-level perspective (MLP) analysis, namely landscape, regime, and niches, is presented to set the institutional background of China's power sector. Then, a scenario of power supply and demand is compiled, and its main features are elaborated to justify the necessity of developing SGs. The overall transition pathways of China's power sector are drafted, and then, the road map for developing SGs in China is proposed. Key policy implications are as follows: first, working out clear national strategy and road map for SG development and carrying out integrated translation research and strong front-end support; second, restructuring power sector in parallel with SG development; and third, reforming pricing mechanism and empowering the customers with rights to choose service/enter power market.

Keywords Smart grids · Multi-level perspective · Transition pathways · China

1 Introduction

During the 18th National Congress of CPC of November 2012, ecological civilization [Sheng Tai Wenming] was highlighted for the first time among the guiding principles for the completion of a well-off society [Xiaokang Shehui] in 2020. Promoting revolution in energy production and consumption, controlling total energy consumption, enhancing energy conservation, and supporting low-carbon industry and renewable energy development will set the keynotes for China's energy strategy and play essential roles to realize *Scientific Development Perspective* in China.

Y. Jia-Hai (✉)
School of Economics and Management, North China Electric Power University,
Beijing, China
e-mail: yuanjh126@126.com

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Power system is at the center of modern energy system. Logically, the energy revolution calls for radical revolution in power system. Considering the currently coal-based system and the enormous growth potential of power demand in the future, this issue is especially pressing and complicated in China.

Smart Grid (SG), characterized by large-scale integration of renewable energy and energy storage, distributed power generation and smart demand response, is expected to facilitate the energy revolution worldwide. In China, the first road map for SG was proposed by State Grid Corporation of China (SGCC) in May of 2009. Then in July of 2010, Southern Grid of China (SGC) issued its strategy for building "smart, high-efficient, reliable, and green power grid." In March of 2011, in "the 12th Five-Year-Plan of National Economy and Social Development" (12th FYP), SG was regarded as a key strategy to upgrade the power sector and enhance its core competency. Then in May of 2012, the Ministry of Science and Technology (MOST) issued "the 12th Special Program for Key Industrialization of Smart Grid during 12th FYP Period." The program is a clear signal that SG has been incorporated into the national energy strategy and that the Chinese Government is resolute to implement it seriously in the coming decades.

Up to now, to the best of our knowledge, primarily the "hard parts" or the technical aspects of SG are addressed. However, the transformation of current carbon-locked and dumb power system to future low carbon and smart one represents a radical system transition. The "soft parts," i.e., the organization, institution, and policy, which are essential to the transition, are seldom discussed. This chapter will address the following issues: Why is SG so important for China's low-carbon economy? What are the key features of SG in China? How can China build SG and set clear road map for it? From a perspective of socio-technical systems transition, what are the main institutional barriers for developing SG in China and what are proper policies to overcome them? Section 2 will present a brief analysis of China's power sector in a MLP; Sect. 3 will discuss a scenario for power demand and supply scenario into year 2030 and analyze the landscape and driving forces; Sect. 4 will elaborate the key features of the power scenario and discuss the unique functions of SG in China; Sect. 5 will propose a road map for developing SG in China; Sect. 6 will discuss the institutional barriers during the transition and propose countermeasures to overcome them; and Sect. 7 concludes.

2 Power Sector in China

2.1 Overview

As summarized in Table 1, the history of China's power system can be divided into four periods. At present, China's power sector consists of two national grid companies, SGCC and SGC, five national generation companies, a dozen of generation companies affiliated to provincial governments, and a few relatively smaller independent private generators.

Table 1 Brief history of the Chinese electric power sector, 1949–present

Period	Guiding policies	Description
1949–1985	Centrally planned and administered system	Vertical integrated state-run enterprise; government agencies plan, finance, manage, and operate the system; oscillations between centralized and decentralized management
1985–1997	Decentralization to provinces; opening of investment	Opening up of the sector to provincial government, private, and foreign investment; guaranteed investment return on generation investment
1997–2002	Separation of government and business	Corporatization of the sector through the creation of the State Power Corporation (SPC); ministry of electric power dissolved, functions transferred to the State Economic And Trade Commission (SETC) and the State Development And Planning Commission (SDPC), later merged into the National Development And Reform Commission (NDRC)
2002–2013	Unbundling of generators and grid companies	Dismantling of the SPC into 5 national SOE generating companies, 2 national grid companies; creation of State Electricity Regulatory Commission (SERC) and National Energy Administration (NEA)
2013-	Merge of NEA and SERC	Creation new NEA and integrating the function of SERC into it

Growth of electric power consumption has been faster than that of primary energy consumption in the past three decades. The rapid growth in power demand has resulted in tremendous growth of generation capacity expansion and rapid electrification. Measured by the ratio of electricity over final energy consumption, the electrification level has increased from 7.7 % in 1980 to 20 % in 2008 [2]. From 1980 to 2009, annual electricity demand in China grew more than 12-fold, from 300 to 3,660 TWh [5]. Demand growth of this magnitude and speed has contributed to consistently severe capacity shortages. At the same time, generation capacity in China has increased significantly to meet with the power demand. In 1980, the total generation capacity in China was only 65.8 GW, while in 2009 the installed capacity amounted to 863.6 GW, which is a 12-fold growth. Especially since 2004, annual increase in generation capacity ranges between 50 and 100 GW, creating a new record in the history of world power system growth. Only the USA maintained an annual growth of over 50 GW during the 1970s.

The coal-based generation mix results in carbon lock-in in China's power system, making it the largest contributor of CO_2 emissions as well as the main source of other serious environmental problems in China [4]. The share of thermal power units in the entire generation mix was as high as 70 %. As a result, the thermal power units consumed more than 50 % of the country's total coal production.

Although China's generation mix has been relatively stable over the past two decades, the composition of coal-fired power plants has undergone a significant shift toward larger and more efficient units. In the 1990s, most of the thermal power generators above 300 MW/unit installed in China were imported, and in 1993, the share of 300 MW units and above accounted for only 23 % of the total thermal generation capacity. In 2007, the share of 300 MW and above, and 600 MW and above accounted for 50 and 21.6 %, respectively. Then at the end of 2009, the shares of 300 MW and above rose to 69 % [5]. As a result of this push toward higher generation efficiency, the average thermal efficiency has sustained a linearly increasing trend since the 1990 s and now reportedly surpasses the average efficiency of American coal plants by a significant margin. In 2007, CO_2 emission per KWh electricity generation in coal-based plants in China was 893 grams (down by 7 % from the 1992 level), lower than world average (903 g), the US average (920 g) and Japanese average (910 g), but was still higher than European Union 27 nations average (835 g).

The imbalance between power load and resource center necessitates long-distance large-scale power transmission in China. China's physical grid is divided into four regional synchronous grids, with the Northeast-North-Central, East and Northwest regions operated by the SGCC, and the Southern grid operated by the CSG. Although basic DC interconnection among regional grids was achieved in 2005 [22], power flow among regions and even between provinces within regions remains limited.

Operation efficiency, especially in an environmental sense, is notoriously low because of the guaranteed return policy during the 1990s. Dispatch in the Chinese power sector has, since the early 1980s, operated under an "equal shares" formula whereby generators of a given type are guaranteed a roughly equal number of operating hours to ensure adequate revenues to recover their fixed costs. Economically and environmentally, this practice is inefficient, as generating units with high heat rates (i.e., low efficiency) may receive the same number of operating hours as those with low heat rates. In addition, equal shares dispatch has contributed to inefficient investment by encouraging overcapacity [13]. A related issue is that many generation services provided by natural gas units in other countries are instead provided by coal or hydropower units in China. In regions that do not have hydropower resources, coal units are used for load-following and peaking generation, requiring significant cycling of coal units and reducing the efficiency of these units.

Without a formal and transparent pricing mechanism that can link real cost and retail price, the current pricing policy poses significant barriers to transition to a more efficient power system. Wholesale generation rates in China have historically been loosely based on average costs. Since 2004, rates for thermal generators have been set using benchmark pricing, in which generators in the same technology class are given the same tariff, based on an estimate of annual output and fixed and variable costs for that class. As coal prices rose in the 2000s, China's central government developed a "comovement" mechanism that allows for some pass through of fuel cost increases. Wholesale rates for renewable generators are set using regional benchmark prices, while rates for hydropower and nuclear generators are set on a facility-by-facility basis (because of the vast initial capital investment cost of these generators). Provision of ancillary services has historically been limited in scale and scope, mandatory, and uncompensated, but plans to compensate generators for services are currently in the early stages of implementation. Because of the dominance of coal in China's electricity system, this predominant benchmark-based approach to wholesale pricing means that generation supply curves in China tend to be relatively flat.

The revenues grid companies receive for transmission and distribution (T&D) services are currently the residual between retail sales and generation costs. This residual is inherited from historical prices and is not based on a bottom-up accounting of T&D costs. Beginning in 2005, SERC developed accounting standards and reporting requirements for grid companies, but the level of detail and transparency in the disclosures required by SERC is not sufficient to assess whether costs are reasonable [3]. Moving toward cost-based T&D pricing is a continuing priority for regulators [18]. Retail electricity prices in China have historically been designed to reflect government policy and social priorities (e.g., maintaining low fuel prices to boost economic growth and affordable fuel prices for households), instead of the cost of service [10].

Developing renewable energy in power systems still faces many challenges. China has a rich endowment of renewable energy and has formulated favorable policy for renewable energy development. Given the relatively high costs for solar and biomass power, wind is and will likely continue to be the principal non-hydro renewable resource in China. Ever since the publication of the Renewable Energy Law formulated in 2005 and the Medium- and long-Term Development Planning for Renewable Energy in 2007, wind power has experienced rapid growth in China [15]. Installed wind power capacity connected to the grid increased from 1.06 GW in 2005 to 31.07 GW at the end of 2010.

Although wind power growth in China has been the most spectacular in the world in the past decade, the following factors have posed and will pose serious threats to its sustainable development. First of all, because of the intermittence of wind power generation, grid companies in China are reluctant to integrate it into the power grid. Even though the *Renewable Energy Law* stipulates the obligation of the power grid to purchase the full amount of renewable energy generated accessible to the grid, without specific operation rules, grid operators simply reject wind power access with reasons such as unpromising access conditions and operation safety requirements. The capacity factor of wind power was as low as 23.7 % in 2009, which was an evidence of the difficulties of grid integration [5]. Secondly, the incompatibility between wind power projects and power grid expansion planning has made grid access difficult. China has formulated ambitious planning for eight large-scale inland wind power bases in 10 GW scale in provinces of Xinjiang, Inner Mongolia, Hebei, Jilin and Shandong. However, without synchronous power grid expansion and proper backup plants, it is unlikely that this plan can be realized. Thirdly, the current policy to develop wind power is unsustainable because it neglects the vast investment requirement on power grids and discriminates against small projects and small investors. So it is no surprise that most wind projects are operated by the five big SOE generators and other large province-owned generators, unlike the success of wind power in Germany and the

Netherlands where various small investors enter into wind power market. Considering the long-term prospective, an optimal development of wind power should consider the solutions of both "large windmill base and long-distance transmission" and "distributed power generation," which in turn call for the entrance of small investors. Besides, there are still no concrete stipulations addressing the issues of grid cost recovery for additional transmission investments and reserve capacity when incorporating wind power into the grids.

2.2 Multi-level Perspective Analysis

2.2.1 Landscape and Regime

The MLP of [7, 16] distinguishes three interrelated levels of changes: the landscape, regime, and niche levels of socio-technical systems. This MLP literature is particularly instructive in understanding the dynamics of transition and the institution interactions during the process.

The current power regime in China for meeting industrial process, lighting, heating, and power-related services may be characterized as a centralized system. Electricity is centrally generated, largely from coal, hydropower, and a small but growing amount of nuclear and renewable sources; it is delivered to businesses and homes through large-scale T&D networks, before being used to provide power, lighting, heating, and services with the aid of end-use technologies and the buildings infrastructure. The absolute low starting point, the vast growth in power demand incurred by rapid industrialization of the Chinese Economy, and the rise of China as a World Workshop, as well as the increasing demand from households as a result of enhanced living standards and the popularization of home appliances, have made rapid growth of supply capability a policy priority in China. The strategic importance of electric power to enabling economic activity and well-being means that the system is the subject of intense policy activity, which focuses on ensuring secure and affordable supplies, and other social objectives. The meta "socio-technical landscape" of electrification in China can be characterized as follows:

- a dependency upon fossil fuel-based energy supply (mainly coal and rising supply capability of gas) and large-scale electricity generation technologies,
- a coal extraction, processing, and transportation infrastructure always unable to catch up with increasing demand,
- province-based power grids and a growing interconnected national grid to ease the geographic imbalance between supply and demand,
- historically vertical integration monopoly just being restructured into two grid operators and a set of SOE generators who are regulated by government bodies,
- a weak but expanding rail and road infrastructure,
- a traditionally centralized administration system, with initiated but rather fruitless market reform.

Key processes that influence or "drive" the power regime at the landscape level in China include the following:

- the increasing power demand from the industrial sector because of the ongoing industrialization process and a big gap in energy efficiency compared to the rest of the world,
- the increasing power demand from households because of increasing income and rapid urbanization,
- a huge population base of 1,340 million, which is still growing,
- the increasing pressure on primary energy supply, environment, and ecology because of the heavy reliance on coal,
- global concern of GHG reductions and increasing pressure on China's "measureable, reportable, and verifiable" obligation to cut GHG emissions,
- the Chinese Government's commitments to reduce emissions and reduce GDP carbon intensity by 40–45 % in 2020 compared to the 2005 level and to promote clean energy sources, increasing the share of non-fossil over primary energy by 15 % in 2020,
- concerns over security of primary energy supplies,
- external factors leading to high and/or volatile oil and gas prices and related concerns over energy affordability and fuel poverty, as well as physical disruption of external supplies (war, terrorism, foreign governments limiting supply, etc.),
- the gradual transition of Chinese Economy from centralized planning to a more market-based economy that will gradually blend into the global economic system,
- the international efforts to deliver renewable energy technologies.

Many processes that drive the power landscape in China, such as energy security concern and international factors, are the same as other countries face. However, under the macroeconomic-social transition process, the interactions of industrialization, urbanization, and energy–environment–ecology constraints will pose important impacts on the power landscape and thus influence the transition pathways. Meanwhile, the international pressure on China to assume "measureable, reportable, and verifiable" CO_2 reduction targets will intensify during China's growth process. Currently, by emphasizing that as a developing country and according to "shared but differentiated" principle, China can and will take active measures to cut CO_2 emissions so far as they do not impede the economic development. As expected in 2020, per capita GDP of China will exceed 10,000 US$, and in 2030, it is expected to exceed 15,000 US$ (2010 constant prices). At that time, with its raised share of global GHG emissions and the expected intensified international conflicts, it is very likely that Chinese Government would need to take a more positive attitude toward GHG reductions. Thus, in the future 5–10 years, the power landscape will definitely experience radical change toward decarbonization and in turn exert more pressures on the power regime to change.

2.2.2 Technical Niches

A wide range of competing energy technologies are currently being developed, reflecting not only the underlying scientific and technological base but also the perceived opportunities arising from the emerging low-carbon socio-technical regime. Shackley and Green [17] have proposed a categorization of these technologies, distinguishing between mature technologies and those that are at various stages of commercialization, demonstration, research, and development. Zhang et al. [21] also appraised the renewable energy technology progress in China and proposed their categorization. However, their categorizations mainly focus on pure technological level and neglect final consumption as a means for efficiency improvement by technology innovation in the industrial process. Based on their work and adapted to our pathway study, we propose our decarbonization categorization for power sector transition in China (Table 2). In our categorization, we classify available and potential options into five streams, namely fossil fuel, nuclear, renewable, demand side and energy carriers and storage technology, and appraise the availability of options according to typical technology innovation stages: mature (being available at hand with affordable prices in large scale); early commercialization (technically feasible but still expensive and in need of technological learning to become fully effective); development and demonstration; and finally the research stage. The time line in the table is not strict, given the uncertainty in innovation and the inaccuracy of appraisals, and is calibrated based on technology launch stage.

3 Planning of China's Power Sector into 2030

3.1 Landscape and Driving Forces

According to the objective of completion of a well-off society in 2020 indicated by President Hu Jintao's report on 18th National Congress of CPC, per capita GDP, measured in 2010 constant price and current exchange rate, will reach 10,000 US$ at that time. Then, with an annual growth rate of 4.5 %, per capita GDP will reach 15,000 US$ in 2030. According to the standard of the World Bank, at that time China will approach the lower bound of high-income group. According to socio-economic comparative study, in 2020, per capita electricity consumption will reach around 5,000 KWh, and in 2030, it will reach around 8,000 KWh.

The output structure will also exert significant impact on power demand. Currently, in the group of lower–middle income, China's output is predominantly in the secondary sector. However, during the ongoing industrialization process, the share in the secondary sector will not decrease significantly until 2020, thus posing great challenge to China's energy supply and low-carbon development.

Table 2 Niche energy technology options

Stage of (technology) option	Fossil fuel based	Nuclear	Renewables	Demand-side technologies	Energy carriers and storage technologies
Mature	USC boilers	Existing fission reactors	Wind turbines	Energy-efficient appliances	Batteries
	Combined heat and power generation (CHP)		Traditional geothermal technology	Compact fluorescent light	Pump storage
	Gas (coal bed gas) power			Industrial process innovation	
	Generation		Solar heat water system	House insulation	
			Biomass generation	Heat pump (geothermal or air)	
			Hydropower		
Early commercialization (6–15 years)	Some gasification technologies	New fission reactors	Some wind turbines	Passive solar	Fuel cells
			Biomass boilers	Low-carbon buildings	
	Some CO_2 capture technologies		Biofuels	LED lighting system	
			PV and CSP		
	CO_2 storage		Grid modification		
	Retrofitting of old boilers to USC				

(continued)

Table 2 (continued)

Stage of (technology) option	Fossil fuel based	Nuclear	Renewables	Demand-side technologies	Energy carriers and storage technologies
Development and demonstration (D&D) stage (15–20 years)	Some CCS technologies	Fourth generation reactors (high-temperature gas reactors etc.)	Wave	Intelligent buildings	Hydrogen from gas and electrolysis
	Integrated gasification combined cycle (IGCC)		Tidal	Smart meter	Fuel cells
	Underground coal gasification		Biofuels, e.g., gasification, AD, transport fuels	The Internet of things	
	Polygeneration		Grid modification		
	Fischer–Tropsch process				
Research stage (20 years and beyond)	Novel CO_2 capture technologies	Nuclear fusion	Biofuels, e.g., pyrolysis		Hydrogen generation from biomass, waste, nuclear, etc.
			Enhanced geothermal system		
			New materials for PV		

(*Source* authors' compilation using Larsson [12], Foxon et al. [6], Weiss and Bonvillian [19])

With an expected income where consumption is bound to take off, what are the most important factors that exert pressure on China's power system regime? Here, we briefly analyze four of them, namely industrialization, built environment, appliances (home and commercial), and transportation.

The leading factor is industrialization. During the past decade, the growth in consumption of energy-intensive products such as steel and cement in China has been very fast. According to Yu [20], China accounts for 70 % of the increased production in crude steel, 83 % in cement, and 118 % in steel during 2000–2008, which implies that with GHG reduction pressures in the industrialized nations, more energy-intensive products are outsourced to China. On the other hand, energy efficiency in China's manufacturing sector is significantly lower than in developed countries. Because of strong domestic and foreign demand, even though the share of heavy industry over GDP will decrease, it will nevertheless experience remarkable growth and the absolute scale will more than double in 2020 and triple in 2030 (as of 2010 level), thereby leading to vast power demand growth and posing perhaps the biggest challenge to the power system transition in China. Therefore, a well-designed industry policy to guide the development of manufacturing sector, as well as stricter energy efficiency standards to promote conservation, will be the most important strategies for China.

The second factor is urbanization. Together with the growth of income, it will exert significant impact on the power system in two ways. First, urbanization is the aggregation of population in urban areas. The urbanization rate in China increased from 36.2 to 46 % during 2000–2010 periods, equivalent to 14 million citizens moving into cities annually, and will increase to 56 % in 2020. Urbanization will be accompanied by vast housing demand, and China has set the goal of constructing new homes for 400 million people by 2017 [12]. Houses are built for the long term, on the expectation that houses will be used for 50–70 years or more. On one hand, a house is a kind of stand-alone system in that a new house could be built using the most modern and energy-efficient technologies (for example, a passive solar house) available without regard for how other houses in the surrounding area have been built. On the other hand once built, buildings will consume substantial amount of energy for lighting, ventilation, cooling, and heating purposes over its life cycle. It is reported that energy consumption per square meter in the existing 40 billion square meters of housing in China is three times that of advanced country level, while 90 % of the newly built houses are energy inefficient. Hence, to cope with the impact of urbanization and reduce power demand in buildings, it makes sense to immediately implement as many available energy-efficient house technologies as possible in the new construction projects. On the other hand, refurbishment of existing houses, by improved insulation, new heating systems such as heat pumps to replace central air-conditioning, can also improve energy efficiency remarkably.

Urbanization will also result in the expansion of cities, in turn increasing demand on regional transportation. The relationship between transportation and power sector is complicated. On the one hand, all kinds of biofuels could also be used for power generation. Considering the gigantic oil demand in the future, the inadequate domestic oil supply and the already high dependence on oil import (50 % in 2009), biofuels should take priority over bio-generation. On the other hand, the next generation vehicles, be it hydrogen/fuel cells or battery driven, will have significant impact on the power sector. Hybrid Electric Vehicle technology may be the only one mature enough in the next 10 years to contribute to energy transition in China [1]. Pending significant improvements in battery technology, plug-in hybrids could possibly start making an impact in about 10 years, while vehicles powered by fuel cells are unlikely to enter high-volume production for at least 20 years. Whatever technology evolves, power demand will be significantly pushed up by direct consumption, by batteries or indirect consumption by hydrogen/fuel production. Considering the vast growth potential of private car demand, transportation alone will vastly increase power demand in China.

With growing per capita GDP and more disposable income, electric appliances will be popularized in households. Comparing the difference of appliance inventories in rural and urban families [14], there is vast potential for the demand of appliances such as refrigerators, washing machines, and computers, which in turn will consume more electricity. On the other hand, with the expected rapid growth of the service sector in the coming two decades, the popularization of office automation and more large-scale power-consuming data centers in operation, there will be growth of power consumption in the service sector.

3.2 Planning Scenario

With demand growth at two digits and the intensified pressure for carbon reduction, it is unwise to simply build more thermal power plants to meet the power demand. More diversified power sources must be included in the generation mix. Similarly, it is unwise to simply increase supply without considering conservation potential on the demand side. This is especially important for China with notoriously low energy efficiency. Hu et al. [9] proposed an integrated resource strategic planning (IRSP) model for power planning, and its core is a minimized power supply planning model considering both traditional power plants (thermal power, hydropower, nuclear power, and renewables) on the supply side and efficient power plants (EPPs, including energy-saving lightings, high-efficiency motor systems, high-efficiency appliances, and others) with environment constraint. Based on the model presented in Hu et al. [9], generation capacity planning for China during 2010–2030 periods is projected in Table 3. Considering the potential of EPPs, in 2020, 142 GW of generation capacity could be avoided and save 285 TWh electricity on the demand side in 2020; in 2030, 277 GW could be avoided and save electricity by 783 TWh. Meanwhile, with a diversified generation mix, in 2020, clean capacity would amount to 593 GW, accounting 35.5 % of total generation capacity and clean generation would amount to 1,948 TWh, accounting for 25.38 % of total generation; in 2030, clean capacity would amount to 1,091 GW, accounting for 46.78 % of generation capacity, and clean generation

Table 3 Scenario planning of power generation capacity for China 2010–2030

(GW)	Coal	Hydro	Nuclear	Wind and solar	Gas	Total	Efficiency power plants
2010	671	200	10	40	12	933	**15**
2015	857	260	23	100	12	1,251	47
2020	1038	335	78	165	44	1,660	142
2025	1141	450	170	280	50	2,091	204
2030	1180	500	230	361	61	2,333	277

would amount to 3,887 TWh, 37.19 % of total electricity generation. The significant increase in clean generation will vastly avoid potential CO_2 emissions from China's power sector. Supposing that the carbon emission factor and clean generation share were constant at 2007 level, 640 and 2,114 million tons more CO_2 would be emitted in 2020 and 2030.

The preceding analysis indicates that with radical improvement in generation mix on the supply side and energy efficiency on the demand side, China's power sector could make obvious progress on decarbonization. Unfortunately, a simple though not precise calculation indicates that these efforts are not enough. Suppose that the efficiency improvement plus the installation of gas power cut the CO_2 emission factor of fossil plants to 803 g per KWh (10 % lower than 2007 level), multiplying by fossil generation share of 63 % (and supposing no emission at all for clean generation), in 2030, CO_2 emission per KWh from China's power sector would be 504 g. Then, multiplying by the expected consumption, power sector alone will emit 5,600 million tons CO_2 or 93 % of China's total emissions in 2007. Including other sectors, it would be very likely to double the 2007 emissions to 11,000–12,000 million tons, which is far beyond the IEA 450 ppm scenario for China [11] and would ruin the global effort to stabilize GHG emissions.

4 Developing Super Smart Grid in China

4.1 Key Features of China's Power Scenario

To fuel socio-economic development properly, while at the same time manage the GHG emissions at controllable scale, we need to understand the key features of China's power scenario and build SG to deliver it.

Start with power demand first. From regional perspective, the demand from developed regions such as Yangtze River Delta, Pearl River Delta, and Bohai Economic Rim will flat and saturate around 2020–2025 after a swift growth from 2010 to 2020. On the other hand, the demand from underdeveloped western and central regions will continue to increase during rapid industrialization and urbanization process. The implication is that the historical imbalance between load and resource will exacerbate until 2020. Due to the bottleneck in the transportation system, ultra-high voltage and long-distance transmission system will continue to be a priority before 2020. However, with the takeoff of economic growth in western and central regions, the local demand from these regions will explode and consume most of the local supply. Besides, with stricter environmental and ecological standard, there will be more constraints on the construction of transmission corridor. All these pressures call for more active regionalized balance of demand and supply.

From the perspective of final use, demand from the manufacturing sector is supposed to flat and saturate at around 2020 when China finishes the industrialization process. Meanwhile, demand from service, residential, and transportation will take off when tertiary sector dominates the GDP, and higher disposable personal income results in the burst of domestic consumption. One implication is that at around 2020 when demand from service, residential, and transportation sector begin to challenge the role of manufacturing sector in total consumption, the demand will become more irregular, unpredictable, and hard to be managed. The other implication is that the pattern of the new demand from service, household, and transportation sector depends on how the city, buildings, and transportation system are designed and managed during the urbanization process. The key decision making of city planning, building standard, and transportation system should incorporate energy, environment, and ecology objectives in the priority agenda and be the results of integrated planning. Market mechanism, energy efficiency standard for new buildings and electric appliances, energy management service, and technology innovations would play major roles for smart management of the demand. Retrofitting of existing buildings can contribute significant energy-saving and GHG abatement. All kinds of demand-side measures can serve as low-cost energy storage options when incorporating intermittent renewable generation in large scale.

Now we turn to supply side. For thermal power, enhancement of energy efficiency by building more new USC and/or CHP units can save coal and avoid GHG emissions. With available technology, retrofitting existing coal-burning units into USC can make another contribution. Because coal-based units will still account for half of the generation capacity in 2030, to control total GHG emissions, carbon capture and storage (CCS) technology must be put into commercial application beginning from new coal units above 300–400 MW at around 2015 after pilot projects. With growing and secured supply from both regular and shale gas, gas generation will enter into the generation mix in China as reserve units and improve the capability of the power grid to integrate more portion of renewable generation. Exploitation of hydropower in China will peak at around 2020 when technically and economically exploitable resource is used up. Nuclear power will peak at around 2020–2025 at scale of 80–120 GW installation. But next generation reactor, in cogeneration of power and hydrogen, will open a new window for reshaping power system. Large-scale integration of inland wind power and solar power will peak at around 2020 when the wind/solar power bases at scale of 1/10 GW are completed and commissioned. Then, the pressure on the construction of more transmission lines and the requirement of regionalized balance of demand and supply will call for the integration wind/solar and other forms of renewables at small scale in the form of distributed generation or microgrid, which in turn calls for a radical change in the pattern and management of power system.

4.2 Function Analysis on SSG in China

A strong power grid infrastructure is needed to manage the challenges/opportunities of the scenario and deliver the transition. According to the preceding analysis, in China, the power grid should be able to assume the following functions in the future:

- Optimize primary energy supply structure and facilitate clean generation access, which in turn requires large-scale semi-reliable and intermittent power generation units such as wind and solar power and thus poses big challenge to power system planning, operation, and control. On the other side, to promote clean generation as much as possible, generation technologies in different types and sizes, connected into distribution networks plus self-generators injecting into, or taking from the grid from time to time, should be installed to the grids (especially the distribution grids), which in turn calls for reconfiguration of distribution systems.
- Serve as an alternative system besides railway, waterway, and road systems for large-scale energy transportation, which in turn calls for renovation of the current 500 kV backbone grid with less than 800 km transmission radius to 750 kV and higher with a longer transmission radius, functioning as long-distance and large capacity resources optimization framework.
- Promote energy conservation on power demand side, as well as on supply side, which in turn calls for more consumer choices, customized power services and smart energy management.
- Control GHG emissions effectively within the power sector and leave more space for other sectors, which in turn calls for the construction of large coal power bases nearby collieries to reduce energy consumption for coal transportation and to provide the base for large-scale CCS applications, innovative dispatch rules to support carbon-free or low-carbon generation, and exploration of the demand-side energy conservation to the utmost extent.

Super smart grid (SSG) has been studied to integrate SG and super grid for energy conservation and renewable energy utilization in many countries. However, “SGs” do not enjoy a commonly accepted definition in the literature. Even its architecture and basic elements are of universal sense, its functions must be tailored to accommodate the differences in resource and demand in different countries.

Here, we would only discuss the main features of SG that could satisfy the above functions. We define super SG as the power grid system that will economically accept and transmit renewable power on the supply side and operate energy efficiency improvement on the demand side. On the transmission side, SSG can take advantage of renewable and clean power generation over a long distance and integrate huge amounts of power generation into the grid, and on the distribution side, SSG can stimulate customers to save electricity and sell their renewable power generation to the grid (Table 4).

Table 4 Key components of developing SSG in China

Aspects	Transition direction	Key SSG components
Generation	• Large-scale access-in of intermittent renewable generation in northwest resource center • Development of large-scale thermal and hydropower bases in western resource center • Development of nuclear power plant in east coastal areas	• Wind power grid-access technology • Solar power generation and grid-access technology • Grid-access technology for novel renewable generation • Cogeneration of power, heat, and hydrogen
Transmission	• Long-distance large capacity energy transmission • Resilience to disturbance, attack and natural disasters	• Advanced power transmission technology (Superconductors, FACTS, HVDC) • Wide-area monitoring and control technology • Information and communication integration technology
Distribution	• Integration of different generation and storage technologies (small wind turbine, roof solar, biogas, fuel/cell among others) and in different sizes	• Distributed generation and management technology • mini-grid technology • Step-down transformer technology • Advanced voltage control technology
Utilization	• Diversified power supply options for customers (based on both cost and product differentiation offered) • More active involvement opportunity for customers as power operators and small generators • Customized services	• Power consumption information feedback technology • Integrated design of green building and energy system • Energy efficiency and demand-side response management technologies • Electric vehicle charging load management technology • Bilateral energy management and smart billing system • Smart homes technology integration

5 Road Map for Developing SSG in China

5.1 Transition Pathways of Low-Carbon Power Sector in China

Geels and Schot [8] proposed a typology of transition pathways as, reproduction: ongoing processes of change within the socio-technical regime (i.e., not involving interaction with the landscape or a technological niche); transformation: processes of change that arise from the interaction of an evolving landscape with the socio-technical regime (but not with the technological niche level); substitution: replacement of one dominant technology within the socio-technical regime by another as a consequence of interaction between all three levels; de-alignment/realignment: interaction between the three levels resulting in competition between a dominant technology within the regime and a number of other competing options, which have different performance characteristics, eventually resolved through emergence of a new dominant option; and re-configuration: replacement of a set of interlocking technologies by an alternative array of inter-related technologies which fulfill the same or similar functions.

According to analysis on technology niches, we propose the transition pathways for low-carbon power system development in China (Table 5). In the table, we classify available and potential options into five streams, namely fossil fuel, nuclear, renewable, demand side and energy carriers and storage, and appraise the availability of options according to typical technology innovation stages: mature, being available at hand with affordable prices in large scale; early commercialization, though technically feasible but still being expensive and in need of a technological learning process to become technically effective; development and demonstration; and the research stage. The time line in the table is not strict, given the uncertainty in innovation and the inaccuracy of appraisals, and is calibrated based on technology launch stage.

5.2 Milestones and Key Tasks for Building SSG in China

Based on the overall transition pathways of China's power sector and the requirements on SSG, we propose the milestones for SG development developing SSG in China (Table 6). Again, even the timeline is not strict, the road map is divided into three periods: 2010–2015, with the emphasis on transmission system and large-scale integration of renewable generation; 2015–2020, with the emphasis on integration of middle-scale renewable generation and energy storage; and 2020–2030 and beyond, with the emphasis on integral of smart transmission, DG, and microgrid.

Table 5 Possible transition pathways of power system in China

Stage pathway	First stage: 2010–2020	Second stage: 2020–2030 (and beyond)
Reproduction: efficiency enhancement in coal-based large-scale power system	Regular efficiency enhancement; CHP; substitution of small-scale inefficient unit with UVC unit; power grid operation optimization	Same as first stage
Transformation: minor modifications to coal-based large-scale power system	Demand-side options as technology innovation in industrial process, popularization of energy-efficient appliances, house refurbishment such as insulation and double glazing; isolated distributed generation (DG) in remote areas	Low-carbon building
Substitution: technology substitution or power demand substitution within centralized power system	Gas power, waste (biogas) power, and/or gas + CHP; fission nuclear power; inland and onshore wind power; solar power in demonstration and commercialization; heat pump; passive solar	Gas + CHP power; GIF nuclear; offshore wind power; advanced solar power; fuel cells; Micro-CHP
Reconfiguration: major modification to coal-based large-scale power system	CCS research and experiment and demonstration; Fuel cells research and experiment and demonstration; Centralized power grid + solar/wind/hydro/biogas and other combined DG	Regional power grid + ultra voltage transmission connection + expansion of kinds of DG technologies including fuel cells
De-alignment/realignment: power system coevolves with hydrogen/fuel cell technologies	Research and development of hydrogen technology	Macrogird with large-scale UVC + CCS units and other traditional carbon-free units or large-scale fuel cell plants based on underground coal gasification + hydrogen production as carriers + DG and microgrid with fuel cell, wind, solar, and other renewable units

Table 6 Milestones and key tasks for developing SSG in China

Period	Milestones	Key tasks
2010–2015	• **Developing super transmission system** • Optimizing of generation mix • Integrating large-scale renewable generation (GW scale) • Cogenerating of power and heat and other low-cost energy storage form	• Optimizing generation mix with traditional technologies • Building smart transmission system • Integrating large-scale renewable generation • Piloting distributed generation • Piloting smart management of electric vehicle • Testing superconductor transmission system • R&D of next generation energy storage technology • Testing the feasibility of smart customer management and related technology R&D
2015–2020	• **Developing super transmission + distributed generation system**	• Piloting superconductor transmission system
	• Integrating medium-scale renewable generation (10 MW scale) and energy storage	• Optimizing power generation with CCS units piloting and testing next generation energy storage technology • Building DG • Piloting smart customer management • Piloting microgrid operation and management technology
2020–2030 and beyond	• **Developing super transmission + distributed generation + microgrid system**	• Building smart superconductor transmission system
	• Integrating small-scale renewable generation (1 MW scale) • Preparing for integration of cogeneration of power, heat, and hydrogen	• Optimizing DG operation and management • Building microgrid and all kinds of smart customer management technologies • Optimizing and reshaping the architecture of the power grid • Building infrastructure and architecture for the cogeneration of power, heat, and hydrogen • Preparing for the integration of smart grid and internet of things

6 Policy Implications

Transition to a smart and low-carbon power system represents multiple institutional challenges. For one thing, renewable energy in different forms is distributed and intermittent in nature. For another thing, without technically feasible energy storage options, power system must be balanced in real time. Therefore, historically, operators of the "dumb grid" were primarily concerned with stable and reliable operation of the system. The grid was operated using a combination of command-and-control actions and hierarchical decision making. Perhaps most importantly, the preferences of customers were largely left out of the planning and operations process in traditional power grids.

Integration of medium- and small-scale renewable generation will face huge challenge. As discussed above, SG based on renewable generation and energy storage technologies radically differs with traditional one. In China, renewable generation as wind and solar power is integrated into the system by building large-scale bases and then constructing transmission system to deliver it. In this way, wind farms are taken as bulk generation of coal-based units. However, the integration of medium- and small-scale renewables into the grid means that the renewables will be connected in the distribution system or directly built on customers' houses/buildings. So first of all, level playground for small and private investors is needed to attract millions of prospective individuals into the power sector. Then, regarding power grid as public-accessible public goods and ensuring fair grid access is another priority to overcome this barrier.

Pricing mechanism is the biggest challenge for smart management of customers and innovations in demand-side technologies. Though currently smart meter and the related information and management technologies are the focus of R&D and pilot projects, price reform is ultimately the final answer to it. For one thing, retail tariff must reflect the cost of energy service in consideration of the time served and quality requirement. For another thing, currently, there is only wholesale generation price, and final consumption tariff based on customer classification and grid companies' revenue is the difference between them multiplying by power supply to different customers. Under this situation, grid companies have no incentive to deliver demand-side management. Also, electricity price policy has historically assumed too much economic growth and social stability function in China, instead of economic function to signaling for the scarcity of resource. So to reflect the cost clearly, there must be price catalog of wholesale generation, distributed generation, and microgeneration and the separation of generation, transmission, distribution, and retail prices, which in turn calls for a new perspective on the regulation of T&D network. Understanding that there is deep-rooted origin of the current tariff policy, pricing reform can be regarded as a touchstone to see whether Chinese Government is determined to the *Scientific Development Perspective* and power sector deregulation.

The integration of medium- and small-scale renewable generation as well as pricing mechanism reform also calls for the gradual redefinition of the power grids and restructuring of the utility companies. It would pose the most difficult institutional puzzle for developing SG in China. Currently, SGCC, the biggest national grid company, is the first mover of SG. But the focus of SGCC is on ultra-high voltage and long-distant transmission system, which can serve as a physical infrastructure to maintain and strengthen its vertical monopoly power. However, the worldwide trend requires splitting the grid company into transmission operator, distribution operator, and retailers, among which T&D operator will provide public goods to generators, retailers, and customers. Without clear-cut separation of public goods and private goods, it is unlikely that SG can function as expected. The puzzle is that the grid company would have no incentive to develop SG if it was destined to be dismantled. Therefore, a subtle design to synchronize the SG road map with power sector deregulation is necessary.

Finally, there is another challenge to draft a clear national strategy and road map for developing SSG when trying to put all the elaborated components together and into operation. SG is perhaps the most complicated manmade system and involves at least electric equipment manufacturing industry, power industry, information and communication industry, and other novel industries which provide component solutions. Some components, such as smart substation, FACTS, HVDC, wide-area monitoring and control technology, are mature and available. Others, such as smart meters, DG, microgrid, next generation communication and control system, Internet of Things, are still in R&D or early pilot stage. Therefore, drafting a clear national strategy and road map based on comprehensive appraisals of numerous component technologies and their launch pathways poses another puzzle for developing SSG in China. An accompanied issue is how to integrate the international endeavors with domestic efforts.

7 Conclusion

This chapter adopts the framework of socio-technical systems transition to discuss the development of SG in China. As a starting point, we present the brief history and key features, landscape and regime of power sector in China for understanding the institution background. A low-carbon scenario for power sector into 2030 is compiled, and its salient features are discussed to understand the necessity and the requirements on SG. We then address the main functions of SSG in China and draft the transition pathways to a low-carbon power sector. A road map for developing SSG in China is proposed based on the overall transition pathways of the power sector. Institutional barriers on the road map are outlined and policy implications discussed. Based on the study in this chapter, we have three main findings.

Clear national strategy and road map is needed in China. To fill the institutional gaps, the government body (currently National Energy Administration) should be empowered to be responsible for national strategy formulation, a roadmapping think-tank should be formed to develop and update the road map, combining world-wide industrial, government, and academic expertise to assess technologies and identify obstacles and recommend appropriate policies, and an industry-government consortia should be formed to provide integrated translation research and strong front-end support.

Restructuring of the power sector should be synchronized with the development of SG. Dismantle the grid companies into regional transmission companies and provincial distribution companies to provide public goods to the private users. Set level playground in both technology and investor sense, encourage entry, and open the power sector to private investors. A national dispatch center is needed to take charge of national power system planning, regional interconnection, and the development of super smart transmission system. Power market could be established on both national and regional level.

Pricing mechanism reform should take the precedence of SG, in order to provide proper signal to power customers. A parallel institutional arrangement is to empower the costumers with rights to choose their own power retailers or energy management suppliers or to engage themselves as microgenerators.

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