Renewable and Sustainable Energy Reviews 132 (2020) 110102

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Transition of China's power sector consistent with Paris Agreement into 2050: Pathways and challenges

Haonan Zhang [a], Xingping Zhang [a,b], Jiahai Yuan [a,b,*]

[a] School of Economics and Management, North China Electric Power University, Beijing, 102206, China
[b] Beijing Key Laboratory of New Energy and Low-Carbon Development (North China Electric Power University), Beijing, 102206, China

ARTICLE INFO

Keywords:
Power sector
Low-carbon transition
2050 scenarios
Pathways
Challenges
China

ABSTRACT

With a high-carbon fuel mix and enormous space for efficiency potential, the power sector is critical to cope with global emission mitigation targets. The climate targets of less than 2 °C and even ambitious 1.5 °C confront China's power sector due to the rising momentum of power demand and the power mix dominated by coal power. Considering the potential carbon-emissions space of the power sector in China, this paper sets the alternative high-share renewable power, 1.5 and 2 °C scenarios that necessitate the zero-emissions and even negative-emissions for the power sector by 2050, and then proposes the pathways and outlines challenges to demonstrate the arduousness and uncertainty of the mega-project of power transition. The results indicate that a package of options is needed for the transition while unconventional bio-energy is the key to a 1.5 °C scenario. Notably, the coal power represents the largest barrier to low-carbon transition owing to the rising installation and massive stranded assets during the long-term reconfiguration of the power sector.

1. Introduction

In the Paris COP21 meeting, nearly 200 countries ratified the Paris Agreement stating "the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to below 1.5 °C above pre-industrial levels". The imperative issues coping with climate change are to mitigate carbon emissions and to increase carbon sequestration. Wherein, reducing carbon dioxide (CO_2) generated in the process of energy production, conversion and consumption is the crucial measure. Due to the combustion of massive fossil fuels, the accumulation of carbon dioxide predominately causes global warming intensifying, which shows the global average land surface temperature rising by about 0.85 °C during 1880–2012 [1]. At present, global greenhouse gas emissions are still growing, and the lock-in of high-carbon economic growth is such that it drives the emission trend likely to continue for a long time in the future [2].

China is the largest consumer of energy and emitter of CO_2 in the world. In 2018, the primary energy consumption is 137 EJ (equal to 3273.5 million tonnes of oil equivalent, Mtoe) and the aggregated carbon emissions are 9419.6 million tonnes of carbon dioxide equivalent (CO_2eyr^{-1}) in China, representing 23.2% and 27.6% of the world respectively [3]. Mitigation in China matters a lot to the global low-carbon transition and the realization of the 2 °C and even 1.5 °C targets. In Nationally Determined Contribution (NDC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat, China pledged to lessen the carbon intensity by 60–65% from the 2005 level, peak the carbon emissions around 2030 and strive to peak as early as possible. Matching with the NDC target, the Strategic Revolution in Energy Production and Consumption (2016–2030) (2030 Strategy hereafter) is promulgated to realize the mitigation targets and commitments. The 2030 Strategy commits to cap the energy consumption within 175.8 EJ (equal to 4199 Mtoe) and to increase the non-fossil energy share to 20% and natural gas share to 15%, with the increasing energy demand relying on the clean energy [4]. Whether the 2030 Strategy implies the decoupling of economy and coal use is subject to debate [5]. However, carbon-emission peaking is a challengeable issue for China. Ref. [6] Insisted that the 2030 Strategy cannot peak carbon emissions earlier than 2030, which confirms the early research of Ref. [7]. However, several pieces of research claim that CO_2 emissions from energy use are expected to peak no later than 2030 on certain conditions with more aggressive actions in China [8–11]. The low-carbon transition strives with multiple future uncertainties. Even if all countries' NDC targets are met as scheduled, by the end of the 21st century, the global average temperature will still rise by 2.6–3.1 °C [12],

* Corresponding author. School of Economics and Management, North China Electric Power University, Beijing, 102206, China.
E-mail address: yuanjh126@126.com (J. Yuan).

https://doi.org/10.1016/j.rser.2020.110102
Received 22 November 2019; Received in revised form 15 June 2020; Accepted 14 July 2020
Available online 27 July 2020
1364-0321/

Abbreviation definition

CO_2	carbon dioxide
IPCC	Intergovernmental Panel on Climate Change
EJ	Exajoule
Mtoe	million tonnes of oil equivalent
CO_2eyr^{-1}	carbon dioxide equivalent
NDC	Nationally Determined Contribution
UNFCCC	United Nations Framework Convention on Climate Change
GW	gigawatts
CEC	China Electricity Council
HRS	high-share renewable power scenario
LCS	low-share coal power scenario
HCS	high-share coal power scenario
SGERI	State Grid Energy Research Institute
BAU	business-*as*-usual
TWh	terawatt-hours
GDP	gross domestic product
CCS	carbon capture and storage
USD	United States dollar
BECCS	biomass energy CCS
DAC	direct air capture of CO_2
NAREC	National Renewable Energy Center
PV	photovoltaic
CCHP	Combined Cooling Heating and Power
DR	Demand Response
CSP	concentrated solar power
LCOE	levelized cost of electricity
NDRC	National Development and Reform Commission
FiT	feed-in-tariff
VRE	variable renewable energy
EE	energy efficiency
PJM	Pennsylvania—New Jersey—Maryland

which means that the emission reduction commitment of the Paris Agreement is far to achieve the long-term 2 °C target.

According to the China Electricity Council (CEC) database, by 2018, the total installed capacity of power generation in China has been 1899 GW (GW), including 1008 GW of coal power, 352 GW of hydropower, 44.7 GW of nuclear power, 184 GW of wind power and 174 GW of solar power [13]. The diversity of power supply transforms the power structure which used to be dominated by coal-fired and hydropower. China has achieved remarkable progress in cleaner power supply that includes 40% share of non-fossil power capacity and 30% share of clean power generation. In 2018, though the carbon intensity of the power sector has fallen from 758 g/kWh in 2007 to 592 g/kWh, China's carbon emissions from the power sector are 4140.9 million tonnes of CO_2eyr^{-1}, accounting for 44% of total national carbon emissions [13], which is originated from the specific resource endowment and high-share coal-fired power. However, the carbon reduction performance of the power sector in China is still worse than that in developed countries, which attributes the carbon lock-in of China's power system to the coal-based power generation. Therefore, in the future, addressing climate change is an important part of the development strategy of the power sector to promote the construction of a resource-saving and environment-friendly society.

China is in an important stage of accelerating industrialization and urbanization. How to cope with climate change under the condition of meeting the national power demand has become an urgent issue to debate. Also, the power sector is facing enormous challenges in carbon emission reduction. On the one hand, China's renewable energy power is difficult to achieve large-scale substitution of fossil power in the short term, and the specific uneven-distribution of power resources and load centers challenges the cross-regional allocation of power resources. On the other hand, China's coal consumption of coal-fired power supply and power line losses have reached or approached the international advanced level, so the potential for reducing the intensity of carbon emissions has gradually narrowed. Therefore, the process for the power sector to meet the 2 °C/1.5 °C target is underwhelming and challenging.

The feasibility of a 100% renewable power system has been demonstrated as a promising carbon mitigation option in many researches, which notably relies on sizeable storage facilities and advanced transmission networks [14–21]. The superior advantages of low carbon and environmental value enable the policy-driven boom of renewable energy deployment, which has gradually bloomed into a new techno-social paradigm. With the support of sufficient power system flexibility, renewable energy is expected to replace fossil energy as the dominant energy in the future. However, considering the designed generating life-cycles of 30–40 years, coupled with the ongoing construction of new thermal power units, the traditional fossil energy generating units will massively distribute over China for a long time to come unless China would enact more ambitious policy to phase out coal power. The State Grid Energy Research Institute (SGERI), an authoritative institution, believes that the peak installed capacity of coal power will reach 1230–1350 GW around 2030, so it is not suitable to eliminate coal power in a large scale too early or too fast.[1] The conclusion is similar to Refs. [22,23]. Consequently, this paper considers alternative options including decarbonization of fossil energy and high-share renewable power to expound the scope of China's transition. This paper sets a high-share renewable power scenario (HRS), high-share coal power scenario (HCS) and Low-share coal power scenario (LCS) respectively, to discuss the low-carbon transition of the power sector under distinct assumptions.

Distinct from the resolute viewpoints of 100% renewable power system, this paper also considers the possibility of thermal power sustaining in China by 2050 as a reference for scenario study. Through investigating the key zero-emission and negative-emission technologies such as advanced non-fossil power, biomass power generation, carbon capture technologies and energy storage, and evaluating the reasonable techno-economic prospects of various generating resources, this study analyzes the path constraints of low-carbon power transition to explore the possible scenarios of power planning schemes by 2050. Due to the anticipated trend of electricity dominating the energy mix, it is worth discussing the feasible pathways facing 1.5 °C and 2 °C targets for China's power sector.

This study unfolds as follows. Section 2 introduces the literature review. Section 3 describes the methodology framework and hypothesis. The scenario analysis is illuminated in Section 4. Section 5 and Section 6 reveal the pathways and challenges for China's low-carbon power transition. Finally, we conclude this study and provide some policy implications.

2. Literature review

The power transition scenarios, especially the virtual 100% renewable power system, usually require high-resolution hourly time series of wind and solar power generation and electricity demand [14,18]. Typically, the Integrated Assessment Model and Energy System Models are popular methods to present feasible scenarios for reaching global or regional high-share renewable energy supply [24]. Moreover, the dynamic simulation model [25], the integrated MARKAL-EFOM system

[1] http://news.bjx.com.cn/html/20190911/1006357.shtml.

model [26] and the bottom-up material flow analysis model [27] are conducted to analyze China's power transition. Many scholars have investigated the possibility of a 100% renewable energy system in the level of nations [18,28], regions [14,16,17] and the whole world [19,20]. The crucial flexibility for hosting a high-share renewable system can be provided by developing optimal mixes of renewable power supply to accommodate temporality issues, demand response solutions, supply-side management of dispatchable renewables, sector coupling, grid extensions and energy storage [24]. Controversially, the debate over whether the flexibility is insufficient for a 100% renewable power system has been extensively displayed in the discussion on feasibility criteria definition by Ref. [29] And Ref. [30]. But the consensus is that large-scale deployment of renewable energy is vital for carbon emission mitigation.

The target of 2/1.5 °C conducts a high demand for clean low-carbon energy, which will push up the demand for electricity. Such an idea is embodied in the share of electricity consumption in the total energy demand of the three primary end-use sectors – industry, buildings and transport –doubling from around 20% in 2015 to 40% in 2050 [31]. In business-*as*-usual (BAU) scenario, China's power demand would increase to 10,700–11600 TWh by 2050 [9,32]; under 2 °C and 1.5 °C scenarios, China's power demand would reach 11,750 TWh and 14,860 TWh, respectively [33]. There is an even large gap of 4000 TWh in electricity demand. Moreover, it should be noted that there is a high risk of insufficient resources carrying capacity for the excessive power demand caused by low-carbon targets. Considering energy efficiency improvement, it is expected that China's terminal energy consumption per unit gross domestic product (GDP) by 2050 would be only 30% of that in 2015, which would reduce the terminal energy consumption by 146.5 EJ (equal to 3500 Mtoe) compared with the BAU scenario in 2050 [34]. Ref. [2] Proved that energy efficiency is one of the keys to achieving the ambitious mitigation target. Thus, it is a must for China to rely on ultra-high energy efficiency to effectively curb the growth of electricity consumption.

The low-carbon power transition in China has been a hot-debated topic. Ref. [35] Elaborated on the transition to low-carbon power systems and proposed an interactive framework for low-carbon transition management in China. If the coal power capacity peaks at 1300 GW in 2030 as anticipated by SGERI, an average of 650 GW of coal power should be eliminated every year to realize the zero coal in 2050. This mission with significant risks is virtually impossible to accomplish. Due to the long-term role of coal power in China, the most promising transition pathway for decarbonization of the power sector is to retrofit coal-fired power plants with carbon capture and storage (CCS) applications, and to improve the installed capacity and power generation ratio of renewable energy by adopting ambitious policies [36]. CCS technology has been experimented to reduce 90% of carbon emissions from fossil power plants [37]. In the new-policy scenario of IEA, more than 15% of total coal power plants should be retrofitted with CCS devices by 2035 [38]. For the nations with surviving fossil power plants, a substantial use of CCS assists the targets of limitation of global warming to 2 °C and below [39]. 1.5 °C target requires removing 100–1000 billion tons of CO_2 from the air in the 21st century, most of which rely on a combination of biomass energy CCS (BECCS) [40]. BECCS is a potential technology that can transition the high-carbon fossil fuels to net negative-emission power by co-firing biomass and fossils [41–46]. Moreover, direct air capture of CO_2 (DAC) technology is recommended for fuels in the transport sector, in particular marine, aviation, and chemical industry, where sustainable options are hardly existing [47]. If it can be deployed commercially, DAC technology would promise to be a considerable technology for ambitious carbon mitigation [48]. BECCS and DAC can be recognized as negative emission technology in the power sector, while BECCS can provide flexible service and DAC will pose higher power consumption. In line with the climate objectives outlined in the Paris Agreement, the power sector would require an 85% share of renewable energy in total electricity generation by 2050 [49]. Ref. [50] Supposed that the share of non-fossil power capacity in total power installation would reach 90% and 92% in the BAU and less-2°C scenarios respectively, with nuclear and hydropower approaching the resource capping in China. And under 2 °C target, the ratio of renewable power capacity in China should be even 94% by 2050 [51]. To achieve a 1.5 °C target, the critical issue is to realize negative-emissions for the power sector through massive deployment of non-fossil power installation and biomass power coupled with CCS [52]. All these assessments provide insight into the phase-out of coal power in China.

With the widespread adoption of solar and wind power, the variability and uncertainty of variable renewable energy challenge the safety of the power system. The variability is defined as the fluctuating nature of solar and wind resources, which translates into potentially rapid changes in electricity output, and the uncertainty is regarded as the inability to predict perfectly the future output of solar and wind power sources [49]. The high penetration of solar and wind power necessitates sufficient flexible resources and heightens the scheduling complexity. To cope with such challenges, four steps of transition planning are defined as generation expansion planning (20–40 years), geospatial planning (5–20 years), dispatch simulation (weeks to a year) and technical network studies (current and near-time) [53]. Thus, the power grid is crucial to the power system transition characterized by a high proportion of renewable energy. Considering the landscape where China's energy resources and load centers are unevenly distributed, the cross-regional transmission is necessary to promote the efficient development and utilization of clean energy. By bundling renewable energy (60%) and coal-fired electricity (40%) to the eastern region through long-distance cross-regional transmission network, the air-pollution-associated deaths in China can be reduced by 16%, and the carbon emissions can be reduced by over three times than transmitting only coal-based electricity [54].

Overall, the flexibility and stability of 100% renewable power system has been virtually simulated by many previous researches, which is a plausible and valid scenario for ambitious carbon mitigation targets. However, this hypothesis is determined by the withdrawal of fossil power plants. There is great uncertainty about the phase-out of China's coal power by 2050, if ambitious climate change policies are not put in place. Considering the status and perspectives on the coal power industry and macro-economy in China, this paper proposes the alternative fossil decarbonization scenarios and discuss the transition challenges in particular.

3. Methodology

3.1. Research framework

China has promulgated the 2030 Strategy to guide energy issues by 2030. The carbon emissions reduction targets in 2030 are conjectured likely realizable. However, the energy development roadmap towards 2050 has not been proposed due to the mega projects and various challenges of 2 °C and 1.5 °C goals. This paper aims to explore the feasible pathways for China's power transition in alignment with the carbon emissions abatement. Without an hourly-time resolution model and simulation tools, a scenario analysis for China's power transition is presented in this paper by setting diverse assumptions on technical innovation of power generating to cope with the rigorous and severe carbon abatement goals.

This paper conducts a top-down model with fewer technological details to perform scenario assumptions. First, the national population and economic growth are assumed. Then, the per capita electricity consumption level by 2050 in China is deduced according to the experience in developed countries. Furthermore, the national power demand and maximum load prospect can be concluded in HCS and LCS.

The power generation can be calculated according to Eq. (1).

$$G = \sum_{i}^{n} ca_i \times h_i \tag{1}$$

where G denotes the power generation, i is the type of power technology, ca_i is the installed capacity of the corresponding type, and h_i means the annual utilization hours of the corresponding power type.

The carbon emissions from power generating are calculated in Eq. (2).

$$E_{co_2} = \sum_{i}^{n} G_i \times ef_i \tag{2}$$

where E_{co_2} is the carbon emissions from the power sector, G_i is the generation of the corresponding type, and ef_i means the emission factor of the corresponding power generating.

3.2. Data and assumption

3.2.1. Population and economic growth

In January 2017, the State Council issued the National Population Development Plan (2016–2030). It proposed that by 2020, the two-child policy should be brought into full play to raise the fertility level moderately with the total national population up to 1.42 billion. By 2030, the situation of the dynamic self-balanced population is supposed to drive the total population reaching a peak of 1.45 billion, and then decrease slightly afterward. The main indicators of China's economic and social development are forecasted in Table 1.

3.2.2. Per capita electricity consumption

Throughout the social history of developed countries, per capita electricity consumption will increase with the growth of per capita GDP, as shown in Fig. 1. When per capita GDP is less than 30,000 USD/p, higher per capita GDP corresponds to higher per capita electricity consumption; when per capita GDP is higher than 30,000 USD/p, per capita electricity consumption gradually reaches a plateau rather than increasing with per capita GDP growth. Currently, per capita electricity consumption in major developed countries ranges from 5500 kWh/p to 10,000 kWh/p.

In the medium and long term, China's power demand growth in the process of industrialization and urbanization can refer to the development track of the industrialized economy. Comparing with the growth law of electricity consumption in the major countries, the historical track of per capita electricity consumption in China is similar to that in South Korea. The saturation period of electricity consumption in China is anticipated to occur during 2030–2040. In this progression, the energy-saving technology innovations are capable of lowering future saturation, while emerging power demands (high tech-industry and electric vehicles for example) have a reverse impact. In summary, China's per capita electricity consumption would surpass 4800 kWh/p in 2020 (close to the level of moderately developed countries) and approach 6200–7500 kWh/p, 6700–9500 kWh/p and 7000–11000 kWh/p in 2030, 2040 and 2050, respectively.

3.2.3. National power demand

Whether the scale of energy demand can be effectively capped also

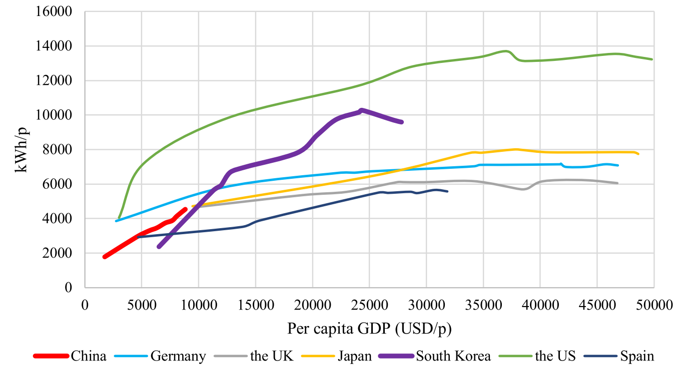

Fig. 1. Relationship between per capita power consumption and GDP, Source: IEA database.

significantly affects the "feasibility window" of achieving the 2 °C target [55]. The high electrification in aligning with HCS pushes up power demand and even exceeds the resource carrying capacity. Thus, we hypothesize the per capita electricity consumption in 2050 is 7000 kWh/p, 10000 kWh/p and 11000 kWh/p in the HRS, HCS and LCS, respectively. According to the insight of population and per capita electricity consumption, the total social electricity consumption of China would increase to 9660–15180 TWh (details seen in Table 2).

Scenario setting：

HRS: Higher per capita electricity consumption scenario, negative emissions in 2040.

HCS: High per capita electricity consumption scenario, zero-emissions in 2040 and negative emissions in 2050.

LCS: Low per capita electricity consumption scenario, zero-emissions by 2050.

3.2.4. Maximum load prospect

Economic structural adjustment, industrial upgrading and improvement of living standards will bring about obvious changes in load characteristics. The power demand of the tertiary industry and residents with relatively low load rates will grow faster, so the maximum load growth rate will exceed that of electricity consumption. As shown in Table 3, it is estimated that the national power load would reach 1100–1160 GW by 2020 with the annual average growth during the 13th Five-Year Plan (2016–2020) being 5.53–6.67%. To depict the trend, a range of linear annual growth rates are presumed at 2.95%–4.49%, 0.56%–2.11% and 0.2%–0.87% for the next consecutive decade-year till 2050.

4. Power transition scenario

The power characteristics and roadmap under the HRS/HCS/LCS

Table 1
Indicators of China's economic and social development.

National indicators	2020	2030	2040	2050
Population (billion)	1.42	1.45	1.415	1.38
Per capita GDP (USD in 2015)	10,208	17,617	23,834	29,895
GDP growth (%)	7.2	5.4	4.1	2.5
Urbanization rate (%)	62%	70%	75%	78%
Primary industry (%)	6.8	5.4	5.0	4.8
Secondary industry (%)	41.1	33.7	32.3	30.9
Tertiary industry (%)	52.1	60.9	62.7	64.4

Table 2
National power demand during 2020–2050.

Power demand indicators	2020	2030	2040	2050
Population (billion)	1.42	1.45	1.415	1.38
Per capita power consumption in HRS (kWh/p)	5000	7500	9500	11,000
Per capita power consumption in HCS (kWh/p)	5000	7200	9000	10,000
Per capita power consumption in LCS (kWh/p)	4800	6200	6700	7000
Total power consumption in HRS (TWh)	7100	10,875	13,442	15,180
Total power consumption in HCS (TWh)	7100	10,440	12,735	13,800
Total power consumption in LCS (TWh)	6816	8990	9480.5	9660
Energy efficiency generation (TWh)	284	1450	3254.5	4140
Power demand growth in HRS (%)	4.65%	4.36%	2.14%	1.22%
Power demand growth in HCS (%)	4.65%	3.93%	2.01%	0.81%
Power demand growth in LCS (%)	3.59%	2.81%	0.53%	0.19%

Table 3
Social power load during 2020–2050.

Power load and growth	2020	2030	2040	2050
Peak power load in HRS (GW)	1160	1800	2200	2400
Peak power load in HCS (GW)	1160	1738	2142	2330
Peak power load in LCS (GW)	1100	1470	1555	1586
Growth of peak power load in HRS (%)	6.67%	4.49%	2.03%	0.87%
Growth of peak power load in HCS (%)	6.67%	4.13%	2.11%	0.85%
Growth of peak power load in LCS (%)	5.53%	2.95%	0.56%	0.20%

framework in China are described in Table 4. All of the current power technologies are available in the scenario hypothesis. The co-firing of biomass and coal power can effectively lower the emission intensity of power generation [43]. The co-firing of biomass and fossil fuels in conjunction with CCS is promising to produce relatively inexpensive carbon negative electricity [44]. A co-firing power plant with CCS can achieve near-zero emissions at a co-firing ratio of 25% and negative emissions of 877 g/kWh from a life-cycle perspective when coal is totally replaced [44]. Although the generation cost of fossil power and nuclear power would be likely higher than that of renewables, the co-firing of biomass and fossil fuels retrofitted with CCS and nuclear power are alternative options for carbon mitigation of power sector.

HRS: all of the coal power plants would be eliminated gradually, but the fossil power (gas and biomass power) would remain in the power system. Wind power, solar photovoltaic (PV) and supporting energy storage devices would be deployed nationwide, and the capacity of hydropower, nuclear power and other renewables would reach the upper limit of resources.

HCS: high-share coal power would be sustained in 2050. The capacity of hydropower, nuclear power, wind power and other renewable energy resources would reach the upper limit of the expected development scale to meet the national power demand. At the same time, CCS of conventional fossil power technology should be considered to ensure the target of zero-emissions in 2040 and negative emissions in 2050.

LCS: low-share coal power than HCS would be sustained in 2050. The capacity of hydropower, nuclear power, wind power and other renewable energy would reach the lower limit of the expected development scale without raising any coal-fired power units. Also, energy efficiency technology has been further improved and electricity consumption has been conserved, which will reduce the overall level of social power demand in 2050.

4.1. HRS analysis

As shown in Table 5, this paper presents China's power landscape of high-share renewable power scenario in 2050. Non-fossil power generation share would increase to more than 90%. Enormous flexible resources satisfy the high-share renewable power system as shown in Table 6. By 2050, the share of flexible capacity in China would approach 37.5%. HRS is a simple hypothesis for China's low-carbon power transition scenario without virtual proof of high-resolution hourly time series, which is beyond the scope.

Power system flexibility is one priority of power system transformation. A power system can reliably and cost-effectively manage the variability and uncertainty of supply and demand across all relevant timescales [56]. The increasing penetration of variable renewable energy necessitates power system flexibility, from the very short to the long term, avoiding curtailment and reliably supplying all the demanded energy to customers [57]. The complementary portfolio of various flexible options could meet the reliable and cost-effective management of variability and uncertainty in both supply and demand, for example, a) flexible plants for generation scheduling and dispatch halt when solar is abundant, b) pumped storage and the battery storage will be charged/discharged according to the sufficient/insufficient power supply, c) DR shifts the peak load at night to daytime.

Table 4
Power technology roadmap in HRS/HCS/LCS.

Technology	HRS	HCS	LCS
Coal power	All of the coal power plants would be phased out by 2050.	Supercritical and ultra-supercritical units would dominate the coal power installation after 2020, and then some units would be retrofitted for cogeneration and CCS coupled with biomass, and the old ones would be gradually phased out by 2030. By 2050, all operating coal power plants would realize biomass blending and CCS installation.	Through strictly capping coal power, the installation of new coal power plants would be prohibited except cogeneration units after 2020. All coal power units would begin to be retrofitted for CCS coupled with biomass after 2040 and the coal power plants without CCS would be decommissioned by 2050.
Gas power	The gas power retrofitted with CCS would mainly provide flexibility for renewables penetration.	The absolute scale of gas power, including baseload power, peaking power and CCHP (Combined Cooling Heating and Power), would more than triple in 2050 compared to 2018. The baseload gas power would be installed with CCS after 2040.	By 2020, China would focus on the deployment of CCHP.
Hydropower	The hydropower development would be completed in 2050, reaching 550 GW.	The hydropower development would be completed in 2050, reaching 500 GW.	The hydropower development would be completed in 2040, reaching 480 GW.
Nuclear power	The raising capacity of nuclear power would reach a scale peak by 2025.	The raising capacity of nuclear power would reach a scale peak by 2025.	The installation of nuclear power would slack comparing to HCS.
Wind power	The large-scale deployed wind power would be one of the dominant powers.	The wind power would be large-scale deployed and become the power source with the largest installed capacity by 2050.	The wind power deployment would be more moderate than that in LCS.
Solar power	The large-scale deployed solar power would be one of the dominant powers.	The solar PV and photothermal technology would be ever-increasing rapidly, reserving second in size only to wind power.	The installation of solar power would exceed that of wind power by 2050.
Biomass power	To realize negative emissions in 2050, the biomass power is necessary.	To realize negative emissions in 2050, the biomass power is necessary.	To realize zero emissions in 2050, the biomass power is necessary.
Energy efficiency	Energy efficiency technologies would improve significantly. The energy storage devices would be essential for system flexibility.	Energy efficiency technologies would improve significantly.	Energy efficiency technologies would improve significantly.

Table 5
HRS power landscape in 2050.

Resources	Installed capacity (GW)	Capacity share	Generation (TWh)	Generation share
Hydro power	550	8.04%	1925	11.06%
Gas power	500	4.14%	500	1.72%
Nuclear	120	1.66%	840	4.83%
Wind power	2800	38.68%	8400	48.25%
Solar power	3200	44.21%	4800	28.73%
Biomass power	230	3.18%	1035	0.81%
Geothermal	19	0.26%	76	0.45%
Ocean power	19	0.26%	32.3	0.19%
Total	6518	100%	16,618	100%

Table 6
Capacity and share of flexible resource in 2050.

Resources	Capacity (GW)
Electric vehicles	120
Pumped storage	300
Demand Response (DR)	586
Gas	500
Hydro	100
Energy storage	1040
Total	2446

4.2. HCS analysis

As shown in Table 7, in HCS, the installed capacity of coal-fired power should peak at 1050 GW in 2020, and then it shows a decreasing trend with the decommissioning of coal-fired power units. By 2050, the installed capacity of coal-fired power would drop to 420 GW accounting for 8% of total power capacity. As important baseload power sources, the installed capacity of hydropower would increase steadily and nuclear power would peak its capacity at 56 GW by 2030. Pumped storage and gas turbine are prominent peak-shaving power sources supporting the large-scale deployment and penetration of renewable energy. Biomass power generation begins its radical development after 2020 as an important technology to reduce carbon emissions.

To cope with the variability and uncertainty of high-share variable renewable energy, the power system should introduce sufficient flexible capacity to smooth out seasonal and daily variability in supply. The flexible resources include dispatchable power plants (coal power, pumped storage, gas power, photothermal power and energy storage), demand response (DR) and electric vehicles (shown in Table 8). By 2050, the share of dispatchable capacity in China would approach 35% with the variable renewable energy capacity accounting for 72.5%.

Table 8
Capacity and share of flexible resource in HCS (GW).

Resources	2050
Electric vehicles	101.25
Pumped storage	300
DR	586
Gas	100
Hydro	100
Coal	126
Energy storage	500
Total	1813.25
Capacity share	34.58%

4.3. LCS analysis

Because the national power demand in LCS is much lower than that in HCS, the installed capacity of diverse power sources in LCS has reached the lower limit of exploitable resources. The share of coal power capacity would be 4%, and the installed capacity of renewable energy in LCS such as wind power and solar power will be greatly reduced than that in HCS. Then, wind power is anticipated to approach 34% of the total installed capacity, and the share of solar power would surpass 39% (depicted in Table 9).

As depicted in Table 10, in the LCS, the flexible power capacity is larger and the share is higher than that in HCS, which could fully meet the large-scale renewable energy access and penetration.

4.4. HCS VS LCS analysis

Based on the power planning of HRS, HCS and LCS, the primary energy consumption corresponding to various types of power generation in different future development stages is calculated. From Fig. 2, it can be seen that the primary energy consumption shows a gradual upward trend in the HCS scenario, but the upward trend slows down gradually. To satisfy the high level of electrification, the scale of energy resources would expand and then push up the primary energy consumption of the power sector. Compared with the sharply rising trend of energy consumption of the power sector in HRS and HCS, it would peak at 77.6 EJ (equal to1856 Mtoe) in 2040 and then lessen by 2050 in LCS.

The assumption of the carbon factor of the corresponding power generating is presented in Table 11. The emission calculations are conducted within the power sector (including coal, coal-CCS, co-firing biomass and coal with CCS, gas, gas-CCS, and BECCS), rather than the life-cycle basis. As shown in Fig. 3, the carbon emissions show a linear downward trend after peaking at 2020 in HCS, which is attributed to the radical improvement in coal-fired coupled biomass power generation mode and CCS retrofit to reduce carbon emission factors of coal-fired power beginning from 2030. Also, to achieve the goal of zero

Table 7
Power planning in HCS.

Resources	Installed capacity (GW)	Capacity share	Generation (TWh)	Generation share
Hydro	500	9.53%	1750	12.44%
Coal power	420	8.01%	1680	11.94%
Gas (baseload)	100	1.91%	300	2.13%
Gas (variable load)	100	1.91%	100	0.71%
CCHP	100	1.91%	450	3.20%
Nuclear	56	1.07%	392	2.79%
Wind	2000	38.14%	6000	42.66%
Solar PV	1800	34.32%	2700	19.20%
Biomass direct fired	130	2.48%	585	4.16%
Geothermal	19	0.36%	76	0.54%
Ocean power	19	0.36%	32.3	0.23%
Total	5244	100%	14065.3	100%

Table 9
Power planning in LCS.

Resources	Installed capacity (GW)	Capacity share	Generation (TWh)	Generation share
Hydro	480	12.49%	1680	16.94%
Coal power	160	4.16%	640	6.45%
Gas (baseload)	90	2.34%	270	2.72%
Gas (variable load)	90	2.34%	90	0.91%
CCHP	90	2.34%	405	4.08%
Nuclear	56	1.46%	392	3.95%
Wind	1300	33.82%	3900	39.33%
Solar PV	1500	39.02%	2250	22.69%
Biomass direct fired	40	1.04%	180	1.82%
Geothermal	19	0.49%	76	0.77%
Ocean power	19	0.49%	32.3	0.33%
Total	3844	100%	9915.3	100%

Table 10
Capacity and share of flexible resource in LCS (GW).

Resources	2050
Electric vehicle	101.25
Pumped storage	300
DR	586
Gas	100
Hydro	96
Coal	0
Energy storage	500
Total	1705.25
Capacity share	44.36%

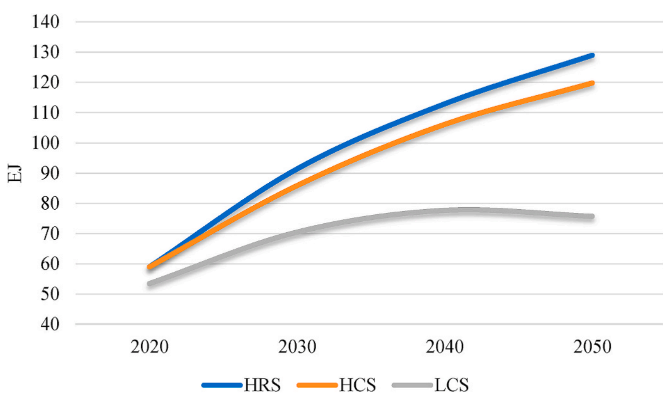

Fig. 2. Energy consumption of power sector during 2020–2050.

Table 11
Assumption of emission factors for fossil power with CCS.

Technology	Coal	Coal-CCS	Co-firing biomass and coal with CCS	Gas	Gas-CCS	BECCS
Factors (g/kWh)	750-930 [13]	79–93	<0 [44]	360 [60]	36	−877 [44]

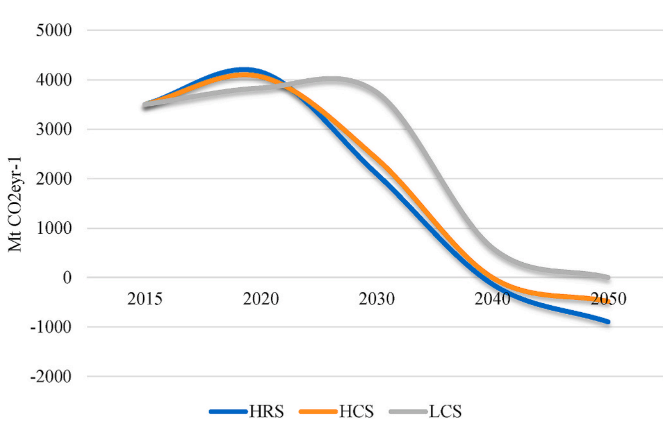

Fig. 3. Carbon emissions from the power sector during 2020–2050.

emissions in 2040 and negative emissions in 2050, BECCS or DAC should expand and further explore the potential of emission mitigation. In the LCS, the less social power demand lessens the installed scale of various power techniques correspondingly and carbon emissions would peak in 2030. Since there is no CCS retrofit of coal-fired and gas-fired power units between 2020 and 2030, the declining trend of carbon emissions is relatively flat. But CCS would boost decarbonization efficiency to 90% after 2040. As a result, carbon emissions show a rapid downward trend until 2050 to achieve zero emissions. Ref. [58] Believed that through promoting advanced technologies and shifting to more renewable energy, China's carbon emissions of power industry could peak at 3717.99 Mt in 2023. However, concerning the feasibility of response actions, the stricter HCS implies stronger and earlier solutions with higher macro-economic costs, which promises a bleak outlook [12,55,59].

4.5. Discussion on power generation economics

This paper is not a detailed financial analysis of project economics, but a discussion on the dynamic technical trend. Strong policy can drive the technical cost reduction, as exemplified by global renewable energy development. In 2018, the global weighted-average cost of electricity declined 26% year-on-year for concentrated solar power (CSP), followed by bioenergy (−14%), solar photovoltaic (PV) and onshore wind (both −13%), hydropower (−12%), geothermal and offshore wind (both −1%) [61]. In China, the benchmarking electricity tariff of wind power for the Class I region will be 0.29 yuan/kWh less than that of local coal power [62]. Continuing cost declines underline renewable power as a low-cost climate and decarbonization solution. The levelized cost of electricity (LCOE) of renewable power is promising much less than that of coal power with CCS, which can validly reduce the power supply cost [14,16,17]. If the energy storage industry achieves its technical revolution, together with power grid flexibility solutions, the high-share renewable power system would be more economical. 80%–90% share renewable power system is feasible to lower the whole cost of power supply (including reserve and flexibility service) to 0.07 USD/kWh by 2040 [63]. And the positive impact of renewables on ecological environment has not been valued and internalized in China, which may underestimate the overall benefits of renewables replacing fossil power. The future high-share renewable power system would be likely more economic than the fossil power system.

However, the technical cost of power generation is not the sole factor determining the planning or layout of the national power system. The deployment of low-carbon technologies should also consider the national energy endowment. Despite the higher cost than renewables, nuclear power can provide a more reliable and powerful electricity service for the current social development without carbon emissions. Given the long technological life span of nuclear power plants, this paper assumes that all of the nuclear power plants in service and under construction would sustain by 2050. For China, coal is expected to dominate the energy mix in the foreseeable future [22,23]. CCS applications contribute to carbon mitigation in China's power sector [26]. Ref. [64] Suggested early deployment of CCS in China's industrial and synthetic fuel production sectors, followed by increased deployment in the power sector by midcentury. With an extensive industrial base of coal-fired power plants in China, CCS as an inevitable option to meet anticipated targets needs more policy supports and commercial deployment to overcome its high technical cost challenge [65]. Though renewables and batteries show the momentum of lower technical cost, fossil power retrofitted with CCS is still potential to improve its economy if the strong policy supports drive its learning rate. BECCS and DAC as prominent negative emission technologies require a concerted support effort to decide the application scenario and scope. Thus, the uncertain economics and breakthrough of various power technologies challenge low-carbon transition options.

5. Low-carbon power transition pathways

5.1. Pathway 1: mass deployment of renewables

In this paper, the massive deployment of renewables is hypothesized based on better power economics. The feed-in-tariff (FiT) of wind power for the Class I region has dropped from 0.51 yuan/kWh to 0.29 yuan/kWh during 2009–2020 [62,66], which indicates the grid parity of renewable energy is approaching in China. The generation economics of renewables is promising better than fossil fuels. Meanwhile, due to the capability to compatible with volatile power, the spot market promoting in China is conducive to the integration of renewable energy. This paper supports that a sun-set mechanism in FiT and then integration with the market are the solution for large-scale development of renewables. China is witnessing the increasing substitution effect of renewable energy on coal-fired power concerning generation cost, policy-making and environmental value, which denotes a stagewise process of large-scale incremental substitution and regional stock substitution. For China, the deployment of renewable power and the mandate for retrofits of existing coal power plants are the most promising for reducing fossil energy consumption and carbon emissions [36]. Scenario estimates in this paper show that if achieving the target of 2 °C and even 1.5 °C in 2050, the proportion of renewable energy generation would inevitably exceed 50% in China and even 90% in high-share renewable power scenario. Thus, the large-scale deployment of wind and solar power is the pillar of the energy supply revolution, replacing coal power.

5.2. Pathway 2: coal power phase-out

This paper assumes the coal capacity stabilizing around 1000GW during 2020–2030 and then a quick phase-out afterward, which is critical for carbon mitigation. Ref. [67] Presciently commented on the signals of coal power overcapacity issue. China has been instituting supply-side reform of coal-fired power through eliminating the substandard units and postponing the approved projects to curb overcapacity of coal power capacity. But the promulgated target of coal power capacity in 2020 is within 1100 GW [68], more than the scenario assumptions. Meanwhile, the installation capacity of coal power remains rising momentum. This will narrow the window of transition opportunity. If more coal power plants are installed during the 13th (2016–2020) and 14th (2021–2025) five-year plan periods, the total carbon emissions in China would likely peak around 2025–2035; but if tightening the cap on coal power capacity after 2020, the peak would likely occur earlier (between 2020 and 2025) [11]. This sentiment is echoed in this paper. Thus, this paper appeals to stronger policy incentives to phase out sizeable coal-fired power plants in the coming decades under the framework of 2 °C/1.5 °C targets.

5.3. Pathway 3: massive biomass deployment

Large-scale development of coal coupled biomass with CCS is an essential technical option for negative-emissions of the power sector [69]. In this paper, the biomass energy retrofitted with CCS is recognized as a crucial option that potentially satisfies the power supply, provides flexible service and meets the requirements of low-carbon development. Given the dominant position of coal-fired power units in the power system, coal-fired coupled with biomass power generation is a powerful measure to optimize the allocation of energy resources, solve pollution problems and mitigate carbon emissions. It is aforementioned that both biomass direct combustion technology and coal-fired coupled biomass power retrofitted with CCS facilities are conducive to the negative emissions in HCS. Therefore, this paper asserts the upcoming expansion of biomass energy.

5.4. Pathway 4: nuclear power development

As a clean, efficient and high-quality modern energy, nuclear power is the stable source of non-fossil energy. In 2018, the nuclear power capacity in China is 44.6 GW, and the capacity under construction is 12 GW ranking the first place in the world [13]. This paper postulates that China would not approve new nuclear power plants and the nuclear capacity would peak at 56 GW by 2030. Therefore, the capacity of nuclear power is set at 56 GW in 2050. It suggests that China needs to intensify efforts to explore nuclear power deployment on the precondition of complying with nuclear security conventions.

5.5. Pathway 5: energy storage deployment

All three transition scenarios set in this paper define energy storage as an important measure to improve the system regulation ability and ensure the flexible operation of the power system. For high-share renewable power system, there is no substitute for energy storage. Common energy storage technologies include conventional pumped storage, physical storage and electrochemical storage. China's energy storage deployment is seriously inadequate due to its poor economics. In 2017, the share of energy storage in total generation capacity is 1.6%, of which 97% is pumped storage. Proper pumped storage resources are rather limited. To be on track, new energy storage especially electric battery must advance quickly in China. China's energy storage capacity is expected to reach 800GW in 2050, of which 63% is electrochemical.

5.6. Pathway 6: CCS deployment

CCS technology is vital to global carbon emissions abatement for the prospect of allowing coal power to survive while resolving coal's high-carbon problem. This paper comments that it is impossible to completely phase out coal power in China by 2050, hence the largest fleet of coal units should be considered attractive for CCS retrofit. The utilization cost of CCS technology is closely related to fuel selection, combustion mode, process efficiency, carbon transport mode and storage conditions, and the overall cost is decreasing significantly [70]. The 1000 MW ultra-supercritical unit equipped with CCS has the largest carbon reduction potential and the lowest unit abatement cost among all power units [10]. IEA forecasted that by 2050, CCS would provide about 14% of the emission reduction for stabilizing the climate, while 20–25% of global CCS emission abatement will come from China, 60% of which will depend on the application of CCS in power plants [71]. This paper underlines that the less-2°C target necessitates 182 GW coal power with CCS retrofit, while 2030–2035 is the best deployment time for China.

6. Challenges for low-carbon power transition

The carbon abatement targets face exogenous cumulative carbon emission constraints and endogenous social carbon cost. The challenges posed by various targets to China are embodied in three dimensions: emission trajectory change, energy structure transformation (or energy reconstruction) and macroeconomic impact [59,72]. This paper discusses the transition challenges of the power sector as follows.

6.1. Challenge 1: provision of flexibility

Many scholars theorize that power low-carbon transition will occupy a systematic feature of high-share variable renewable energy, which necessitates the provision of flexibility to address the intermittency and unpredictability nature of renewable energy. Flexibility is the capability of a power system to cope with the variability and uncertainty that variable renewable energy (VRE) generation – such as wind, solar PV and run-of-the-river hydropower – introduces into the system at different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers [51]. This paper notes that large-scale commercial energy storage, traditional flexible power (pumped storage, flexible coal, gas and photothermal) and new flexible resources (electric vehicles and DR) ensure the reliable operation of the renewable power system. In 2018, the capacity of gas power and pumped storage is about 123 GW, and 40 GW of coal power plants have been retrofitted by flexibility [13]. In this paper, it is estimated that China's flexible resources should reach 1813.25 GW (31.44%) and 1705.25 GW (42.98%) in 2050 under HCS and LCS scenarios respectively. Thus, there is an enormous gap of flexible resources under the framework of the low-carbon transition.

6.2. Challenge 2: massive stranded coal assets

This paper defines the phase-out of coal power as a tough mission for China's government. The combination of "new economic normal" and low-carbon transition is expected to cap the coal power capacity around 970 GW by 2020 [5]. But of most concern is the capping progress is underwhelming. To mitigate the risk of coal power overcapacity, China would phase out the substandard capacity of 20 GW and postpone approved plants of 150 GW [68]. Nevertheless, this act is less ambitious for the coal power transition landscape described in this paper. With an average plant age of 14 years, the retirement plan could lead to the high stranding value of coal power plants. The stranded asset of coal power is defined as the sum of the unrecovered initial investment and the amount that does not meet the expected return of investors [73]. For the coal fleet built-in 2016, this paper estimates that, if stranding 200GW in HCS and 700GW in LCS, the stranded assets could be 150 and 520 billion yuan with 2020 as stranding year or 100 and 340 billion yuan with 2030 as stranding year. The phase-out of coal power under the framework of climate change will be a big challenge for China.

6.3. Challenge 3: inadequate biomass resources

Technical secure, long-term supplies of low-cost and sustainably sourced feedstocks are critical to the deployment of biomass power plants. The potential of conventional biomass resources in China is 13.5 EJ (equal to 322 Mtoe),[2] accounting for 13.4% of broadly accepted global limit for bioenergy use of 100 EJ [74]. Despite the higher value of bioenergy used in the heat and transport sector, to meet the negative emission target, this paper assumes that 48% share of China's biomass would be used to generate about 1000 TWh of electricity by 2050. The assumption is similar to Ref. [75]. However, to meet the negative emission level of 1.5 °C, the consumption of bioenergy for power generation in high-share coal power scenario should reach 22 EJ (equal to 525 Mtoe), which surpass the limit of biomass resource in China. Thus, large-scale deployment of BECCS to meet the negative emission target would burden the land use [76]. Another problem is the high cost and the defective supply chain of conventional biomass materials, such as a shortage of materials, low efficiency of collection-storage-transportation and a small range of resources. The bottleneck of deployment is how to reduce production costs through technological progress with reconciling capital investment, industrial support, enterprise attention and policy motivation. Then, more researches need to further assess the impact of marginal land development on the environment, as well as the feasibility, difficulty and cost-effectiveness of the marginal land transformation. It is supposed to consider the development of bioenergy, rather than ignoring the long-term impact on the ecological environment. Even having enough resources, the life-cycle carbon footprint of conventional biomass is a matter of issue that is uncertain and variable, depending on the biomass source and whether involving land conversion to high carbon reserves such as forests.

6.4. Challenge 4: nuclear power economics and safety

Nuclear power will remain a base-load power source competitive with coal power. The technology innovation of third-generation nuclear (G III) and commercialization processes under oncoming power markets are barriers to expanding nuclear capacity in China. By advancing technical innovation, the carbon emissions reduction potential and cost of nuclear power is greater than coal power with CCS [77], but less than the renewables. However, with the 2011 Fukushima nuclear accident in Japan, the global crisis impels all nations to suspend project approval and conduct comprehensive security checks and mandates on existing plants. Thus, the development of nuclear power should synthetically juggle safety and economics.

6.5. Challenge 5: energy storage commercialization

China's energy storage industry is still in the initial stage of industrial development. This paper summarizes the challenges that the energy storage industry is facing as follows. Firstly, the positioning of energy storage in the electricity market is unclear, which affects the formulation of subsequent policies such as project establishment, market access, charging-discharging pricing, etc. Secondly, the current peak-valley electricity tariff in China is insufficient to fully reflect the value of flexible resources such as energy storage, and it is difficult to effectively stimulate the rapid promotion of energy storage technology on the power demand side. Thirdly, the value relationship and trading mechanism between energy storage and power generation-transmission-distribution-consumption are still not clear, which makes it difficult to form a mature business model. Finally, the prime cost is still high for battery energy storage. Especially with the large-scale popularization of demand response and electric vehicles, the marginal value of energy storage systems may also decline. Therefore, this paper advocates the view that the continuous decline of energy storage costs is crucial to future energy storage applications. Also, the future application should focus on access to a high share renewable energy grid to further solve the stability, reliability, security and other issues.

6.6. Challenge 6: energy efficiency and DR

This paper estimates that the potential power conservation shares by energy efficiency (EE) would be 30–40% of total consumption, depicted in Table 12. With the continuous renewal of technology and the expansion of market scale, EE will play an important role in the future power transition, not only as demand-side resources to save electricity but also as a flexible power supply to assume the role of peak shaving system. For example, with the large-scale interconnection of renewable energy, the traditional source, network planning and grid operation dispatching mode increase the cost of grid construction and operation. The implementation of DR measures can ensure the safe, stable and economic operation of the grid, and promote the further large-scale integration of renewable energy. The size of the PJM (Pennsylvania-New Jersey-Maryland) power system in the United States is similar to that of China's regional power system. It is known that DR capacity is about 8–10% of the maximum load of PJM, which is the largest DR market in the United States. This paper believes that, despite the late start of DR in China, DR mechanisms will play an important role in social and economic benefits, with the acceleration of power system reform and the continuous improvement of the power market. However, deploying EE on such a large scale (more than 500 GW) is a tremendous challenge to China.

Table 12
Electricity saving by EE in China, 2020–2050.

Demand-side resources (TWh)	2020	2030	2040	2050
Electric vehicle	3.6	40	100	270
Efficient lightbulb	187.5	375	450	500
Efficient motor	28	60	100	140
Efficient transformer	28	480	640	800
Variable frequency speed governor	17.5	300	400	500
Ice Thermal Storage	1.6	4	80	9.6
High-efficiency household appliances	16	40	120	120
DR	2	3.5	50	580
Energy efficiency of the building	0	100	1000	1500
Others	0	48	315	156
Total	284	1450	3255	4140

[2] https://www.in-en.com/article/html/energy-2265794.shtml.

7. Conclusion and implications

Low-carbon power transition is critical to climate mitigation. For reasons specific for China, the power sector accounts for 41.9% of total CO_2 emissions in China, which necessitates the zero-emissions and even negative-emissions for the power sector in HCS and HRS/LCS by 2050 to achieve the NDC targets. This study conducts a high-level assessment of China's power transition scenarios focusing on the technically plausible power mix and pathways as well as possible challenges. The scenarios are postulated by the macroscopic social-economic prospect in the process of accelerated industrialization, urbanization and modernization. The high-share renewable power scenario features a 90% share of renewable power capacity and enormous flexible resources. For both LCS and HCS hypothesis, it is a must for China to rely on ultra-high energy efficiency to effectively curb the growth of electricity consumption. And high-share renewable energy is crucial, but not enough to achieve negative emissions in the LCS. Therefore, at the same time, carbon capture and storage of conventional energy and power emissions should be considered to meet the targets.

Concerning the HRS/LCS/HCS power low-carbon transition outlook, the following points are refined to conclude this study:

We can hypothesize the abatement scenarios that are technically possible and plausible, but the pathways remain highly uncertain. China's power mix dominated by coal renders the phase-out of massive-scale coal power plants in 20 or 30 years the biggest challenge of energy system transition in the world and continuing with unchecked growth will make it even difficult. However, the coal power phase-out is not on track with China's existing policy. China is still enacting the landscape of increasing coal power installation. Industry stakeholders have openly lobbied for coal capacity at 1300–1400GW by 2030 while supply security is a key argument for coal capacity increase. The coal policy arrangement is not friendly aligned with the Paris Agreement targets. The long-term energy transition targets must impel the short- and medium-term low carbon pathways.

Transition to an HRS/LCS/HCS power system is possible but with tremendous challenges. The massive stranded assets of coal power plants represent the largest barrier to the LCS transition. And the poor flexibility of the power system poses pervasive VRE curtailment in China, which is the primary obstacle to overcome to support the security of the high-share VRE system. Whereas there is no one-size-fits-all solution, that is, a high share of RE is not enough for LCS transition! Massive CCS retrofits are inevitable to China's carbon mitigation targets.

Today's policy and planning will determine the road towards 2030 and 2050. We suggest implementing a more ambitious 2050 Energy Revolution Strategy and roadmap, meanwhile retrospectively reforming the energy system, making sure that medium- and short-term targets consistent with long-term vision.

Credit author statement

Haonan Zhang: Formal analysis, Data curation and Writing – Original Drat; Xingping Zhang: Writing - review & editing; Jiahai Yuan: Conceptualization, Methodology, Supervision and Project administration.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgments

The authors gratefully acknowledge the funding of the National Natural Science Foundation of China (71673085), the Fundamental Research Funds for the Central Universities (2018ZD14) and the 111 Project (B18021). The authors would also like to acknowledge great thanks to anonymous reviewers for their valuable comments which largely improve the academic quality of this article. The usual caveats apply.

References

[1] IPCC. Climate change 2014: the fifth assessment report of the intergovernmental Panel on climate change. Cambridge University Press,Cambridge,United Kingdom: Intergovernmental Panel on Climate Change; 2014.
[2] Rogelj JLGPR. Energy system transformations for limiting end-of-century warming to blow 1.5°C. Nat Clim Change 2015;5:519–27.
[3] Statistical BP. Review of world energy. Paris: BP; 2019.
[4] NDRC. Strategic revolution in energy production and consumption (2016-2030). Beijing: National Development and Reform Commission; 2016.
[5] Yuan J, Na C, Lei Q, Xiong M, Guo J, Hu Z. Coal use for power generation in China. Resour Conserv Recycl 2018;129:443–53.
[6] Liu Q, Lei Q, Xu H, Yuan J. China's energy revolution strategy into 2030. Resour Conserv Recycl 2018;128:78–89.
[7] Yuan J, Xu Y, Hu Z, Zhao C, Xiong M, Guo J. Peak energy consumption and CO2 emissions in China. Energy Pol 2014;68:508–23.
[8] Duan H, Mo J, Fan Y, Wang S. Achieving China's energy and climate policy targets in 2030 under multiple uncertainties. Energy Econ 2018;70:45–60.
[9] Li J, Ma Z, Zhang Y, Wen Z. Analysis on energy demand and CO2 emissions in China following the energy production and consumption revolution strategy and China dream target. Adv Clim Change Res 2018;9:16–26.
[10] Yu S, Zheng S, Li X. The achievement of the carbon emissions peak in China: the role of energy consumption structure optimization. Energy Econ 2018;74:693–707.
[11] Liu J, Wang K, Zou J, Kong Y. The implications of coal consumption in the power sector for China's CO2 peaking target. Appl Energy 2019;253:113518.
[12] Raftery AE, Zimmer A, Frierson DMW, Startz R, Liu P. Less than 2 °C warming by 2100 unlikely. Nat Clim Change 2017;7:637–41.
[13] CEC. Annual report of China' power industry in 2019. Beijing: China Electricity Council; 2019.
[14] Bogdanov D, Farfan J, Sadovskaia K, Fasihi M, Child M, Breyer C. Arising role of photovoltaic and wind energy in the power sector and beyond: changing the Northeast Asian power landscape. Jpn J Appl Phys 2018;57:8.
[15] Gulagi A, Bogdanov D, Fasihi M, Breyer C. Can Australia power the energy-hungry asia with renewable energy? Sustain. Basel 2017;9:233.
[16] Bogdanov D, Breyer C. North-East Asian Super Grid for 100% renewable energy supply: optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manag 2016;112:176–90.
[17] Breyer C, Bogdanov D, Komoto K, Ehara T, Song J, Enebish N. North-east asian super grid: renewable energy mix and economics. Jpn J Appl Phys 2015;54:8.
[18] Liu H, Andresen GB, Greiner M. Cost-optimal design of a simplified highly renewable Chinese electricity network. Energy 2018;147:534–46.
[19] Deng YY, Blok K, van der Leun K. Transition to a fully sustainable global energy system. Energy Strateg Rev 2012;1:109–21.
[20] Bogdanov D, Farfan J, Sadovskaia K, Aghahosseini A, Child M, Gulagi A, et al. Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat Commun 2019;10.
[21] Liu H, Brown T, Andresen GB, Schlachtberger DP, Greiner M. The role of hydro power, storage and transmission in the decarbonization of the Chinese power system. Appl Energy 2019;239:1308–21.
[22] Zhou W, Zhu B, Fuss S, Szolgayová J, Obersteiner M, Fei W. Uncertainty modeling of CCS investment strategy in China's power sector. Appl Energy 2010;87:2392–400.
[23] Ou X, Xiaoyu Y, Zhang X. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. Appl Energy 2011;88:289–97.
[24] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80.
[25] Wen Y, Cai B, Xue Y, Wang S, Chen Z, Zhu J, et al. Assessment of power system low-carbon transition pathways based on China's energy revolution strategy. Energy Procedia 2018;152:1039–44.
[26] Liu Q, Zheng X, Zhao X, Chen Y, Lugovoy O. Carbon emission scenarios of China's power sector: impact of controlling measures and carbon pricing mechanism. Adv Clim Change Res 2018;9:27–33.
[27] Yang J, Zhang L, Chang Y, Hao Y, Liu G, Yan Q, et al. Understanding the material efficiency of the wind power sector in China: a spatial-temporal assessment. Resources. Conserv Recycl 2020;155:104668.
[28] Liu W, Lund H, Mathiesen BV, Zhang X. Potential of renewable energy systems in China. Appl Energy 2011;88:518–25.
[29] Heard BBBWT. Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems. Renew Sustain Energy Rev 2017;76:1122–33.
[30] Brown TW, Bischof-Niemz T, Blok K, Breyer C, Lund H, Mathiesen BV. Response to 'Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems'. Renew Sustain Energy Rev 2018;92:834–47.
[31] IRENA. Transforming the energy system – and holding the line on the rise of global temperatures. Abu Dhabi: International Renewable Energy Agency; 2019.
[32] Khanna NZ, Zhou N, Fridley D, Ke J. Quantifying the potential impacts of China's power-sector policies on coal input and CO2 emissions through 2050: a bottom-up perspective. Util Pol 2016;41:128–38.
[33] Jiang KHCXX. Transition scenarios of power generation in China under global 2°C and 1.5°C targets. Glob. Energy Interconnect. 2018;1:477–86.
[34] SGERI. Prospects for China's energy and power development. Beijing: State Grid Energy Research Institution; 2018.

[35] Yuan J, Xu Y, Hu Z. Delivering power system transition in China. Energy Pol 2012;50:751–72.

[36] Li M, Patiño-Echeverri D. Estimating benefits and costs of policies proposed in the 13th FYP to improve energy efficiency and reduce air emissions of China's electric power sector. Energy Pol 2017;111:222–34.

[37] ADB. Roadmap for carbon capture and storage demonstration and deployment. Manila, Philippines: Asian Development Bank; 2015.

[38] IEA. World. Energy outlook 2018. Paris: International Energy Agency; 2018.

[39] Huang WCWAG. The role of technology diffusion in a decarbonizing world to limit global warming to well below 2C: an assessment with application of Global TIMES model. Appl Energy 2017;208:291–301.

[40] IPCC. Special report on global warming of 1.5°C. Intergovernmental Panel on climate change. WMO. Geneva, Switzerland: Intergovernmental Panel on Climate Change; 2018.

[41] Bravo JAG, Garcia R, Cadena E. Flexible Co-combustion of high ratios of sustainable biomass with coal in oxy-CFB boiler for CO₂ capture. J Power Energy Eng 2018;6:12–22. 0.

[42] Akgul O, Mac Dowell N, Papageorgiou LG, Shah N. A mixed integer nonlinear programming (MINLP) supply chain optimisation framework for carbon negative electricity generation using biomass to energy with CCS (BECCS) in the UK. Int J Greenh Gas Con 2014;28:189–202.

[43] Johnston CMT, van Kooten GC. Economics of co-firing coal and biomass: an application to Western Canada. Energy Econ 2015;48:7–17.

[44] Yang B, Wei Y, Hou Y, Li H, Wang P. Life cycle environmental impact assessment of fuel mix-based biomass co-firing plants with CO2 capture and storage. Appl Energy 2019;252:113483.

[45] Khorshidi Z, Ho MT, Wiley DE. Techno-economic evaluation of using biomass-fired auxiliary units for supplying energy requirements of CO 2 capture in coal-fired power plants. Int J Greenh Gas Con 2015;32:24–36.

[46] Bui M, Fajardy M, Dowell NM. Thermodynamic evaluation of carbon negative power generation: bio-energy CCS (BECCS). Energy Procedia 2017;114:6010–20.

[47] Haegel NM, Atwater HJ, Barnes T, Breyer C, Burrell A, Chiang YM, et al. Terawatt-scale photovoltaics: transform global energy. Science 2019;364:836–8.

[48] Breyer C, Fasihi M, Bajamundi C, Creutzig F. Direct air capture of CO2: a key technology for ambitious climate change mitigation. Joule 2019;3:2053–7.

[49] IRENA. Innovation landscape for a renewable-powered future: solutions to integrate variable renewables. Abu Dhabi: International Renewable Energy Agency; 2019.

[50] CNREC. Beautiful China's energy ecosystem in 2050. Beijing: China National Renewable Energy Center; 2018.

[51] Global IRENA. Energy transformation: a roadmap to 2050. Abu Dhabi: International Renewable Energy Agency; 2018.

[52] ERI. Scenarios on energy-related emissions in China to achieve the global 1.5 °C target. Beijing: Chinese Energy Research Institute; 2018.

[53] IRENA. Planning for the Renewable Future: long-term modelling and tools to expand variable renewable power in emerging economies. Abu Dhabi: International Renewable Energy Agency; 2017.

[54] Peng W, Yuan J, Zhao Y, Lin M, Zhang Q, Victor DG, et al. Air quality and climate benefits of long-distance electricity transmission in China. Environ Res Lett 2017;12:64012.

[55] Rogelj J, McCollum DL, O Neill BC, Riahi K. Emissions levels required to limit warming to below 2 °C. Nat Clim Change 2020;3:405–12. 2013.

[56] IEA. Status of power system transformation 2018. Paris: International Energy Agency; 2018.

[57] Power IRENA. System flexibility for the energy transition. Part 1: overview for policy makers. Abu Dhabi: International Renewable Energy Agency; 2018.

[58] Tang B, Li R, Yu B, An R, Wei Y. How to peak carbon emissions in China's power sector: a regional perspective. Energy Pol 2018;120:365–81.

[59] Kriegler ELGBN. Pathways limiting warming to 1.5°C: a tale of turning around in no time? Philosophical Transactions of The Royal Soc. Math. Phys. Eng. Sci. 2018;376(2119). https://doi.org/10.1098/rsta.2016.0457.

[60] Khorshidi Z, Florin NH, Ho MT, Wiley DE. Techno-economic evaluation of co-firing biomass gas with natural gas in existing NGCC plants with and without CO 2 capture. Int J Greenh Gas Con 2016;49:343–63.

[61] IRENA. Renewable power generation costs in 2018. Abu Dhabi: International Renewable Energy Agency; 2019.

[62] NDRC. Notice on improving the tariff policy of wind power in 2019. Beijing: National Development and Refrom Commission; 2019.

[63] Better ETC. Energy, Greater Prosperity: achievable pathways to low-carbon energy systems. Energy Transition Commission; 2017.

[64] Yu S, Horing J, Liu Q, Dahowski R, Davidson C, Edmonds J, et al. CCUS in China's mitigation strategy: insights from integrated assessment modeling. Int J Greenh Gas Con 2019;84:204–18.

[65] Fan J, Xu M, Yang L, Zhang X. Benefit evaluation of investment in CCS retrofitting of coal-fired power plants and PV power plants in China based on real options. Renew Sustain Energy Rev 2019;115:109350.

[66] NDRC. Notice on improving the tariff policy of wind power. Beijing: National Development and Reform Commission; 2009.

[67] Yuan J, Li P, Wang Y, Liu Q, Shen X, Zhang K, et al. Coal power overcapacity and investment bubble in China during 2015–2020. Energy Pol 2016;97:136–44.

[68] 13th NDRC. five-year-plan for electric power development. Beijing: National Development and Reform Commission; 2016.

[69] Marcucci A, Kypreos S, Panos E. The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. Climatic Change 2017;144:181–93.

[70] Budinis S, Krevor S, Dowell NM, Brandon N, Hawkes A. An assessment of CCS costs, barriers and potential. Energy Strateg Rev 2018;22:61–81.

[71] IEA. Technology. Roadmap, carbon capture and storage. Paris: International Energy Agency; 2013.

[72] Rogelj J, Elzen DM, Höhne N, Fransen T, Fekete H, Winkler H, et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °c. Nature 2016;534:631–9.

[73] Yuan J, Guo X, Zhang W, Zhou J, Qin C. Stranded coal power assets in China: a case study of jilin province. Emerg Mark Finance Trade 2019;55:2673–88.

[74] Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, Cherubini F, et al. Bioenergy and climate change mitigation: an assessment. Gcb Bioenergy 2015;7:916–44.

[75] Energy Transition Commission RMI. China 2050: a zero carbon landscape of an all-round modernized country.: energy Transition Commission. Rocky Mountain Institute; 2019.

[76] Creutzig FBCHJ. The mutual dependence of negative emission technologies and energy systems. Energy Environ Sci 2019;12:1805–17.

[77] Xu Y, Kang J, Yuan J. The prospective of nuclear power in China. Sustain. Basel 2018;10:2086.