Thoughts on China's energy transition outlook

Wang Zhongying^{1,2} · Kaare Sandholt²

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Abstract

China's strong economic growth over the past 40 years has been followed by similar strong growth in energy consumption, based on coal. A continuation of this development is not sustainable, and China has set new ambitious targets for future energy systems development, which in reality calls for a genuine energy revolution in order to build a clean, low-carbon, safe, and efficient energy system towards 2035 and 2050. This paper looks at the mechanisms behind the energy transition, analysis of a concrete case for a sustainable energy system in 2050, and points to policy measures and instruments to ensure the necessary progress in this energy transition. The case shows that it is possible for China in 2050 to reduce CO₂ emission to one-third of today's emission while at the same time maintaining economic growth, improving security of supply, air quality, and economic efficiency of the power system.

Keywords Energy transition · Chinese energy policy · Renewable energy development · Energy outlook 2050

Introduction and methodology

The mechanisms behind the energy transition in China

Over the past 40 years, China has had tremendous economic growth, creating a better life for the Chinese people by moving more than 750 million people out of extreme poverty [1]. This economic growth was made possible by similar growth in energy consumption. The economic structure has been based on industry sectors with high energy consumption and today the industry sector consumes almost 60% of the total energy consumption, a much higher share than in other countries [2].

In three 5-year plans from 2000 to 2015, coal and oil have been strongly promoted as the main fuels for China's economic development. Coal power plants have been pampered with favorable dispatch rules, access to cheap capital, promoted by strong state-owned companies, and strongly supported by local governments. The industry has been allowed to greatly increase coal consumption without the necessary considerations for the environment, and the transport sector has increased oil consumption to a level where two-thirds of the consumption is imported (Fig. 1).

This build-up of the energy system has enabled rapid economic growth, but is also responsible for severe pollution of air, water, and soil. The energy system is characterized by low energy efficiency, cost-efficiency has not been in focus in the energy sector, and China has become increasingly reliant on imported fuels. Renewable energy has been promoted, but only as an add-on to the existing system. The result has been high curtailment of wind and solar power due to a lack of integration into the power system and relative high subsidy levels to compensate for the additional risk factors for RE projects.

Today, coal covers 64% of primary energy consumption, oil 20%, natural gas 8%, and non-fossil fuels 8%. Electricity is 23% of the final energy consumption. The 2017 energy flow is shown in Fig. 2.

✉ Kaare Sandholt
ks@cnrec.org.cn

Wang Zhongying
wangzhy@eri.org.cn

¹ Energy Research Institute of China Academy of Macroeconomic Research, China National Development and Reform Commission, Guohong Mansion, Muxidi-beili Jia, Xicheng District, Beijing 10038, People's Republic of China

² China National Renewable Energy Centre, Energy Research Institute, Guohong Mansion, Muxidi-beili jia 11, Xicheng District, Beijing 10038, People's Republic of China

Fig. 1 China's total primary energy demand (Mtce: The paper uses the standard Chinese energy unit Mtce = million ton coal equivalent. 1 Mtce equals 0.7 Mtoe and 29.31 PJ) 1990–2016 [2]

Fig. 2 China's energy balance (Mtce) for 2017

New targets for the energy transition—but are they achievable?

In 2015, the Chinese leadership decided to change this development path. The 13th 5-year plan set the target “to build a clean, low-carbon, safe, and efficient energy system” [3]. As part of the implementation of the plan, the favorable conditions for coal power plants have been lessened for new plants, planned and approved coal power projects were stopped or delayed, an effort to better integrate

renewable energy was launched, and more focus was put on the development of electric cars as a long-term solution for the ever-increasing oil dependency in the transport sector. A power sector reform was re-initiated, and an ETS system for CO₂ was launched as regional and national pilots. China launched an innovation plan, China 2025 [4], with focus on quality instead of quantity and with new technologies, including renewable energy technologies and electric vehicles as strategic emerging industries, which should form the backbone of the Chinese economy in the future.

In autumn of 2017, President Xi Jinping reconfirmed the long-term targets for the energy system at the 19th Communist Party Congress and the commitment to the development of “ecological civilization” as the main priority for China and as a precondition for a continuation of the economic development in China [5].

However, with the current strong dependency on fossil fuels and the strong correlation between economic growth and energy consumption growth until now, is it reasonable to believe such high ambitions for the future energy system? In fact, it is.

Several structural mechanisms are currently changing the whole framework for the energy system development, allowing for a much more radical transformation, actually a full energy revolution.

The first mechanism is the changes in the Chinese economic structure. The economic reform, the “new normal”, is transforming the industry sector from heavy industry with high energy consumption to lighter industry and service with less dependency on energy as input. As part of the reform, the China 2025 innovation plan further pushes in the same direction.

The second mechanism is the digitalization, development of Internet of things, electrification of the transport sector, and use of big data as an integrated part of the industry and service sectors. This development requires electricity, not fossil fuels, as input.

The two mechanisms together drive energy consumption to be more efficient, relying more on electricity and less on fossil fuels in the end-use sectors.

The third mechanism is the rapid improvement of the new technologies for power supply. Wind and solar power have in the past 5 years developed into technologically stable and economically viable power production units, and today they are in many cases able to compete with new coal power plants and are clearly more cost-efficient than new gas-fired power plants [6]. The technologies for integrating renewable energy have also been through rapid development. Today, nobody questions the ability of coal power plants to operate flexibly; it is merely a question of incentives, not a technical problem [7]. Different storage technologies, including batteries for electric vehicles and hydro pump storage, are ready to contribute to cost-efficient solutions for system integration.

Combining these three mechanisms gives a positive feedback loop where the individual factors mutually reinforce each other. The economic development and digitalization drive energy efficiency and electrification in the end-use sector, increasing the demand for electricity. The increased demand for electricity drives the need for a clean power supply, which again reinforces the improvement of the technology and cost-efficiency of these technologies, and the investments in clean and efficient power production contribute to

and allow for a continuation of economic growth without growth in energy consumption. The combination of the three mechanisms in fact decouples the relationship between economic growth and growth in energy consumption.

Modeling the Chinese energy system

To illustrate how these mechanisms could work in practice, the China National Renewable Energy Centre (CNREC) has set up and analyzed two scenarios for the energy transition in China in its latest China Renewable Energy Outlook, CREO 2018 [8].

The China National Renewable Energy Centre has, since it was established in 2011, focused on developing comprehensive modeling tools to analyze the energy and socioeconomic impact of development and integration of renewable energy in the Chinese energy system. A large number of different models have been used for energy system modeling, but modeling the integration of a large share of renewable energy in China requires the following [9, 10]:

- a power system model that is able to represent the power system on a provincial level, taking into account the bottlenecks in the transmission system
- represent combined heat and power (CHP) with the constraints that impose on power production from the CHP plants [11, 12]
- represent the current dispatch in the Chinese power system on an hourly basis, with the limitations on the thermal power plants and the limitations in interprovincial exchange of power, as well as the dispatch in a power market, provincial, regional or national, based on least-cost marginal price optimization [13, 14]
- represent variable production from wind power and solar power [15–17]
- represent power plant flexibility and inflexibility, including minimum load, ramp rates, bypass operation, and other flexibility measures [18]
- represent economic dispatch of storage technologies, including hydro reservoirs, hydro pump storage, batteries, EV charging and discharging, as well as demand-side response [19]
- make investment decisions based on least-cost system optimization within given boundaries for both power generation and power transmission, e.g., resource constraints, CO₂ caps, targets for energy production (e.g., non-fossil fuel shares) etc. [12, 20].

Several models are able to fulfill these requirements as generic models [10], but all require substantial work with data input as well as model modifications and adaptation to the Chinese context. China National Renewable Energy Centre chose to build up its power system model using

the Balmorel software model because it complies with the above-mentioned requirements, is open-source software, and allows for flexible add-ons for special requirements [21]. The CNREC model, called EDO (electricity and district heating optimization), was introduced in 2012 and has been constantly developed and enhanced ever since. The EDO model has been used for studies on “2050 High RE Penetration” in 2014 and 2015, and for the China RE Outlook scenarios [8, 22, 23].

For modeling the end-use sectors and the transformation sector outside of the power sector, CNREC has chosen to use the LEAP software, which allows for different representation of relationships between drivers and energy consumption for different end-use sectors [24]. In CNREC’s model, the end-use consumption is divided into five main sectors: industry, transportation, buildings, construction, and agriculture. The industry sector is divided into sub-sector with relationship between economic output and energy consumption and with the possibility for changes in energy intensity, fuel shift, and introduction of new technologies. The transport sector is modeled as a stock model for vehicles with a certain average life time and with the possibility to introduce electric cars as a share of the annual investments in new vehicles. Also, the building sector is set up as a stock model [8, 23].

The two bottom-up models for the power sector and the end-use sector are soft-linked with a CGE model for the Chinese economy, adapted to energy sector analyses. The CGE model calculates the impact on GDP, job creation, and other macro-economic parameters as a consequence of the energy transition [25, 26].

The scenarios are a “Stated Policies Scenario” assuming a vigorous implementation of the current and stated policies for the energy sector, and a “below 2 °C Scenario” with higher ambition for CO₂ reduction, aiming to fulfill the ambitions to create a clean, low-carbon, safe, and efficient energy system by 2050, with the following goals:

- *Clean* The air quality should comply with WHO recommendations [27], and water consumption in the energy sector should be reduced significantly as a major contribution to solving the water scarcity problem.
- *Low carbon* The emission of CO₂ from the energy sector should comply with a global “below 2 °C” development in line with the Paris Agreement [28].
- *Safe* The energy supply should be diverse and the dependence on imported fuels should be significantly reduced.
- *Efficient* The losses in the energy system should be reduced and the energy supply should be driven by the principle of cost efficiency.

Combining these objectives, we get clear guidelines for the 2050 energy system of China:

- The dependency of fossil fuels, in particular coal, is reduced as much as possible, and substituted by non-fossil fuels in all sectors.
- Energy efficiency is obtained by rigorous measures in the end-use sectors, by replacing thermal power plants with large conversion losses with renewable energy, particularly solar and wind, and by electrifying the end-use consumption, primarily the industry and transport sector. Efficient deployment of distributed energy sources further reduces overall system losses.
- The economic efficiency of the energy system is ensured through efficient power markets, and an incentive and taxation system, reflecting the direct and indirect costs of energy supply. This includes efficient costing of CO₂ emission and other pollutants.

The preparation of the scenarios starts in the end-use sectors, where the development of the final energy consumption is driven by economic reforms, energy efficiency measures, and electrification. The electrification is mainly implemented in the industry and service sectors, both heavily influenced by the digitalization of the economy, the Internet of things, big data, and smart controls. The transport sector is electrified directly by introducing electric vehicles or indirectly by introducing hydrogen as fuel produced with electricity as the main energy input.

Key assumptions for the scenarios

The following boundaries and assumptions are used for the scenario setup.

Scenario boundaries

The boundaries for the long-term energy and economic development are constraints to the deployment of various energy technologies:

- Renewable energy resources are constrained at a provincial level, and wind and solar are divided into categories of costs, type, and quality.
- Hydro power plants are limited to deployment of 532 GW, based on existing capacity and environmentally sustainable build-out opportunities.
- Nuclear capacity is limited to 120 GW along coastal regions.

Scenario assumptions

The scenarios are based on the following main assumptions:

- Economic development objectives must increase GDP by a factor of four in real terms, from RMB 82 trillion in 2017 to RMB 324 trillion by 2050.
- Population is expected to be at today's level at 1.38 billion in 2050.
- The short-term goals in the 13th 5-year plan on energy will be fulfilled in 2020, as well as the targets in the 3-year Action Blue Sky Protection plan [29], the 13th 5 year plan for environment protection [30] and the North China clean heating plan [31].
- Energy efficiency vigorously reduces final energy consumption, e.g., in the below 2 °C scenario is thereby 56% of a no improvement situation by 2050 and slightly higher in the Stated Policies scenario.
- China achieves the goal of 10% of natural gas in total primary energy consumption by 2020 and in the Stated Policies scenario, natural gas consumption will increase to 15%. The below 2 °C scenario does not require the share to increase after 2020.
- The 50% non-fossil electricity generation target of the Energy Consumption Revolution Strategy [32] is attained, and in practice exceeded in the scenarios.
- The Stated Policies scenario has the carbon intensity reduction target of 40–45% by 2020 and 60–65% by 2030, though this is not binding. CO₂ prices in the power sector rise linearly from RMB 50/ton in 2020 to RMB 100/ton in 2040.
- In the below 2 °C scenario, the accumulated energy sector emissions from 2017 to 2050 are kept below 230 billion tons. This is based on several different simulations from the IPCC AR5 scenario database [33] with a greater than 66% chance of staying below 2 °C.
- Technology costs are assumed to have declining installation and operational costs per MW as well as quality improvements of RE technologies. Grid parity is achieved for most wind and solar installations in the 2020s on LCOE basis, and most mainstream RE is significantly less costly than fossil generation by 2050.
- Coal and natural gas prices follow the indexed development of the IEA's New Policies scenario in the Stated Policies scenario, and the IEA's Sustainable Development scenario in the below 2 °C [34].
- China maintains the current strict policy on the coal cap and coal reduction. Hence, the coal consumption is constrained to 1 billion tons by 2050.

Results

Main result of the scenario analyses for 2050

Using the above-described methodology, scenario boundaries, and assumptions, we get the following result for the

Fig. 3 Final energy consumption of different sectors in 2017 and 2050

Fig. 4 The shares of different energy sources in the final energy demand

Chinese energy system in 2050, described with focus on the main scenario, the below 2 °C scenario [8].

Lower final energy consumption and much more electricity in industry and transport sector

Due to the transformation of the Chinese economy, massive focus on energy efficiency and electrification of industry and transport sector, the final energy consumption in 2050 is lower than in 2017 (Figs. 3, 4) and the distribution on energy sources is much different (Fig. 5).

Renewable energy replaces fossil fuels in the energy supply

The energy supply in 2050 is dominated by renewable energy, mainly wind and solar in the power sector, as shown in Fig. 6. Coal consumption is reduced to a minimum, allowing for flexible use of the coal power plants. Oil is confined mainly to the transport sector and reduced through electrification despite significantly higher transport activity in 2050. Natural gas does not play a big role in the energy supply in 2050 since it is too expensive compared to renewable energy sources. Hydro and nuclear power deliver steady power production, although both of these energy sources are limited in potential and siting possibilities.

Fig. 5 The primary energy consumption in 2050 in the below 2 °C scenario compared to the 2017 (left) and the composition of renewable energy sources in 2050 in the below 2 °C scenario

Fig. 6 China's energy balance (Mtce) in 2050 in the below 2 °C scenario

The transformation of the end-use sectors and the supply system in combination with energy efficiency measures give a completely different energy balance in 2050 compared to the 2017 situation, as illustrated in Figs. 2

and 6. Transformation losses have been reduced significantly, and renewables and electricity dominate the supply.

Fig. 7 Levelized costs of electricity generation (LCOE, in RMB/MWh) in 2050

Power economic generation in 2050 points to renewable electricity

In 2050, wind and solar will be the cheapest and most abundant sources of electricity (Fig. 7)—indeed, they likely already are, considering external costs. Ensuring efficient system integration of variable renewable energy is the primary power system development challenge.

Wind and solar dominate future-generation investments

Coal must peak in the short- or mid-term to meet air quality and climate goals. The price of gas, and dependence on imported gas, limits its development, and in the long-run so does its associated carbon emissions. Hydropower development is slowing due to environmental impacts and increasing investment cost. Biomass resources are scarce, and several other applications have a higher value than power generation. Geothermal resources and development costs are uncertain, and ocean energy is in its infancy. Nuclear is restricted to coastal areas for safety reasons. Hence, wind and solar will be the two main energy sources in the future, as illustrated in Fig. 8.

Fig. 8 China's power generation mix in 2017 and 2050

The power system in 2050 is dynamic and radically different from today's

The power system characteristics in terms of mix of assets, dispatchability, operational paradigm, cost structure, operational timescales, and topology, will be transformed. The system cannot be operated according to today's principles, using today's sources of flexibility, nor today's regulatory paradigms. Every aspect of the power industry will change, from market designs and regulatory setups, to product and service definitions, to stakeholder roles. Power system planning, innovation, and reform must be forward-looking, and be able to manage uncertainty, variability, and increasing complexity.

Balancing the system in 2050 requires optimal use of flexible resources

Reliability will depend on greater sharing of resources between regions, through a strong grid and advanced coordination between grids. Reliability will also depend on introducing a variety of power sources that can reduce the risk of failure due to weather-related technical failures and shortage of resources and fuels. Figure 9 shows the hourly dispatch of the power system for a week in 2050 using the EDO dispatch model.

The development pathway

To achieve the visions for 2050, the energy system must change rapidly in the coming years. In the below 2 °C scenario, coal is phased out of the end-use sectors onwards from now, electricity consumption increases rapidly from the mid-2020s, the use of oil (including oil products blended with biofuel) decreases throughout the period, and hydrogen (produced using electricity) is introduced as a new secondary fuel in the industry and transport sectors. The development pathway for the final energy consumption is shown in Fig. 10.

Fig. 9 Hourly balance of supply and in China's power system for a week in 2050

Fig. 10 Total final energy demand from 2016 to 2050 in the below 2 °C scenario

Fig. 11 Total primary energy demand (Mtce) from 2017 to 2050 in the below 2 °C scenario

Primary energy demand peaks before 2025 and wind and solar gradually become the dominant energy sources in the energy system (see Fig. 11). Coal consumption is reduced throughout the period with an accelerated phase-out from the late 2020s. While natural gas increases in the short term due to the policy priority, it does not play a major role as a bridging fuel between coal and renewable energy, since

renewable energy quickly becomes economically more attractive than natural gas in the power sector.

Renewable energy, especially wind and solar, is deployed throughout the period, most rapidly in the late 2020s, as shown in Fig. 12.

Key figures for the milestone years are shown in Tables 1 and 2.

Fig. 12 Renewable energy production (Mtce) from 2017 to 2050 in the below 2 °C scenario

Table 1 Key figures on total primary energy demand and total final energy demand for the below 2 °C scenario in 2017, 2020, 2035, and 2050

	Unit	Current	Below 2		
		2017	2020	2035	2050
Total primary energy supply	Mtce	4360	4640	4167	3483
Coal	Mtce	2806	2648	1351	387
Crude oil	Mtce	864	939	716	487
Natural gas	Mtce	306	441	334	164
Nuclear	Mtce	96	165	274	341
Renewable energy	Mtce	288	448	1492	2105
Hydro	Mtce	142	153	199	225
Wind	Mtce	40	61	634	935
Solar	Mtce	22	47	378	570
Bio (solid, liquid, gaseous)	Mtce	83	165	206	218
Geothermal	Mtce	0	22	72	144
Ocean	Mtce	–	0	3	12
Total final energy demand	Mtce	3182	3296	3166	2805
Coal	Mtce	1192	945	391	88
Oil products	Mtce	340	356	367	290
Natural gas	Mtce	242	385	299	136
Solar	Mtce	4	11	73	137
Bio (solid, liquid, gaseous)	Mtce	58	65	63	44
Geothermal	Mtce	–	–	–	–
Electricity	Mtce	748	852	1315	1481
Heat	Mtce	213	238	288	317
Hydrogen	Mtce	3	10	107	163
Biofuel blends	Mtce	381	434	262	150

The Stated Policy scenario

The Stated Policy scenario is based on the current and stated policies regarding the energy transition, climate policy, and environmental policy. Compared to the below 2 °C scenario, the main differences in the assumptions and target setting are

Table 2 Installed power generation capacity and total electricity generation for the below 2 °C scenario in 2017, 2020, 2035, and 2050

	Unit	Below 2			
		2017	2020	2035	2050
Total power generation capacity	GW	1746	2108	5366	6814
Renewable	GW	621	842	4362	6159
Hydro	GW	313	343	454	532
Wind	GW	163	221	1826	2664
Bio (solid, liquid, gaseous)	GW	15	48	64	57
Solar	GW	130	224	1962	2803
Solar CSP	GW	0	5	38	33
Geothermal	GW	0	1	5	20
Ocean	GW	–	0	13	50
Nuclear	GW	36	58	96	120
Fossil fuels	GW	1088	1208	907	536
Total electricity generation	TWh	6313	7859	13,324	15,324
Renewable	TWh	1676	2186	9545	13,488
Hydro	TWh	1153	1249	1622	1831
Wind	TWh	328	496	5159	7612
Bio (solid, liquid, gaseous)	TWh	44	146	221	268
Solar	TWh	151	277	2380	3439
Solar CSP	TWh	0	14	100	86
Geothermal	TWh	0	4	38	153
Ocean	TWh	–	0	26	100
Nuclear	TWh	257	442	735	915
Fossil fuels	TWh	4381	5231	3044	920

- More ambitious targets for CO₂ reduction in the below 2 °C scenario to ensure compliance with a below 2 °C increase in global temperature.
- Targets for use of natural gas until 2030 in the Stated Policy scenario, while the below 2 °C scenario has no targets after 2020.
- Increased emphasis on electrification of end-use consumption.

As a result, the Stated Policy scenario has a lower deployment of renewable energy after 2020, and a higher consumption of coal, oil, and natural gas than the below 2 °C scenario, as shown in Fig. 13, and the electrification of end-use consumption is also less than the below 2 °C scenario.

Compliance with the Beautiful China energy system visions

The quality of the two scenarios are measures by their ability to fulfill the policy visions for the energy system in 2050—building a clean, low-carbon, safe, and efficient energy system.

Fig. 13 Differences in primary energy demand (Mtce) between the below 2 °C scenario and the Stated Policy scenario towards 2050

Clean 2050 system in both scenarios, but cleaner pathway in below 2 °C scenario

Air pollution from the energy system falls substantially by 2050 in both the below 2 °C and the Stated Policies scenarios on all air pollution parameters except for ammonia (NH_3), which originates mainly from the agricultural sector. However, the below 2 °C scenario projects a faster reduction of air pollutants than the Stated Policies scenarios. Black carbon (BC), organic carbon (OC), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and non-methane volatile organic compound (NMVOC) emissions are all lower in the below 2 °C scenario in the 2030s due to the earlier reductions of coal and oil use in this scenario. This leads to relative reduction in pollution-related cases of serious illness and premature mortality, resulting in significant socio-economic benefits.

In both CREO scenarios, total water consumption for energy falls despite a doubling of power production due to improvements in technology. Energy sector water consumption in the below 2 °C scenario is much lower than in the Stated Policy scenario. In the below 2 °C scenario, water consumption is reduced from 2020, while the Stated Policies scenario sees increased water consumption until 2030, after which it declines.

Significant CO₂ reduction in both scenarios

In its design, the below 2 °C scenario sets a limit on total CO₂ emission from 2017 to 2050 of 228 billion tons, aiming for China to provide a significant contribution to meeting the Paris Agreement goals. Based on the allowable accumulated emissions, an annual CO₂ budget is established to ensure a smooth reduction from today's level to the 2050 level. The largest reduction in CO₂ emission is in the industrial sector, which is due to its extensive

Fig. 14 Energy-related CO₂ emissions in the below 2 °C scenario 2017–2050 on sectors

Fig. 15 CO₂ emission (mill. ton CO₂) and differences between below 2 °C scenario and Stated Policy scenario 2017–2050

electrification (Fig. 14). The power and district heating sectors also realize significant carbon emissions reductions despite doubling in electricity consumption.

The Stated Policies scenario is less ambitious in terms of CO₂ emission reductions and does not comply with the CO₂ cap. Compared to the below 2 °C scenario, the power sector has higher emissions (Fig. 15).

Fig. 16 Import share of oil and natural gas in below 2 °C scenario and Stated Policy scenario

Fig. 17 Power system costs (RMB/MWh) for 2017 and 2050 in the below 2 °C scenario and Stated Policy scenario

Dependence on imported fuels significantly reduced

The energy system in 2050 is much more diverse in terms of the mix of different energy sources compared to the situation today, where coal and other fossil fuels dominate the energy supply. Dependence on fossil fuels declines to 40% in the below 2 °C scenario and to 50% in the Stated Policy scenario (Fig. 16).

Dependence on fuel imports is reduced in both scenarios as well. The below 2 °C scenario has a quicker and deeper import reduction than the Stated Policies scenarios for both oil and natural gas, which constitute the main import challenge.

More efficient use of energy

By 2050, China's primary energy consumption is only 80% of the 2017 consumption in the below 2 °C scenario. Meanwhile, the economic gross domestic product (GDP) quadruples and energy intensity improves greatly.

In the two scenarios, energy efficiency offsets increasing demand for many end-uses. It compensates for the inertia in the industrial supply chain and enables the system to radically shift the energy mix. Increased efficiency also mitigates energy consumption growth in the buildings and transport

sectors and flattens the upwards trends in final energy consumption between 2017 and 2050. On the supply side, the shift from coal-based thermal power plants with high losses to renewable energy losses add to the energy efficiency of the entire energy system.

Cheaper electricity in the future

Due to continued cost reductions in renewable energy technologies and the gradual retirement of uneconomical assets, it is possible to supply electricity at a lower cost than today. In both scenarios, the cost of electricity supply is lower in 2050 (Fig. 17). The more stringent focus on CO₂ emissions reductions in the below 2 °C scenario promotes a more rapid transition to an energy system based on renewable energy. As a result, society spends less on fuel and relatively more on infrastructure and system-related costs.

Job creation and GDP impact

The rapid development of the renewable energy industry will play a positive role in promoting macroeconomic development. From 2025 to 2035, the swift growth of manufacturing scale will boost the demand for employment in sectors directly or indirectly related to renewable energy. This positive effect is greater than the negative effects related to a decrease in employment in fossil energy such as coal and thermal power generation.

The development of the renewable energy industry promotes the overall adjustment of the country's macroeconomic structure. The renewable energy supply chain covers electronic components, information and communication, computers, professional technical services, and other industries. These sectors feature high added value and the modernization of the economy.

Falling costs for renewable energy technologies will increase the operating efficiency of the energy industry. This creates development space for the provision of value-added services such as energy information and data analysis based on basic energy services, distributed energy, energy production and consumption (prosumer) services, energy storage, and EV charging.

Significant progress in Stated Policy scenario, additional benefits in below 2 °C scenario

In summary, all the criteria for the future energy system are greatly improved both in the Stated Policy scenario and the below 2 °C scenario. However, from a comprehensive viewpoint, considering energy security, environmental impact, and energy system costs, it is worthwhile taking the energy transition one step further than the pathway given by the current and stated policy framework. Hence, the below 2 °C

scenario could be the feasible vision and basis for the coming year's policy-making.

Discussion

Implementation of the energy transition

While the long-term benefits of the energy transition are clear, the short-term implementation is more challenging. In order to harvest all benefits, the implementation of the different policy measures must be swift and vigorous.

As mentioned, China already today has most of the needed policy measures on the agenda: reduction in the favorable conditions for coal power plants, better integration of renewable energy, focus on development and deployment of electric cars, restarting the power sector reform and setting up an ETS system for CO₂ are all measures, which takes the energy transition in the right direction.

For the successful implementation of the future energy transition, power sector reform is one of the most important policy measures. An efficient market setup would introduce economic efficiency in the power sector, give economic incentives for flexible dispatch of coal power plants, ensure efficient integration of variable energy production, and give incentives for flexible demand and storage options. A power sector reform could also ensure a flexible development and use of the transmission system between provinces, allowing for dynamic integration of renewables instead of a fixed transport profile.

Institutional reforms and coordinated procedures for deployment of wind and solar in the provinces with high energy demand would be necessary to boost the deployment rate. This included a clear national framework for the activities on the province level.

The implementation of a carbon pricing system would add to the incentives for a shift from fossil fuels to renewable energy with the right setup of allocation mechanisms.

Finally, it will be necessary to address the barriers and challenges for the transformation of the coal industry in provinces, where the economy is heavily dependent of income from mining or use of coal for industry or power. The social cost of the coal reduction might not be a big problem on a national scale but could have a severe impact in some provinces, and compensation mechanisms should be developed and implemented.

Next step—the 14–5 plan

The short-term actions for the energy transition should be part of China's next 5-year plan in 2020.

The single most important step here is to reduce coal consumption and reduce the growth in oil consumption, using the following measures:

- Keep coal reduction as a key priority for the energy policy and enforce strict control of the implementation.
- Stop new coal-fired power plants now to avoid stranded assets in the future.
- Implement measures to reduce coal and promote electrification in the industry sector.
- Encourage rapid and ambitious deployment of electric vehicles in the transport sector.
- Ensure a sufficiently high cost on CO₂ emission, also in the short run by a carbon tax and/or a floor-price within the carbon market. The carbon pricing should include both the power sector and the industry sector.

The measures for reduction of fossil fuels should be followed by measures to increase the deployment rate of renewable energy. According to the undertaken analyses, the 14th and 15th 5-year plan periods should have significantly higher deployment levels of solar and wind power than the 13th 5-year plan period. This will further accelerate the economic viability of renewable energy compared to fossil fuel technologies.

According to our analyses, the targets for installed capacity in 2025 should be a minimum 600-GW solar power, 421-GW wind power, 385-GW hydro power, and 55-GW power from bioenergy. To follow the below 2 °C pathway, the targets should be even higher: 650-GW solar power, 572-GW wind power, 385-GW hydro power, and 57-GW power from bioenergy.

However, renewable energy remains vulnerable to policy choices, and it is important to focus on removing barriers for RE deployment and set incentives to encourage investors and developers to accelerate this massive effort. The following measures would help move in this direction:

- Set clear and ambitious targets for renewable energy in the power sector, with a minimum of the above-mentioned capacity.
- Promote power market designs, which encourage cost efficiency and integration of variable energy production on a cross-provincial basis.
- Remove barriers for small-scale deployment of wind and solar in provinces with high energy consumption.
- Minimize risk for RE projects with focus on market-based measures, PPAs, and guaranteed access to the grid.

With such measures, China would not alone be able to pursue its own ambitious targets for the energy transition, but also confirm its position as a global frontrunner and role model for energy transition in other countries and regions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest related to this work.

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