# China's High-Quality Economic Growth in the Process of Carbon Neutrality

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China has the largest energy system in the world, with fossil energy accounting for 84%. The carbon neutrality target calls for peaking carbon emissions by 2030 and achieving net zero carbon emissions by 2060. By then, the non-fossil energy will account for over 80% of China's energy mix. Based on China's national conditions, this paper makes scenario analysis of carbon peaking in 2030. The results of this paper indicate that the peak values of carbon emission in 2030 depends on both the development of clean energy and the growth of energy power demand. Therefore, the growth rate of the two should be balanced to control the peak carbon emission. High-quality economic growth in China in the context of carbon neutrality requires "double decoupling", namely, decoupling GDP from the consumption of fossil energy and the growth of energy power demand as much as possible. To this end, this paper proposes a systematic solution considering both the demand and supply sides, with market-oriented measures that are workable for it. Ensuring the safe and stable supply of energy (power) is the basic principle of clean and low-carbon economic transformation, as well as a major challenge for energy system transformation. Therefore, it is necessary to develop a path for coal power decommissioning and low-carbon transformation in line with China's national conditions.

**Keywords:** carbon neutrality, economic growth, high-quality development, energy system transformation

## 1. Introduction

The climate crisis is a challenge for all and no country can stay out of it. China has announced to achieve carbon peaking by 2030 and carbon neutrality by 2060, adding the targets to its overall plan for ecological conservation, and an all-round action plan is being developed. The proposal of "promoting a sound economic structure that facilitates green, low-carbon and circular development" in the report at the 19th National Congress of the Communist Party of China has charted the course for high-quality economic growth in the new era and laid the foundation

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for achieving carbon neutrality. The target of carbon neutrality by 2060 proves the Chinese government's solid determination and acts to address the climate crisis, on account of China's huge economy, energy system and inherent industrial inertia. The task should be arduous as the time for China moving from carbon peaking to neutrality will take only 30 years, nearly half shorter than that of developed countries. Given the urgency of carbon neutrality, the low-carbon transformation program will only progress effectively in accordance with China's national conditions.

The carbon neutrality in China should be understood from two dimensions—domestically, the relationship between economic development level and energy consumption, and internationally, the impacts of differences in economic development levels and development stages between China and developed countries on carbon neutrality. China as a developing country must maintain high-quality economic development in the pursuit of carbon neutrality. For China's economic growth prospect, the long-range per-capita-GDP objective through the year 2035 is to reach a level that of medium-developed countries, the Communiqué of the Fifth Plenary Session of the 19th Central Committee of the Communist Party of China announced. Lin (2021) believed that China's per capita GDP is expected to reach half of that of the United States by 2049, about USD 30000; Li (2016) predicted China's per capita GDP in 2050 will be 70% of that of the United States, about USD 40000. China's economy will grow into the future, according to economic growth targets and the predictive analysis of experts and scholars. The linkage between economic growth and energy power consumption over the past 40 years of reform and opening up is shown in Figure 1. The average correlation coefficient between electricity consumption growth and GDP growth was about 0.91, and that between the primary energy consumption growth and GDP growth was about 0.58. Since recent years have seen no evident downward trend of the two coefficients, it means the growth of energy power demand is still closely related to GDP. The energy power demand will continue to grow significantly if China's per capita GDP follows the above prediction. Going forward, the low-carbon transformation needs to replace the past huge consumption of fossil energy while satisfying the increase in energy demand brought by economic growth. Considering this, how to gradually lower the correlation coefficient between energy power demand and GDP growth is a major challenge for carbon neutrality.

Carbon neutrality requires increasing levels of electrification to expand the use of renewable energy. As carbon-neutral energy systems in 2060 will focus on the consumption of electricity, the electricity mix also needs attention. The comparison of major countries (regions)'s electricity mix in 2019 is shown in Table 1. Generally speaking, the industrial electricity consumption (secondary industry) of a nation will take on an inverted U-shaped trend with the increase of per capita income, ascending

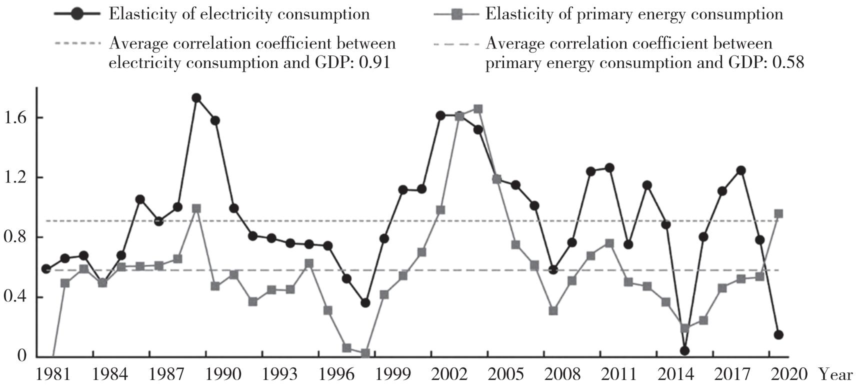


*Figure 1*. Correlation Coefficient of China's GDP, Electricity and Energy Consumption Growth Rate from 1981 to 2020

Source: CEIC.

first and then descending, on the basis of the environmental Kuznets curve. At current stage, China's high concentration of electricity in industry (67.7%), especially in high energy-consuming industries (49.4% in 2019),[1] makes GDP and power demand growth tightly-connected. GDP growth is accompanied by industrial output growth and further drives up electricity demand. Due to the large proportion of coal power in China's electricity supply mix (62%),[2] the pressure of growing power demand is mostly borne by coal power, making it harder to cut coal consumption (Lin and Wu, 2018). On the other hand, China's residential and commercial sectors will use significantly more electricity as income levels rise, causing an increase in peak loads and then a significant increase in electricity system costs, and carbon neutrality will be harder to achieve.

Table 1. Electricity Consumption Mix in Major Countries (Regions) in 2019 (%)

| Country (Region) | Industry | Transportation | Agriculture | Residential & commercial sectors |
|---|---|---|---|---|
| China | 67.7 | 2.3 | 1.8 | 28.2 |
| US | 19.6 | 0.4 | 2.0 | 78.1 |
| Europe | 36.9 | 2.3 | 2.0 | 58.8 |
| Germany | 44.7 | 2.3 | 1.1 | 51.9 |
| Japan | 36.9 | 1.9 | 0.3 | 60.9 |
| India | 41.7 | 1.5 | 17.4 | 39.4 |

Source: NBS, IEA.

[1] Based on data from the National Bureau of Statistics (NBS).
[2] Data from the *China Statistical Yearbook*.

The carbon neutrality process will also be influenced by resource endowment and energy consumption mix. In current global energy consumption mix, the percentage of fossil energy is about 85%.[1] The share of fossil energy consumed in China and the United States was about 84% and 82%, respectively (Table 2), both approaching the world average. China, limited by special resource endowment conditions, has formed a coal-based mix of energy consumption over its long course of development. The status of coal as a principal source of energy is unshakable in the short to medium term, for the current proportion of coal consumption remains high (56.6%) despite that its share in the primary energy consumption mix was declining at an average rate of about 1% annually over the past decade. Accordingly, the basic direction of energy restructuring in China now should be to stabilize oil, increase natural gas, reduce coal use and develop new energy on a large scale.

Table 2. Energy Consumption Mix in Major Countries (Regions) in 2020 (%)

| Country (Region) | Coal | Oil | Natural Gas | Other |
|---|---|---|---|---|
| China | 56.6 | 19.6 | 8.2 | 15.7 |
| US | 10.5 | 37.1 | 34.1 | 18.3 |
| Europe | 12.2 | 33.8 | 25.2 | 28.8 |
| Germany | 15.2 | 34.8 | 25.8 | 24.4 |
| Japan | 26.8 | 38.1 | 22.1 | 12.9 |
| India | 54.8 | 28.2 | 6.7 | 10.3 |

Source: The *BP Statistical Review of World Energy*.

Based on China's basic national conditions, major challenges facing carbon neutrality include: (1) the need for considerable economic growth; (2) the high energy consumption of the industrial mix (industry-based); (3) the coal-rich resource endowment and high-carbon energy consumption mix; and (4) the relatively slow energy market reforms due to consumers' weak ability to pay. The main contradictions and difficulties mentioned above are from the supply side and closely related to the demand side. The target of carbon neutrality is not solely a matter of energy restructuring, but involves profound changes all over the society and economy, and policies should take into account both the supply and demand sides.

## 2. Analysis of Peak Values of Carbon Emission

Here is an analysis of electricity mix changes in 2030 as carbon peaking is reached, starting from 2020. The Chinese government has made planning of the gross energy

[1] Data from the *BP Statistical Review of World Energy*.

consumption no more than 6 billion tons of standard coal in 2030, so the projection on peak values of carbon emission in 2030 will only consider scenarios of energy power mix changes. The government-set target of 25% of energy mix from non-fossil energy by 2030 limits the growth rate of energy demand. This paper analyzes electricity mix changes in different scenarios of electricity demand growth, referring to the planned installed capacity of wind power and photovoltaics to 1.2 billion kilowatts. China's power supply mix in 2020 is shown in Figure 2, 68% contributed by thermal power and 61% by coal. The share of thermal power has dropped by about 10% in the last decade, meaning that electric vehicles are about 10% "cleaner" than they were a decade ago. The installed capacity of wind power and photovoltaics accounted for about 24%, higher than the 17% of hydropower. In terms of generation capacity, however, wind power and photovoltaics have contributed only 9% to the total, half of the contribution of hydropower. China needs to increase natural gas-fired power generation if it is to make its generation system more efficient, but the state of natural gas resources is not optimistic and it is unrealistic to grow the proportion of natural gas-fired power on a large scale. Currently, China's nuclear power accounts for only 2% of the gross installed capacity but contributes 5% of the supply. Compared with coal power, stable but high-carbon, and wind power and photovoltaics, low-carbon but unstable, nuclear power can have both stability and low carbon. It should be a good option for carbon neutrality if safety and layout issues are well considered.

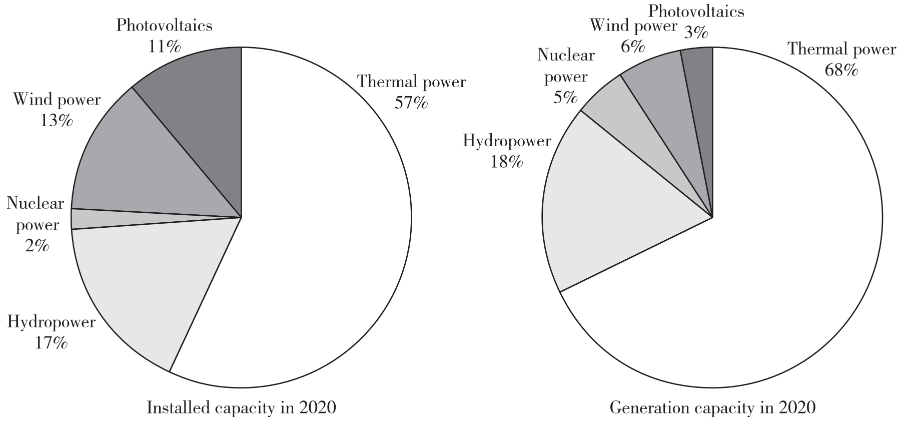


*Figure 2*. China's Electricity Mix in 2020

Source: The *China Statistical Yearbook 2021*.

Changes in availability hours by generating mode over the last decade in China are shown in Figure 3. The disposal of wind power and photovoltaics has been in progress, though, the overall availability hours were low that the impact of their installed capacity growth rate on the low-carbon transformation should not be overestimated.

The availability hours of hydropower that is decided by nature have stayed relatively stable, while those of coal power, as is observed, gradually dropped from over 5000 to more than 4000 in the last decade. The continuous decline in availability hours indicates a functional shift of coal power to be more involved in peak and frequency modulation and securing the stable operation of electricity systems.

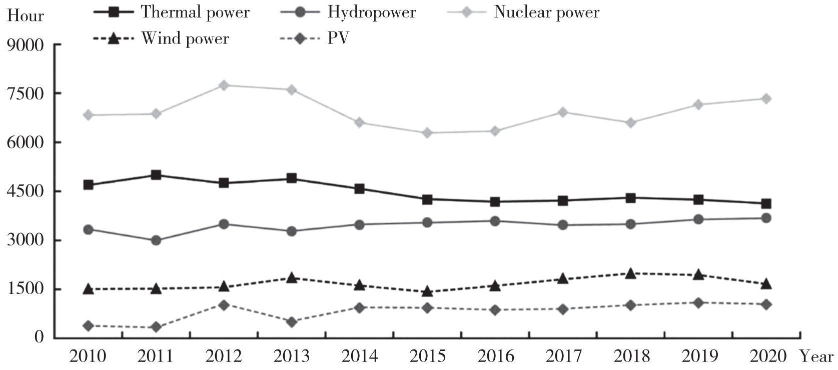


*Figure 3*. Annual Availability Hours of Each Generating Mode from 2011 to 2020

Source: CEIC.

The analysis of peak values of carbon emission in 2030 consists of three parts: (1) the planned targets proposed by the government for 2030 are set as specific quantitative boundary conditions; (2) reasonable assumptions are made on variables including primary energy consumption and availability hours of each generating mode according to historical development trends, and some internal parameters of the prediction framework are concluded; (3) based on historical growth trends of electricity demand, two prediction scenarios are set—the average annual growth rate of electricity demand is set at 3% and 5%, respectively. The electricity mix in 2030 can be concluded with three boundary condition constraints, and specific settings and bases are listed in Table 3.

Table 3. Setting of Boundary Conditions for Scenario Prediction

| Boundary condition | Set value | Basis |
| --- | --- | --- |
| Government planning for 2030 | | |
| Percentage of non-fossil energy in primary energy | ⩾ 25% | *Building on Past Achievements and Launching a New Journey for Global Climate Actions*, remarks by Chinese President Xi Jinping at the Climate Ambition Summit on Dec. 12th, 2020 |
| Installed capacity of wind power and photovoltaics | 1.2 billion kilowatts | |
| Gross primary energy consumption | ⩽ 6 billion tons of standard coal | *Strategy for Energy Production and Consumption Revolution (2016–2030)* released by the National Development and Reform Commission and the National Energy Administration |

| Boundary condition | Set value | Basis |
|---|---|---|
| Assumption | | |
| Average annual growth rate of primary energy by 2030 | 2% | Historical development trends and control over gross energy consumption |
| Average annual availability hours of each generating mode[a] | Same as 2020 | Historical development trends |
| Average annual growth rate of hydropower generation by 2030 | 2.5% | Historical development trends and current development of hydropower resources |
| Average annual growth rate of nuclear power generation by 2030[b] | 8% | Current projects and historical development trends |
| Scenario setting | | |
| Average annual growth rate of electricity demand by 2030 | 3% | By historical correlation coefficient between GDP and electricity demand growth |
| Average annual growth rate of electricity demand by 2030 | 5% | By historical correlation coefficient between GDP and electricity demand growth |

Source: Author's compilation.

Note: a. Availability hours of each generating mode are set by 2020 data: 4133 hours for thermal power, 3676 hours for hydropower, 7340 hours for nuclear power, 1666 hours for wind power and 1044 hours for photovoltaics, which are from CEIC. b. Other generating forms such as biomass, very small in volume and developing at a similar rate as nuclear power, are taken into the nuclear power category.

The Chinese government's planned energy targets for 2030 mainly include: the percentage of non-fossil energy in the primary energy mix reaches about 25%; the gross consumption of primary energy is controlled within 6 billion tons of standard coal; and the installed capacity of wind power and photovoltaic reaches over 1.2 billion kilowatts (Table 3). Further, assumptions are made by historical development trends and the future development potential of primary energy consumption and availability hours of each generating mode as follows. First, primary energy consumption: the average annual growth rate over the past decade and the past five years was 3.3% and 2.8%, respectively, and are on a downward trend. An average annual growth rate of 2% is assumed for the period of 2020–2030, as the government target is to control the gross primary energy consumption no more than 6 billion tons of standard coal in 2030. Second, availability hours: the variation of availability hours of each generating mode in the past decade was small, fluctuating around 10% of the decade average value, on which basis the annual availability hours of each generating mode in 2020–2030 are assumed to be the real value in 2020. Third, hydropower: the average annual growth rate of hydropower generation in the last five years was 3.8%, and has shown a decreasing trend. Given that current development of hydropower resources has entered the late stage, the installed hydropower scale is basically formed, the hydropower development potential is small and the marginal cost grows, the average annual growth rate of hydropower generation by 2030 is set at 2.5% in the prediction. Fourth, nuclear power: because of long development periods and intractable problems on safety and layout, the average annual growth rate of nuclear power generation in 2020–2030 is set at 8% (other generating forms, given their very small volume, are incorporated into nuclear power) according to historical development trends and related project progress. The electricity mix changes in 2030 under different demand scenarios are derived by the above assumptions.

In a scenario with an annual average growth rate of 3% in electricity demand (see Figure 4), the percentage of installed capacity of thermal power will fall to 47% in 2030, while that of clean energy will be more than half—the installed capacity of wind power and photovoltaics will account for 36%, with generation increasing to 16%. In terms of generation capacity, the percentage of thermal power will drop to 60% in 2030, down 8% from 2020. Since the share of natural gas power has stayed relatively stable (3%~4%), coal power will remain as the major source of electricity supply.

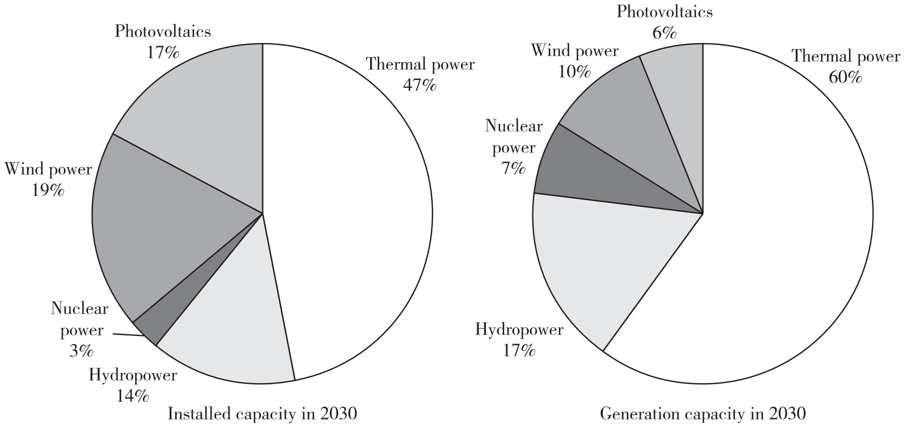


*Figure 4*. Electricity Mix in 2030 under the Scenario of Electricity Demand Growth Rate Being 3%

When the annual average growth rate of electricity demand is 5% (see Figure 5), compared to 2020, the proportion of installed capacity of thermal power slightly decreases (55%) and that of clean energy increases (45%) in 2030, with the installed capacity of wind power and photovoltaics rising to 30% and generation capacity to 13%, merely 4% higher than in 2020. On the other hand, the percentage of thermal power generation in 2030 is 68%, roughly the same level as 2020. Nonetheless, with electricity demand growing and the overall electricity system expanding, there is still a need for more new coal power plants, in spite of increasing installed capacity of thermal power in absolute terms and generation capacity from 2020, and it conflicts with the government's planning to strictly control coal power projects.

Projected results of the two scenarios illustrate the planned targets on the supply side promote a cleaner electricity mix. The demand side is also worthy of attention. In scenarios with higher electricity demand growth rates, it is ineffective promoting a clean electricity mix by supply-side targets alone, and electricity demand changes could largely determine the future electricity mix and peak values of carbon emission.

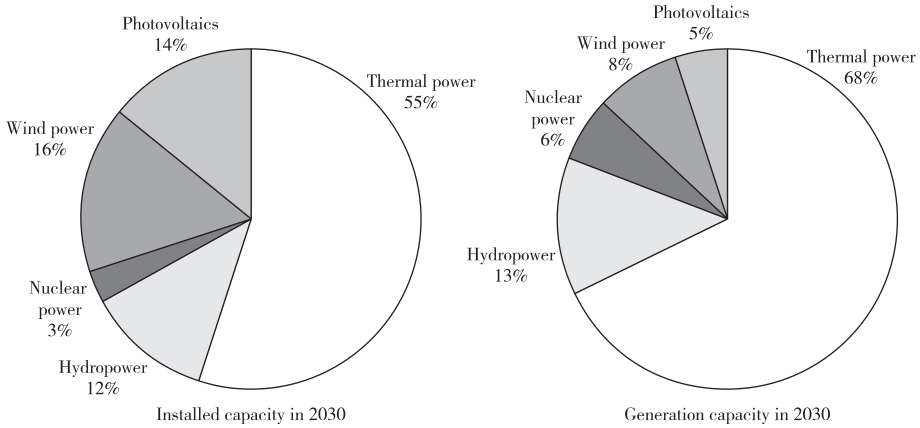


*Figure 5*. Electricity Mix in 2030 under the Scenario of Electricity Demand Growth Rate Being 5%

"China has committed to move from carbon peaking to carbon neutrality in a much shorter time span than what might take many developed countries, and that requires extraordinarily hard efforts from China," as Chinese President Xi Jinping noted at the Leaders Summit on Climate on April 22, 2021. As the time for "carbon peaking to carbon neutrality" is short in China, achieving carbon neutrality requires a strict control over peak values of carbon emission in 2030, for a high peak value will mount difficulties for the progress. Since the peak values of carbon emission are determined by both the supply and demand sides and depend on clean energy development as well as energy power growth, the progress in clean energy must match the rate of energy demand growth (Lin and Li, 2015). The government can boost the planned installed targets of wind power and photovoltaics or control the growth rate of electricity demand. The former is more straightforward but constrained by cost and the grid's ability to dispose. Controlling electricity demand is relatively complex, especially in the case of high correlation coefficient between GDP and electricity demand growth, and it is even more difficult in implementation. An effective solution for carbon neutrality needs the government's policy effort to promote "dual decoupling". One is to decouple GDP growth from fossil energy consumption with accelerated development of wind power and photovoltaics; another is to decouple GDP from electricity demand growth, pooling efforts to reduce the correlation between the two, and supporting higher GDP growth with lower electricity demand.

## 3. A Systematic Carbon-Neutrality Solution Supporting High-Quality Economic Growth: Government and Market

With a net zero carbon emissions target set for 2060, a systemic solution must be able to support "double decoupling" by gradually reducing the correlation coefficient between GDP and energy power demand and boosting higher GDP growth with lower energy power demand, while balancing national energy security and equity. Carbon neutrality begins with the fight against climate change and is part of environmental governance, so it is nothing contradictory to China's high-quality economic growth (Xu *et al.*, 2021). Current low-carbon transformation policies are focused on the production side, with fewer regulatory instruments that directly target carbon emissions on the consumption side. A major reason is that the production side is more concentrated and carbon-intensive, and policies are easy and operational to design and implement. Therefore, most countries take electricity, transportation and construction as the key industries of regulating carbon reduction. But, the consumption side is equally important to carbon neutrality and cannot be neglected. The ultimate purpose of production is consumption, the fundamental source of carbon emissions. Consumer behavioral preferences determine their consumption and also guide and constrain the production decisions of the production sector. Lin and Jiang (2009) argued that besides per capita income, energy intensity, industrial structure and energy consumption mix exert important effects on carbon emissions. The target of carbon neutrality by 2060 is a mechanism pressing for the linkage among energy, environment and high-quality economic growth. On account of the strong relevance and significance of energy to production and life, the planning for carbon peaking must balance system costs and construct systematic solution, and this systemic solution must promote "double decoupling" wherever possible to support the high-quality economic growth in China. The systemic solution considering both the supply and demand sides covers the following actions.

### *3.1. Improving Energy Efficiency: Energy Conservation Is a Cost-Effective Carbon Reduction Measure*

Energy conservation is still a cost-effective measure to cut carbon emissions while China's energy mix is coal-based now. In 2020, China's GDP per unit decreased by 83% as compared with 1978,[1] but its energy consumption per unit GDP was about 1.5 times the world average.[2] Today's energy consumption is concentrated in industry, transportation and construction. The Chinese government proposes the reduction of energy consumption in its every five-year plan to the level of national policy. That being said, China is a developing country and still has more room for energy conservation compared with developed countries, even with remarkable progress in lifting energy efficiency (Lin and Du, 2013; Bai and Nie, 2018). The rebound effect of energy efficiency suggests energy efficiency improvements can lower prices of energy services, by which the demand for energy services is grown to partially or fully offset the reduction in energy consumption caused by energy efficiency improvements (Barker *et al.*, 2007). As a result of the rebound effect, energy efficiency improvements following

[1] Data from the NBS.

[2] Data from "Down by 13.5% in energy consumption per unit of GDP to accelerate fostering an energy-conserving society" published on the *People's Daily*, Aug. 10th, 2021.

the technological progress may increase rather than decrease energy consumption, and the impact of this rebound effect could be even greater if energy market reforms, especially the energy pricing reform, are not thorough enough. The nature of energy commodities makes the choice between lower energy prices or more efficient energy consumption a complex trade-off for the government to make when the potential consequences of reform remain unknown. However, efficient energy consumption will be a necessary option after the carbon neutrality target is established. China urgently needs to find a rational industrial structure and economic growth pattern that are compatible with its energy and environmental realities. Both theories and practices have proven how important the invisible hand of the market, so market-oriented reforms are imperative. The reduction of energy consumption will become increasingly difficult as China reaches a higher level of economy development. Effective energy conservation must consider both supply and demand. Energy conservation policies and market-oriented reforms are designed to create an appropriate mechanism that internalizes the costs of emissions and keeps emitters legally and financially constrained. On the other hand, energy market reforms allow the government to focus more on energy production and consumption and the market to play a greater part in micro energy investment decisions through energy systems, plans and optimal resource allocation.

### *3.2. Building a Clean Power-Based Energy System: Wind Power and Photovoltaics Will Be the Major Growing Forces*

China's high-quality economic growth requires GDP growth be decoupled from fossil energy as much as possible, i.e., building a clean energy-based electricity system. In energy mix of the future, where a large proportion of clean energy will be produced in the form of electricity, carbon neutrality needs an accelerated electrification of energy consumption. The government's proposal to build a clean energy-based electricity system essentially refers to a new energy system dominated by clean power. China's clean energy currently includes hydropower, nuclear power, wind power, photovoltaics and biomass. Hydropower, the largest part of clean energy, is limited by the remaining hydro energy potential to expand largely. Nuclear power is stable, clean and efficient, but its safety issues and site limitations caused by China's dense population make its capacity "ceiling" low. The tiny proportion of biomass makes it impossible to create a truly meaningful structural contribution to clean energy. Therefore, wind power and photovoltaics will be the major growing forces of clean energy. Research predictions of this paper reveal that, according to the government's planning of non-fossil energy being 80% of the total by 2060, if the proportion of hydropower remains stable (8%) and that of nuclear power rises to 4%, a conservative estimate of wind power and photovoltaics will be over 65%, only 5.2% in 2019, despite that the innovation effect brought by technological progress and the scale effect arousing from large-scale expansion will further drive down generating cost of wind power and photovoltaics. However, with uncertainty, instability and discontinuity, wind power and photovoltaics' disposal and connection to the grid as well as effective deployment will be the bottleneck for the development of energy systems, and will give rise to generous costs. Specifically, the uncertainty of wind power and photovoltaics will cause shocks to the grid, affect reactive voltage and transient stability and significantly increase the cost of consuming electricity. The strong nonlinearity and vulnerability of power electronic device makes it easy to cause a chain reaction when a failure occurs (Xie *et al.*, 2021). For this reason, a large scale of wind power and photovoltaics connected to the grid will affect the security and stability of the entire grid. It is likely to pose a threat to the grid's supply-demand balance, frequency stability and the system's overall security and stability. Besides, as it features reverse distribution of resources and demand because of the uneven, unconcentrated geographical distribution of wind power and photovoltaic resources in China, cross-regional long-distance transmission will become another obstacle to the large disposal of new energy. What's more, unlike thermal power generation that can have peaking and frequency modulated flexibly by demand, wind power and photovoltaics are less flexible and subject to time period and weather. Further, a large scale of wind power and photovoltaics connected to the grid will mount difficulties for the grid's peaking and frequency modulation, and hence the standards for system flexibility are raised, as well as the proportioning for energy storage facilities. The original electricity system is operated in a "source-following-load" mode. The generator is coordinated and controlled according to the forecast of power terminal and the system balance is guaranteed by rolling regulation. With the scale of wind power and photovoltaics expanding, the controllability and measurability of both generation and consumption sides are greatly weakened that the original mode is incapable to the demand for safe, stable operation of the grid.

### *3.3. Lifting Energy System Efficiency by Use of Energy Storage, Digitalization and Intelligence: The Instability of New Energy Is a Major Challenge*

In line with the large-scale development of wind power and photovoltaics and high-proportion connection to the grid, energy storage, digitalization and smart grids will be necessary for energy systems to operate stably. Digitalization in the energy sector enables digital technologies such as big data and cloud computing to apply throughout energy production and consumption, while smart grids are equipped with new types of grid using new technologies, including the digital technology, so smart grids will be realized with a combination of emerging technologies and existing grids (Tao *et al.*, 2019). Into the future, the stability of electricity supply in the case of a large scale of wind power and photovoltaics connected to the grid will be secured by grid digitalization and intelligence. On the one hand, new types of grid, with the help of digitalization and intelligence, predict and sense real-time situations. New electricity systems realize well-rounded sensing, precise prediction and control of each part by use of digitalization and intelligence. Smart grids which are digitally integrated monitor and evaluate electricity systems in real time and multi-dimensionally, and feed precise data to the control center so that each component is well controlled, the operation of new energy plants is informed in time, and potential system failure is sensed and predicted as soon as possible. On the other hand, with digitalization and intelligence, new types of grid are capable of taking timely measures to overcome load and frequency fluctuations. By digital and intelligent integration, grids will make sound decisions quickly to guarantee a stable electricity supply at the time when system instabilities are predicted or sensed. Moreover, the coordination of power source-grid-load-storage is promoted to make the fastest response to various fluctuations, which keeps the continuous, stable transmission of electricity and the balance of electricity systems, and then the contradiction between connecting wind power and photovoltaics to the grid and securing the stable supply is resolved. Going ahead, as energy systems need to maintain a stable supply through energy storage ratios, higher costs could be a major obstacle to the development of energy storage. Therefore, in achieving carbon neutrality, it is crucial to embrace innovative ideas in addition to reducing the cost of energy storage through technological progress and scale development.

### *3.4. Driving Industrial Restructuring and Upgrading: Economic Growth Is Decoupled from Energy Consumption as Soon as Possible*

As the previous analysis illustrated, for smoothly promoting carbon neutrality, China's high-quality economic growth requires that GDP be decoupled from energy power demand, and only by reducing the correlation between the two will higher GDP growth be guaranteed with lower demand for energy power increment. Now in China, energy power is mainly consumed in industry (67.7%), especially in energy-intensive industries (49.4% in 2019). The concentrated industrial consumption is a major reason for the tight correlation between GDP and electricity demand growth, and the key to lowering the correlation between the two is the reduction of industrial energy consumption. Since the reform and opening up, China has rapidly moved from an agricultural economy to an industrial power, and its maturity of the manufacturing chain has been significantly enhanced, shaping its "production-based" rather than "consumption-based" energy consumption. In the case of China's coal consumption, for example, only one-third is used for direct consumption and the rest is for capital formation (Lin and Wu, 2018). Under a coal-based energy mix, GDP growth will bring sustained increase in energy consumption and carbon emissions if the industry is not restructured (Lin and Li, 2015). China's energy consumption by energy-intensive industries accounted for 49.4% of its gross energy consumption in 2019, with 86.9% of coal consumed. Therefore, the key of "decoupling" will be to prioritize the restructuring of energy-intensive and emission-intensive industries.

### *3.5. Encouraging Low-Carbon Consumer Behavior: Consumption Presses for Low-Carbon Production*

China is a developing country and its sustained growth in GDP per capita will be a long-term fact. Consumption is encouraged for the sake of fueling economy and must be made solid support for China's economic growth. If other conditions are not considered, more consumption means greater use of energy and emissions of carbon dioxide, and this contradiction should be addressed by encouraging clean, low-carbon consumption. As the economy develops and living standards improve, both energy consumption and carbon emissions in the consumption sector go up, and the efficiency gains from technological advances are generally offset by increased consumption (Liu *et al.*, 2016). Additionally, the dependency of consumption behavior and habits could result in a lock-in effect of carbon emissions. Consumer behavior dominates the market supply and demand. Business will not truly realize low-carbon transformation if consumers do not actively turn to low-carbon consumption. Carbon neutrality needs consumer participation. By developing consumers' low-carbon perception, their understanding of carbon neutrality will be enhanced and by other policy instruments, their patterns of consumption will start to change. Raising consumers' low-carbon perception also increases their willingness to pay directly for carbon costs and indirectly for low-carbon goods to create a clean growth pattern featuring "more consumption and lower carbon" as much as possible. In the end, carbon reduction on the production side cannot cover all sources of carbon emissions, so the unavoidable and irreplaceable sources of carbon emissions need the carbon reduction mechanism on the consumer side to cope with. Therefore, policy design should draw more attention to carbon emissions on the consumption side and choose measures that are efficient, operable and acceptable. Consumers' reaction to the carbon neutrality target and willingness to pay for carbon reduction are likely to be the decisive factors for achieving carbon neutrality. Less carbon of consumption should be an essential implication of carbon neutrality.

### *3.6. Advocating Circular Economy: Resource (Energy) Inputs Are Reduced While Consumption Is Encouraged*

The circular economy is another solution to the contradiction between consumption growth and carbon emissions. Its promotion helps reduce energy inputs and cut carbon emissions while boosting consumption. There is a clear correlation between circular economy and carbon reduction, and the three basic principles of circular economy (reduction, reuse, recycling) are also applicable to carbon reduction. The reduction principle calls for minimizing resources invested into production and consumption to cut the carbon emissions directly from resource consumption; the reuse principle encourages increasing the frequency and time of material use, and the reuse of waste resources can have the life-cycle value realized, which helps reduce the consumption of material resources; and the recycling principle advocates the resourceization of waste and recycling again to prolong the life cycle of resources. The principles of circular economy are constraints on resource utilization and use from source to end, consuming less resources in total without cutting consumption, by which hidden carbon emissions are reduced accordingly. Promoting the circular economy is a basic need for the sustainable economic development in China, as it will address the problems of extensive use of resources and waste of resources and help remove carbon emissions hidden in the life-cycle use of resources.

## 4. Key Packages for Systemic Carbon-Neutrality Solution

First, because carbon emissions involve externalities, it is impossible to tackle the externality problem by relying solely on the market. Second, the environmental Kuznets curve suggests an inverted U-shaped relationship between economic growth and carbon emissions (Kuznets, 1955). Many developed countries peaking carbon emissions essentially follow the environmental Kuznets curve in reducing their energy consumption and carbon emissions. But when carbon neutrality is set to happen at a particular moment, it will only be made possible with a government-led approach to pool resources and forces. Meanwhile, due to policy limitations and implementation efficiency, the process of carbon neutrality needs to be led by the government to reduce carbon emissions, improve the efficiency of transformation and lower the costs as much as possible through market means. To conclude, China's carbon neutrality process will be government-led and market-supported.

### *4.1. Key Domestic Package: Carbon Trading Market and Electricity Market*

With available technology options, if clean energy shares more than 80% of the energy mix by 2060 in China, the percentage of wind power and photovoltaics could reach 60%~65% (Zhao *et al.*, 2018). This means that mankind will have to cope with complex climate issues with increasingly unstable energy power systems. It is foreseeable that the costs will increase greatly if the security, stability and adequate supply of energy systems are to be guaranteed. What cannot be neglected is that the government's subsidies for the development and use of clean energy such as wind power and photovoltaics put the finances under pressure, and how to get rid of the heavy reliance on financial resources will be a major issue for the government in moving forward carbon neutrality if renewable energy continues to expand on a large scale. Therefore, apart from direct guidance and support from government policies, market regulation is necessary to raise the prices (costs) of fossil energy and curb high-carbon energy consumption, guide industrial restructuring and enhance the competitiveness of clean energy. The carbon trading market can drive up the cost of using fossil energy so that end product prices will reflect the cost of low-carbon transformation. Electricity market reforms enable electricity rates to truly reflect the electricity market's supply and demand and carbon neutrality costs, having the carbon reduction cost smoothly transmitted.

China's carbon trading market needs expanding and improving. What is more imperative now is to deepen electricity market reforms so that electricity rates truly reflect market supply and demand and the cost of cutting carbon emissions. The ultimate purpose of reforming systems and mechanisms of the electricity market is to better sustain the electricity system. Under carbon neutral constraints, the electricity system needs pricing and compensation mechanisms adapting to different attributes of electricity and must rationalize the profit distribution mechanism for all stages of the market. After carbon pricing, generators are burdened with heavy costs and need to transfer carbon costs to the demand side through end-user electricity rates to achieve the design goal of carbon trading. A benign interaction between electricity rates and carbon prices is shaped based on the interaction between the carbon market and the electricity market. Since power is vital to the national economy and people's livelihood, the sharing of carbon costs among stakeholders in the electricity market must be treated carefully in the light of reality. In any case, let electricity rates reflect the market supply and demand and the cost of carbon reduction should be one of the key principles of electricity market reforms.

### *4.2. Key International Package: Globalization of Trade and Globalization of Fighting Climate Change*

The increasingly severe climate change has triggered countries to think about globalization of fighting climate change, and a series of conventions and treaties, such as the *Paris Agreement* and the *Kyoto Protocol*, have been signed. Like the globalization of trade, the globalization of fighting climate change is for the optimal allocation of global resources. First, the impact of carbon emissions from different countries and regions on climate change is not geographically different and should be the same. Besides, carbon emissions can be transferred among countries and regions through industrial restructuring. In spite of considerations over political factors and economic interests among different countries and regions, unlike the globalization of trade, the globalization of fighting climate change is based on responsibility and contribution. Therefore, it needs more dialogue and cooperation. Only by leveraging the contributions and comparative advantages of each country or region and achieving coordinated reduction of carbon emissions through cooperation and dialogue will it be possible to address climate change effectively. The risk of reverse globalization has been mounting with the rise of trade protectionism in recent years. If the global division of labor system is damaged, the energy consumption and energy mix of each country will likely turn to domestic energy resources as the mainstay, and then the global allocation of clean energy resources will be impaired and the global effort to address climate change will be reduced. The low-carbon transformation and carbon neutral progress of each country will face greater challenges.

The globalization of trade can support the globalization of fighting climate change.

Trade provides important platforms for the flow and diffusion of technology and capital, which can facilitate countries' technological R&D and innovation for reducing carbon emissions, improve resource allocation efficiency, and lift their marginal conditions for addressing climate change. Developed countries should give more understanding and support to developing countries which are in the midst of rapid economic growth so that carbon emissions are impossible to fall rapidly in a short period of time. Actually, economic prosperity of developed countries has also experienced the "pollution-before-treatment" pattern. Therefore, specific climate policies should consider both "historical accumulation of carbon emissions per capita" and "consumption-side carbon emissions" as they are developed. While developed countries propose to reduce emissions from the status quo, to effectively combat climate change, the historical accumulation of carbon emissions could not be neglected. A reality unavoidable is that the long-established international industrial chain puts developing countries in a more energy-intensive position, and since production is for consumption, carbon emissions on both the production and consumption sides must be considered in an integrated manner when accounting for emission reductions. Regardless of the stage of development, the green and low-carbon transformation of developing countries will not be successful without the cooperation and help of developed countries. Developed countries' investment and technology transfer in developing countries should be tilted towards clean and low-carbon sectors to avoid "barriers to green technology" and "trade barriers" and to create a favorable external environment for global low-carbon transformation. The proposal of "carbon neutrality" target, the green development of the Belt and Road Initiative and the abandonment of new coal power projects abroad have increased China's contribution to the global fight against climate change and showed its responsibility as a major country. As developing countries are in a period of growth in carbon emissions, with whatever effort to cut carbon emissions, it may be "an insufficient action" from the perspective of developed countries. China as a developing country must be ready to deal with a carbon border adjustment tax for mandatory reduction of carbon emissions.

## 5. A Safe, Stable and Adequate Supply of Energy for Carbon Neutrality

A scientific process of carbon neutrality requires a safe, stable and adequate supply of energy. The Chinese government stressed in July 2021 that the work of carbon peaking and carbon neutrality must be done in a coordinated and orderly manner and the action plan for carbon peaking before 2030 be rolled out as soon as possible and that a whole-of-nation approach would be taken and the campaign-style carbon mitigation be avoided. At the same time, it will insist construction before destruction and firmly curb the irrational expansion of energy-intensive and high-emission projects. Non-fossil energy will share over 80% of energy consumption by 2060 and a clean energy-based electricity system will be built, according to the government's development plans. Given that hydropower is limited by development potential and nuclear power is troubled by safety issues, wind power and photovoltaics will become major energy in the electricity mix.

The phaseout, concession and transformation of coal power are the way to build a new electricity system based on wind power and photovoltaics, but fundamental issues—the electricity system's transformation cost and its security and stability—must be taken into account. There have been many literature discussions over the impact of grid-connected wind power and photovoltaics on costs. It is believed that this grid-connection will drive up capacity cost, and also bring additional system cost of peak and frequency modulation to the grid. As a result of an increasing sacle of wind power and photovoltaics connected to the grid, grid costs will show a non-linear growth, with the cost of disposal rising slowly when the percentage of wind power and photovoltaics is low, while the overall costs will climb rapidly as the percentage of wind power and photovoltaics rises (Lin, 2018).

Still, how a large scale of wind power and photovoltaics connected to the grid will impact the electricity system's stability is not estimable, the coal power system must play the role of "stabilizer" and "ballast" in pushing forward carbon neutrality to ensure a safe, stable and adequate supply of electricity, and better solutions are sought at the same time. On the one hand, with a comprehensive view to the technical route, resource endowment, cost-benefit and so on, a large-scale wind power and photovoltaics connected to the grid will pose serious challenges to the stability and security of the electricity system. "Wind power and photovoltaics plus energy storage" seems to be a solution, but the realization of energy storage configuration on a large scale is subject to technology and cost. On the other hand, China's coal power plants are known to be new, efficient and large in inventory in the world. In 2020, its installed capacity of coal power was 1.03 billion kilowatts, with an average service life of only 11.6 years, where the proportion of advanced plants such as supercritical and ultra-supercritical plants reached over 55%, and a more reasonable capacity layout has been formed. Therefore, coal power could escort the low-carbon transformation and ensure the electricity system safe and stable. To keep system stability and cope with climate extremes by retaining the coal power system intact is consistent with the call for construction before destruction and the basic principle of ensuring a safe, stable and sufficient supply of energy. Especially when extreme weather occurs or when electricity demand is volatile, coal power could be taken as a backup source of stable and reliable electricity to protect normal production and life.

From a cost perspective, coal power will need to be retired completely for the carbon neutrality target by 2060. In addition to zeroing out fixed costs, demolition expenses and relocation, employee resettlement and re-employment costs will be brought about for decommissioning coal power plants. Therefore, if the "decommissioning expectation" of coal power plants is included and full consideration is given to the various costs of dismantling and retiring plants as well as the flexible retrofitting expenses, coal power may cut carbon emissions by slowly reducing annual availability hours and shifting its profitability from electricity rates to capacity rates

(Lin, 2021a). The overall cost of electricity system may be somewhat lower than that of the high energy storage ratios required for a large scale of wind power and photovoltaics connected to the grid. Further, due to the uncertainty of carbon sinks (e.g., forest and ocean carbon sinks), the coal power system can only play a greater role in future electricity systems if carbon capture, utilization and storage (CCUS) technology is introduced. Today, the society is full of doubts about the economy of CCUS, resulting in a serious lack of investment in the industry chain. Notably, the economic assessment of CCUS tends to directly add up the costs of coal power and CCUS, without including the "decommissioning expectation" of coal power plants. If the economic assessment of "coal power + CCUS" only cover a small part of variable generation costs and CCUS retrofitting cost, its cost competitiveness will be largely enhanced compared with the "wind power and photovoltaics plus energy storage" model (Lin, 2021b). Therefore, China may as well use existing young and advanced coal power plants for CCUS retrofitting to reduce the demand and pressure on energy storage systems in the context of a large scale of wind power and photovoltaics connected to the grid, to support economic growth and achieve carbon neutrality at lower costs, and to indirectly make efficient use of huge coal power plants and coal resources. For the sake of both economic growth and carbon neutrality, China will insist construction before destruction and break a low-carbon transformation path with national characteristics.

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