

Path Selection and Policy Study for the Carbon Neutrality Required Technology

Xu Jun*

Department of Science and Technology for Social Development, Ministry of Science and Technology, Beijing, China

Abstract: *The carbon neutrality goal is of far-reaching influence to China's socio-economic systems. Domestically, carbon neutrality will promote China's high-quality economic development and green transition. Internationally, it represents an opportunity for China to lead the global low-carbon technology development. Yet daunting challenges lie ahead for this ambitious goal to be achieved in such a short time. As a driving force of technology progress, innovation plays a pivotal role in achieving carbon neutrality, but is faced with many obstacles in China, including the currently low level of innovation, institutional inadequacies, lack of innovation input, and inadequate fundamental conditions. Under the vision of carbon neutrality, we should identify technology innovation pathways on the three aspects of energy supply, energy consumption and carbon sink. Following those technology pathways, progress should be made in technology development in various stages with different priorities and objectives based on China's energy mix and industrial carbon emission characteristics. On the policy side, we should deepen top-down design, enhance strategic researches, expedite technology development and commercialization, and foster R&D talents to bring out the full potentials of technology innovation in supporting carbon neutrality.*

Keywords: *Carbon neutrality, technology innovation, technology pathways, policy recommendations*

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1. Introduction

Since the Industrial Revolution, carbon dioxide (CO₂) and other greenhouse gas emissions from mankind's consumption of fossil fuels and resources, industrial production and conversion of land use have been widely believed by the science community as the dominant driver for climate change and especially global warming. This assertion has been reaffirmed in the latest Sixth Assessment Report (AR6) published by the Intergovernmental Panel on Climate Change in August 2021 (IPCC, 2021).

Global warming will cause myriad unpredictable environmental impacts. Extreme weather and climate events will occur frequently and climate risks will continue to rise. Meanwhile, high-impact low-probability events have also received attention and consideration. Rising temperature may cause Arctic glaciers to melt into the North Atlantic Ocean and weaken the Atlantic Meridional Overturning Circulation (AMOC).¹ As a result, Europe may experience extremely low temperatures. For China, the benefits of global warming to some extent could outweigh the costs. Rising mean temperature and precipitation could be a boon to China's arid northwestern region, where humid weather in ancient times

* CONTACT: Xu Jun, e-mail: john_sheng1998@aliyun.com.

¹ Maxwell's Science. 2021. The Atlantic's overturning currents threaten to bring extreme cold to Europe. <https://baijiahao.baidu.com/s?id=1707808886327021297&wfr=spider&for=pc>.

allowed the Han and Tang dynasties to thrive on fertile land and crisscrossing rivers (Chen, 2015; Yao, *et al.*, 2022; Zhang *et al.*, 2021). From a global perspective, however, unlimited global warming will eventually wreak havoc on the environment with catastrophic consequences.

The motivations for countries in Europe and elsewhere to embrace low-carbon initiatives are threefold: First, environmental degradation poses a real threat to human survival; moreover, environmental protection gives them a moral high ground to cement their global influence; last but not least, green economy represents an opportunity to reshape the rules of world development, foster new growth drivers, and jumpstart European economic recovery.

China's environmental pressures are relatively small compared with the consequences of climate change facing Europe. As a developing country, China's economic and social development presents a growing demand for fossil fuel consumption. Yet on many occasions, China has reaffirmed its will to achieve carbon peak and carbon neutrality with the bravery of cutting one's own wrist, which shows its sense of responsibility for protecting mankind's common habitat and building a community with a shared future for mankind (Xi, 2020).

Without a doubt, carbon neutrality will influence every aspect of China's political, economic, cultural and social life. China's ministerial agencies, local governments and large enterprises have enacted policies or work plans towards carbon peak and carbon neutrality goals (Lai, 2021). Chinese experts, scholars, strategists and business executives have also shared their views on the current situation and challenges for carbon peak and carbon neutrality, carbon emission pathways and future scenarios, stirring a nationwide wave of research on those topics (Wang and Zhang, 2020; Chai *et al.*, 2020; Wang, 2021).

As a researcher in the field of green and low-carbon technology management, the author has focused on research and policy planning for carbon neutrality and innovation over the past year or so. This paper sheds light on the opportunities and challenges faced by China under the carbon neutrality vision and the pathways and policy design for innovation to support carbon neutrality.

2. Opportunities Coexisted with Challenges under the Carbon Neutrality Vision

On November 2021, the 26th UN Climate Change Conference of the Parties (COP26) reached the Glasgow Climate Pact and reaffirmed the commitment to mitigate greenhouse gas emissions in line with the provision "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" as originally stated in the Paris Agreement under the principle of "fair, common but differentiated responsibilities". It also called for cutting coal subsidies and phasing out inefficient fossil fuel subsidies.² Replacement of coal and other fossil fuels will be accelerated, which poses opportunities and challenges for China's ongoing industrial and urban development.

In terms of the opportunities, green energy and low-carbon technologies are poised to set off a profound technological and industrial revolution. As the world's second-largest economy, China should seize the opportunities from this great transformation and pursue high-quality economic development. Moreover, carbon peak and carbon neutrality are the intrinsic requirements of China's ecological civilization. Coordinated efforts to reduce both carbon emissions and pollution will help the green transformation. Behind the race for carbon neutrality is a global competition for green and low-carbon technologies, where countries remain at the same start line. China should take the opportunity of this global technological transition and lead future global technological development by overtaking on the

² COP26 Summit reached an agreement and released a joint communiqué on the Glasgow Climate Pact, ThePaper.cn. <https://baijiahao.baidu.com/s?id=1716368873630146441&wfr=spider&for=pc>. 2021.11.14.

curve.

In terms of the challenges, China overtook the United States as the world's largest carbon emitter in 2006. According to the IEA (2020a), China emitted 11.2 billion tons of CO₂ in 2020, which were twice as much as those of the US and three times as much as those of the EU and accounted for over a quarter of global total emissions. China's per capita carbon emissions stood at 7.1 tCO₂/person, which was 1.6 times of the world average level and above the average levels of the European Union and G20. China's carbon emissions per unit of GDP was 0.7kg CO₂/USD (constant price of 2015), which was 1.7 times of the world average level and 3.5 times of the US level. China's carbon peak is expected to stay within 11.5 billion tons, which is twice the US level and three times that of the EU. While Europe and the United States promised to achieve carbon neutrality in 43 to 70 years after carbon peak, China only has three decades to do so. Achieving carbon peak and carbon neutrality in such a short time is an extremely arduous task. Moreover, there is a strong interconnection between China's economic development and carbon emissions. China remains on an upward trajectory of economic and social development, which entails high carbon emissions and carbon intensity. In the coming four decades, China needs to continue economic development, increase urbanization, and raise people's living standards, all of which require massive energy consumption. A sustainable mode of economic development, therefore, must be explored to decouple economic and social development from carbon emissions. In terms of economic development stage, aggregate and per capita carbon emissions, carbon neutrality cycle and technological development, China needs to make greater efforts to achieve carbon peak and in particular, carbon neutrality (Zhang *et al.*, 2021).

3. Technology Innovation: The Only choice towards Carbon Neutrality

3.1 Technology Innovation: The Only Path to Go Carbon Neutral

Carbon neutrality entails the reduction, avoidance and reversal of carbon emissions from the conversion of energy and resources, which cannot be achieved without technology. In this sense, technology is the fundamental pillar for carbon neutrality.

According to an estimate by the Administrative Center for China's Agenda 21 (ACCA21), China may see its CO₂ emissions peak before 2030 at the current level of technology development and the low-carbon policy intensity for the 14th Five-year Plan period (2021-2025) (i.e. carbon intensity and energy

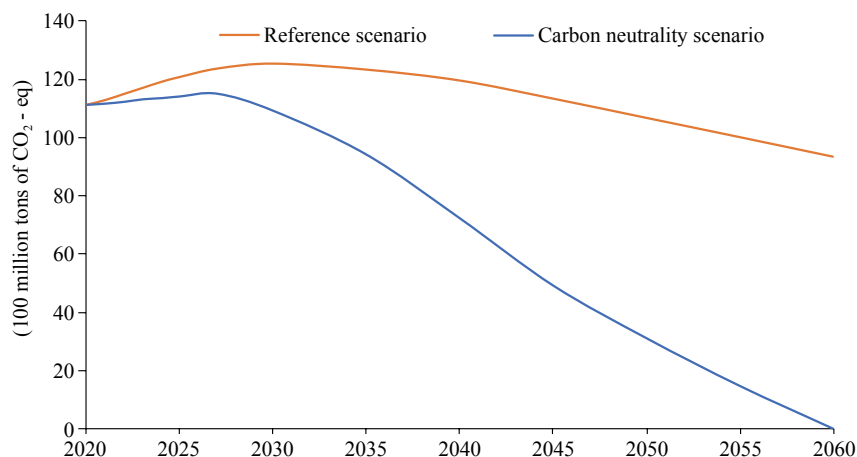


Figure 1: China's Carbon Emission Trends under Different Scenarios

Source: *China's Carbon Neutrality Technology Development Roadmap* (Consultation Draft).

Note: Drafted by the Administrative Center for China's Agenda 21 (ACCA21) in 2021.

intensity drop by 18% and 13.5% every five years, respectively). Under this scenario, however, China's carbon peak will be as high as 12.6 billion tons with carbon emissions at 9.4 billion tons by 2060, which falls short of its carbon neutrality goal. That is to say, the current level of technology is insufficient to support the realization of carbon neutrality.

To raise the level of technology, the only thing we could do is to relentlessly innovate and make all-round progress in development philosophies, scientific research, technological inventions, and industrial innovation. Technology innovation is both the end and the means of carbon neutrality.

3.2 Global Race for Low-Carbon Technologies

Around the world, key regional blocs, advanced economies and international organizations have all carried out systematic research and strategic planning on the technology pathways for carbon emissions abatement in key sectors based on the carbon neutrality goal. The European Green New Deal enacted by the European Union in 2019 called for allocating 35% of the budget of the Horizon Europe program to support climate change research and proposed key policies, technologies and implementation plans in seven critical areas, including energy, industry, construction, transportation and consumption;³ in the *European Climate Law (Draft)* submitted in March 2020, the EU identified green economy as a key pillar for future economic, social and diplomatic affairs.⁴ Meanwhile, the EU also developed specific strategies on some key technologies. In July 2020, for instance, the European Commission published the EU hydrogen strategy, which identified three stages for hydrogen development in the EU and set targets for 2050, and announced the launch of the European Clean Hydrogen Alliance. By 2050, the EU's hydrogen energy investment is expected to reach 180 billion to 470 billion euros on a cumulative basis. In the Ten Point Plan for a Green Industrial Revolution, the British government vowed to invest 12 billion pounds on the research and development of offshore wind power, low-carbon hydrogen, advanced nuclear power, zero-emission vehicles, green buildings and carbon capture, utilization and storage (CCUS) technologies.⁵ US President Joe Biden identified climate change as one of the top four priorities in his *Plan for a Clean Energy Revolution and Environmental Justice*, which aims to achieve zero-carbon power generation in the US by 2035 and net zero emissions and 100% clean energy consumption before 2050.⁶ Regarding low-carbon technologies, the US vowed to ramp up research and technical support in such areas as liquid fuels, low-carbon transportation, renewable energy power generation, and energy storage technologies. Japan's *Green Growth Strategy* identified the technology roadmaps and development targets for carbon emissions reduction in 14 key areas, including offshore wind power, fuel cell, hydrogen energy, nuclear energy, transportation logistics and construction, with a view to achieving the carbon neutrality goal and creating a "zero-carbon society" by 2050.⁷

Based on its long-term assessment of carbon emissions technologies and publication of the carbon emissions technology roadmap, the International Energy Agency (IEA) has systematically reviewed clean technologies for reducing energy emissions in various energy sectors such as electric power, hydrogen energy, biofuels and CCUS technologies. It called for vigorously developing and deploying clean energy technologies to achieve net zero emissions by around 2050 while ensuring the resiliency and security of energy systems (IEA, 2020b).

³ EUROPEAN COMMISSION. The European Green Deal[A/OL]. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. 2019.11.12.

⁴ Source: <https://xw.qq.com/amphtml/20200401a0lx7o00>.

⁵ The Ten Point Plan for a Green Industrial Revolution. <https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title>. 2020.11.18.

⁶ Source: <https://climatecrisis.house.gov/sites/climatecrisis.house.gov/files/Climate%20Crisis%20Action%20Plan.pdf>.

⁷ Source: https://www.meti.go.jp/english/press/2020/1225_001.html.

3.3 China's Strategy for Low-Carbon Technology Innovation

The Chinese government has fully recognized the great significance of technology innovation to achieving carbon peak and carbon neutrality. In the *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy*, the Chinese government vowed to “create a new-type whole-nation system leveraging both government and market forces to enhance technology and institutional innovation and speed up the green and low-carbon technology revolution”. In its *Action Plan for Carbon Peak before 2030*, the State Council called for “giving play to the leading role of technology innovation and improving institutional mechanisms to enhance innovation capacity and accelerate the green and low-carbon technology revolution.” The central steering group on carbon peak and carbon neutrality is creating a “1+N” policy system with a slew of assurances led by technology support. In the *Guiding Opinions on Advancing High-Quality Development of Central Enterprises and Work on Carbon Peak and Carbon Neutrality*, the State Assets Supervision and Administration Commission (SASAC) called for “expediting the green and low-carbon transition and high-quality development of central enterprises”.

Over the years, China has supported the R&D and demonstration of critical green and low-carbon technologies in such areas as energy, construction, transportation and waste recycling with significant results (Liu *et al.*, 2021). After adopting the carbon peak and carbon neutrality targets, the Ministry of Science and Technology has launched ten special key projects, including the Research and Demonstration Program for Critical Carbon Peak and Carbon Neutrality Technologies, renewable energy technologies, hydrogen energy and energy storage and smart grid, as well as 16 less related key projects such as green biological manufacturing and disruptive technology innovations. The National Natural Science Foundation of China (NSFC) has initiated the special project of “Major Fundamental Scientific Problems and Countermeasures for National Carbon Neutrality”. The Chinese Academy of Sciences (CAS) is also planning to launch a special project on carbon peak and carbon neutrality. Many localities such as Shanghai, Jiangsu and Chongqing are deliberating or have already initiated relevant research programs.

4. Key Problems of Technology Innovation in China

However, China's current technological and R&D strengths fall short of supporting those goals.

(1) Uneven development of low-carbon technologies: China has yet to make sufficient investment in fundamental research, from which new technologies derive. Moreover, significant gaps exist in the level of technological development across various domains. In the energy sector, for instance, while China leads the world for photovoltaic energy, hydropower, coal chemicals and long-process steelmaking, it is also a laggard in energy storage, hydrogen power, and short-process steelmaking. China has yet to promote systematic R&D and commercialization and increase the localization ratio of high-value energy equipment. It still lags far behind internationally advanced levels in terms of high-performance and high-tech energy equipment, and relies on importation and imitation.

(2) Imperfect institutional mechanisms for low-carbon innovation: While the carbon neutrality goal has aroused broad public discussions, the government has yet to coordinate innovation programs in various sectors to bring about synergy and form a consistent, science-based and fair approach at the national level. Key national carbon neutrality policies have yet to be fully researched and implemented in a foreseeable, stable and sustained manner. Carbon neutrality is a systematic issue and requires a systematic and efficient mechanism to mobilize and coordinate innovation in various sectors. Moreover, the commercialization of low-carbon technologies calls for conducive fiscal, financial and industrial policies and legal assurances, the absence of which impedes the application of R&D results and the formation of innovation value chains.

(3) Underinvestment in low-carbon innovation: Take the energy sector for instance, China's energy

R&D investment as a share of national total R&D input is decreasing in both public and private sectors. Energy companies rely on technology renovation, importation or domestic acquisition for technology upgrade at a low level. In the energy sector, less innovative technology upgrade and importation have received the bulk of R&D spending, leaving technology assimilation and re-innovation underfunded.

(4) Poor fundamentals for low-carbon innovation: Despite rapid growth, China's low-carbon industry, R&D workforce and innovation capacity fall short of demand. Few R&D programs have been carried out in partnership with innovation platforms such as state key laboratories, state engineering technology centers, state-designated corporate technology centers, and state key laboratories of enterprises. With overlapping priorities, those innovation platforms should be more focused on specific areas of research and receive more stable support from the state.

5. Reflections on Innovation Pathways under the Carbon Neutrality Vision

Carbon neutrality requires integrated efforts on the three fronts, of the substitution of fossil fuels and feedstocks, the emissions abatement of industrial, construction, transportation and terminal processing activities, as well as CCUS and carbon sink. In terms of energy supply and consumption, it takes the joint effects from power generation, energy consumption and carbon sink to achieve carbon neutrality.⁸ Technology pathways for carbon emissions abatement vary across sectors, including the electric power sector as energy producer, industry, construction and other social and economic sectors as energy consumers, and negative carbon technologies such as carbon sink and CCUS on the carbon sequestration side. Technology innovation should proceed in a step-by-step manner with priorities and targets for each stage following the laws of technology development and latest trends in various domains.

5.1 Technology Innovation Pathways on the Energy Supply Side

In 2020, China consumed 4.98 billion tons of coal equivalent (tce), of which coal consumption accounted for 56.8%. China's coal-fired generation capacity made up 49.1% of total installed capacity and generated 60.8% of China's total electricity. According to Su *et al.* (2021), China's energy consumption will keep rising to meet the needs of the country's economic and social development and peak at 6 billion to 6.4 billion tce in 2030-2040 before decreasing gradually. By 2025, 2030 and 2060, China's total energy consumption is expected to reach 5.8 billion, 6 billion and 5.6 billion tce per year, respectively (see Figure 2).

As the keynote of its energy transition, China will reduce coal, stabilize oil, increase natural gas and scale up renewable energies in the coming four decades. With an overall surplus and basic supply-demand equilibrium, China's coal production is poised to meet its demand of 4 billion tons per year. Under the carbon neutrality goal, however, coal consumption is expected to shrink and ultimately serve as a ballast in China's energy consumption system. China's crude oil and natural gas shortages will persist. In the absence of revolutionary technologies, China will stabilize crude oil production at around 200 million tons, and try to keep natural gas production at the plateau after peaking at 300 billion cubic meters by 2030. China's abundant renewable resources, especially wind and solar in the western regions and offshore wind in the eastern coastal regions, will satisfy its goal to increase the share of non-fossil fuels to over 80% of total energy consumption by 2060.

We forecast the following trends of China's energy mix. First, China's overall energy demand will increase before decreasing in a later stage. Second, fossil fuels will continue to dominate China's energy consumption before 2040. Third, non-fossil fuels as a share of primary energy demand will keep rising and replace fossil fuels by 2040 to become a major energy source. Non-fossil fuels as a share of primary

⁸ Source: <https://www.in-en.com/article/html/energy-2311652.shtml>.

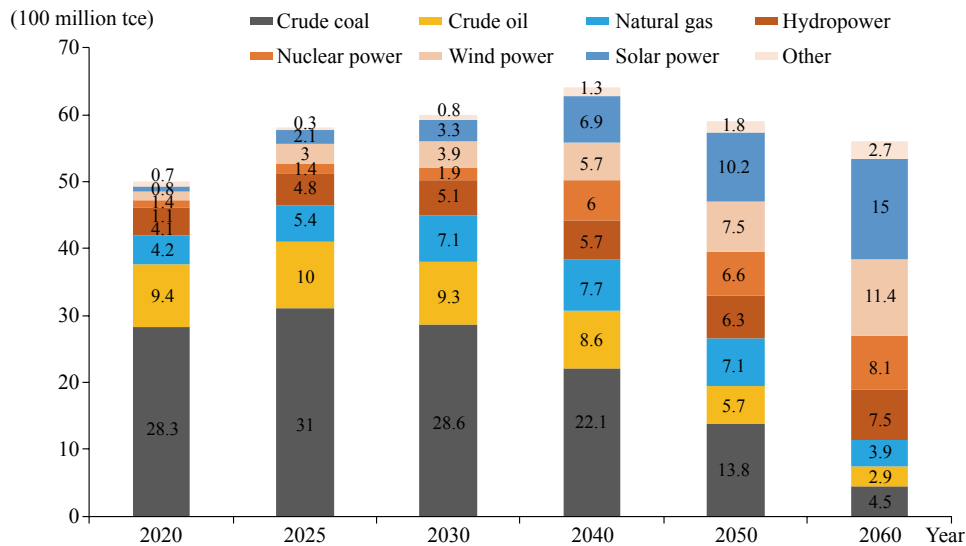


Figure 2: Forecast of China's Total Energy Consumption and Energy Mix

Source: Su *et al.* (2021).

energy demand will jump from 20% in 2025 to around 80% by 2060. Fourth, the importance of electric power primarily fueled by renewables will come into greater play. In 2020, China's electric power as a share of terminal energy consumption stood at 27%. By 2030 and 2060, this share will rise to 39% and 70%, respectively.⁹

The electric power sector is vital for energy conversion and supply. It may still rely on fossil fuel combustion as the primary form of power generation in China before the goal of carbon peak is achieved or in a longer timeframe before 2040. Coal innovation is primarily driven by coal-fired power generation units. Priority should be given to deploying single reheat ultra-critical units, double reheat ultra-supercritical technology with cross-compound, high and low positioned steam turbo-unit, and efficiency enhancement technologies for the low-load operation of coal-fired power plants. Before energy storage technologies are ready for mass deployment, coal-fired power for peak-load regulation may facilitate the absorption of renewable energies. Steady progress should be made in the development of photovoltaic and wind power. After reaching the carbon peak, thermal power plants will decarbonize feedstock by mixing or completely adopting biomass pellets for zero-carbon thermal power generation. New botanical species such as giant reeds should be developed as photosynthetic energy storage devices through genetic engineering to provide sufficient biofuels for the transition towards "zero-carbon biomass thermal power".¹⁰

Meanwhile, the electric power sector should adopt CCUS technologies for the partial conversion and utilization of carbon resources. Regarding renewable power, technological breakthroughs should be made in high-efficiency and low-cost crystalline silicon photovoltaic (PV) cells to substantially increase the conversion efficiency and storage capacity of renewable power. Wind turbines should be deployed further offshore and become taller, larger, smarter and more reliable. We should acquire critical technologies such as renewable hydrogen production and smart grid, and create an integrated and smart multi-energy hybrid power system led by photovoltaic, wind, biomass and hydrogen power with the assistance of big data and new-generation information technology. In the carbon neutrality stage, we

⁹ Source: National Energy Information Platform. <https://baijiahao.baidu.com/s?id=1711103389482683034&wfr=spider&for=pc>. 2021.09.17.

¹⁰ Source: http://xincailiao.com/news/news_detail.aspx?id=604161.

expect the thermal power sector to achieve negative emissions on the basis of zero-carbon thermal power technology as CCUS becomes ready for mass deployment. With progress in the Generation IV nuclear reactors and experimental fusion reactors, nuclear power will further contribute to decarbonization in the electric power system.

5.2 Technology Innovation Pathways on the Energy Consumption Side

On the energy consumption side, the low-carbon transition relies on both systematic supply-side change and industrial technology innovations.

The manufacturing industry is a key priority for achieving carbon neutrality. China's industrial carbon emissions reached 4.9 billion tons in 2020, accounting for 44% of total emissions, and are expected to peak by around 2025 at 5.5 billion tons and stand a suggested level of 300 million to 500 million tons by 2060.

(i) Before reaching carbon peak, the manufacturing industry may curb carbon emissions primarily by consuming less energy, improving product quality and durability, and reducing overall output through further production process integration and optimization. Smart manufacturing and secondary resource recycling may help, too. Steel and nonferrous metals sectors may slash carbon emissions by integrating production processes, improving the quality of metallurgical products, and adopting hydrogen smelting and residual heat recovery technologies. For the building materials sector, a key solution is the adoption of low-carbon industrial materials and the reuse of solid wastes from other sectors. For the chemical industry, carbon reduction solutions also include system optimization and integration between various production units, the re-engineering of key energy-consuming processes, the promotion of energy cascade use, material recycling, as well as the integrated use of low-grade heat energy, ash and slag. New industrial projects should embrace internationally advanced technologies, increase product yield, reduce energy and resource consumption, and promote low-carbon industry development. Such technologies include, for instance, coal-water slurry gasification technology with a cooling screen, the third-generation dimethyl ether/methanol to olefins (DMTO-III) process, and methanol-naphtha coupling for manufacturing light olefins.

(ii) In further reducing carbon emissions after reaching carbon peak, China should promote feedstock replacement and short-process technologies. Steel and nonferrous metals sectors should promote short-process smelting technologies with waste and used metals as feedstock through industrial process transformation. The cement sector should widely adopt low-calcium clinker and clinker-free or low-clinker feedstock, as well as hydrogen fuel substitution technology. The chemical sector should apply short-process energy-efficiency and low-carbon technology, low-carbon feedstock substitution technology, and CO₂ utilization technology. Some areas of the chemical sector with favorable conditions should apply CCUS technology and support the near-zero emissions of the chemical industry.

(iii) In the carbon neutrality stage, CCUS/carbon removal technologies will be deployed on a mass scale in the industrial sectors and play a critical role in achieving carbon neutrality.

The building sector is a key energy consumer. In 2020, China's building sector emitted 620 million tons of carbon dioxide (excluding rural bulk coal for heating and cooking), accounting for 6% of the total. Having entered a plateau with relatively mature zero-carbon solutions, China's building sector carbon emissions should take the lead in reducing carbon emissions and achieving near-zero emissions as early as possible. The realization of low-carbon/zero-carbon transition in the building sector should be predicated upon the development of energy-efficient buildings and all-round electrification.

(i) Before reaching the carbon peak, existing buildings should be retrofitted for energy efficiency, and new buildings should follow ultra-low energy consumption and near-zero energy consumption standards. Energy consumption of buildings should be reduced by adopting high-performance envelope structure and new materials, products and processes.

(ii) In further reducing carbon emissions after carbon peak, the building sector should first improve

construction quality and durability; second, promote building electrification and electric and zero-emission alternative technologies and equipment for heating, cooking, water boiling and steam in hot-summer-frigid-winter regions; third, expedite technology innovations for combined heating and power, develop the photovoltaic-energy storage-direct current-flexibility (PEDF) technology, adopt low-carbon building materials and low-carbon building structure, and make coordinated carbon reductions in the electric power and industrial sectors; and fourth, promote building-integrated photovoltaics (BIPV) to maximize renewable potentials in buildings.

As a major consumer of oil and electricity, the transportation sector has great carbon reduction potentials, but the achievement of which is a tall order. In 2019, carbon emissions from China's transportation sector stood at some 1.15 billion tons, accounting for some 10% of total. The sector is expected to reach carbon peak by 2030 or so at 1.25 billion to 1.35 billion tons. Considering such factors as the safety and convenience of mobility and emissions reduction technologies and costs, the transportation sector will strive to reduce carbon emissions to less than 200 million tons by 2060. Priority should be given to vehicle energy efficiency, carbon reduction and new energy substitution. Before reaching carbon peak, we should proactively encourage public transportation and non-motorized transportation to reduce energy consumption. Priority should also be given to developing energy-efficiency technologies for fossil-fueled cars, including energy efficiency and lightweight bodywork technologies. Shared mobility systems should be encouraged to increase the utilization of mobility services and resources. In the further carbon production stage after reaching carbon peak, priority should be given to developing high-performance electric and hydrogen fuel cell vehicles for all-round new energy substitution. Smart mobility should focus on making breakthroughs in critical technologies, smart sensing, integrated big data processing and coordinated command and dispatch to increase overall transportation efficiency.

5.3 Technology Innovation Pathways for Carbon Sink

Negative carbon technologies such as carbon sink and CCUS are the underlying technologies for China to go carbon neutral. (i) Before reaching carbon peak, we should enhance research on the mechanism of carbon sink based on forest, pasture, wetland and maritime ecosystems, explore space-air-ground integrated carbon sink precise monitoring technologies, create an accounting system for dynamic monitoring, reporting and verification, adopt innovative typical ecosystem protection and repair technologies, and stabilize and enhance the carbon sink capacity of existing ecosystems. We should proactively carry out fundamental research on CCUS and demonstrative research for CCUS applications. (ii) In further reducing carbon emissions after reaching carbon peak, we should strengthen technological breakthroughs in various processes including carbon capture, separation, transportation, utilization, sequestration and monitoring, and ramp up the development and mass deployment of new-generation CCUS technologies featuring low energy consumption, low cost and high safety performance. Fiscal incentive similar to US 45Q tax credit should be offered to pave the way for the future commercialization of those technologies. Priority should be given to the mass deployment of CCUS technologies in the industrial sectors. (iii) In the carbon neutrality stage, the priority is to promote all-around commercial applications of CCUS technologies.

6. Reflections on Technology Innovation under the Carbon Neutrality Vision

The first is conducting top-down design for integrating technologies, energy sources and energy-consuming sectors. We should create a nationwide cross-departmental coordination mechanism led by the Ministry of Science and Technology to draw upon collective wisdom of strategic scientists, carry out extensive forward-looking cross-disciplinary research to identify future technology frontiers for carbon peak and carbon neutrality, and form a dynamic top-down design blueprint for carbon neutrality

technologies.

The second is ramping up scientific research on energy strategy for achieving carbon peak and carbon neutrality goals. Under the premise of the national top-down scheme for carbon neutrality, we should formulate mid- and long-term strategic plans for carbon abatement, low-carbon and zero-carbon technologies on the basis of five-year plans for science and technology development, promote non-carbon-based energy technology iteration, and assess various technology pathways in terms of economic and environmental performance to safeguard national energy security.

The third is expediting the pilot demonstration applications of new technologies and business modes. Based on the assessment of demand for energy efficiency and carbon reduction technologies under the carbon peak and neutrality goals, pilot programs should be carried out in various sectors and use cases to roll out mature technologies. We should foster a virtuous cycle of technology research, commercialization and accumulation and encourage the development and deployment of new technologies, processes and business modes.

The fourth is establishing institutional mechanisms for the market-based operation of low-carbon technologies. The government should research market-oriented emissions reduction policies, carry out study on Net-Zero Techno-Economics, and investigate how efforts to achieve carbon neutrality may contribute to innovation and reshape future energy and industrial landscapes. The effective state and efficient market should be brought into play to coordinate technology, fiscal, investment and financing policies. Low-carbon technology evaluation and transaction systems should be put into place to inspire low-carbon innovation and apply low-carbon technologies in industrial sectors. Net-zero carbon technologies should play an important role in the economic and social transition towards carbon neutrality.

The fifth is cultivating carbon neutrality professionals. For the purpose of achieving carbon peak and carbon neutrality, the government should bring together scientists and policy researchers, scale up support to leading research institutions, and improve the layout of innovation entities by setting up key national laboratories and innovation centers. Moreover, it is also important to develop a technology information platform to integrate resources across various sectors, giving priority to fostering young scientists and engineers specialized in carbon neutrality.

The sixth is deepening international innovation cooperation for mutual benefit. We should promote carbon neutrality innovation with major countries. The two-way flow of green and low-carbon technologies should be encouraged by sharing climate change knowledge and technology and establishing technology transfer platforms and databases to match the international supply and demand of green and low-carbon/decarbonization technologies. 

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