Supportive Technologies and Roadmap for China's Carbon Neutrality

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Abstract: *The vision of carbon neutrality is a climate ambition of milestone significance for China and a key step for China's transition from industrial civilization to ecological civilization. The realization of carbon neutrality requires profound changes in China's technological and socioeconomic systems involving zero-carbon electric power, low-carbon and zero-carbon end-use energy consumption, and negative emission technologies. Achievement of carbon neutrality is subject to the choice of pathways for various sectors, especially the electric power, industrial, transportation and construction sectors with significant carbon emissions and decarbonization difficulties. The goal of carbon neutrality will influence China's economic and industry systems, resource and industrial layout, technological innovation and ecological environment in profound ways. Hence, China's future policymaking on carbon neutrality needs to consider environmental, technological, economic and social impacts, establish a correlation between carbon peak and carbon neutrality, identify climate-friendly clean technology innovations in real earnest, and put carbon neutrality into the overall plan for ecological civilization.*

Keywords: *carbon neutrality, low-carbon technology, low-carbon development path*
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1. Introduction

The vision of carbon neutrality was put forth in the context of global climate governance. China's socio-economic development and ecological civilization should, in the final analysis, achieve carbon neutrality. The past three decades have seen great progress in the scientific awareness, political process and industry actions for global response to climate change. Against the backdrop of global climate governance, carbon neutrality is an inevitable stage of countries' response to climate change. China's carbon neutrality commitment will bring great opportunities and challenges to its socio-economic development. China's carbon emissions and carbon intensity are both among the highest in the world. In the foreseeable future, China will remain in the late stage of industrialization and urbanization. With China's economy on the rise and carbon emissions yet to peak, China's economic development has yet to be decoupled from carbon emissions. For a long period of time, China's carbon emissions and carbon intensity will both remain high. It will take about three decades for China to move from carbon peak to carbon neutrality. Within this short span, it will take much greater efforts for China to achieve the vision of carbon neutrality compared with developed countries in Europe and North America. Yet the vision of

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中国实现碳中和的支撑技术与路径

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***摘　要：**碳中和愿景是中国具有里程碑意义的气候雄心目标，也是推动中国从工业文明迈向生态文明的重大举措。碳中和的实现需要深刻的技术体系和社会经济系统变革，主要涉及零碳电力系统、低碳甚至零碳终端用能技术和负排放技术。碳中和目标的达成也依赖于各个部门的路径选择，特别是碳排放量大且脱碳难度高的电力、工业、交通、建筑四大部门。同时，碳中和目标将对中国的经济产业体系、资源产业布局、技术创新体系、整体生态环境等方面产生深远的影响。因此，未来面向碳中和的政策体系需要充分考虑环境、技术、经济和社会影响，明确碳达峰与碳中和的关系，识别真正气候友好的清洁技术创新，将碳中和纳入生态文明建设的整体布局之中。*

***关键词：**碳中和；低碳技术；低碳发展路径*

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一、引言

碳中和愿景的提出既是全球气候治理进程推进的必然结果，也是我国经济社会发展和生态文明建设的必然要求。过去30年来，全球应对气候变化的科学认知、政治进程和产业行动不断深入并加速推进。在全球气候治理的大背景下，实现碳中和是全球各国应对气候变化的必然阶段。我国向世界许下庄严的碳中和承诺将为我国经济社会发展带来巨大的机遇与挑战。我国碳排放的基本特征是碳排放总量大、碳排放强度高，两者均居于世界前列。当前和今后一段时期，我国仍处于工业化和城市化后期，同时也处于经济上升期、排放达峰期，经济发展与碳排放尚未实现脱钩，我国碳排放总量和碳强度“双高”的状况仍将持续较长时间。我国从碳达峰到碳中和的时间仅为30年左右，这意味着我国实现碳中和愿景目标的任务十分艰巨，要付出比欧美发达国家更多的努力。我国实现现代化的过程中还面临能源安全、经济安全和生态安全等必须要解决的重大战略问题，碳中和愿景恰恰提供了解决这些问题的机遇。我国迈向碳中和愿景，就是迈向新发展路径，不再走大规模消耗化石能源的老路。这意味着通过构建新的能源体系和工业体系，我国在保障能源和生态安全的同时，能够加快促进产业经济走向更广阔的新增长空间。

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carbon neutrality opens up opportunities for China to address challenges to its strategic energy, economic and ecological security in its modernization drive. In achieving its vision for carbon neutrality, China needs to embark upon a new path of development less reliant on fossil fuels. By reshaping its energy and industrial systems, China will unlock greater growth potentials for its industrial economy while ensuring energy and ecological security.

2. China's March towards Carbon Neutrality

On September 22, 2020, Chinese President Xi Jinping declared for the first time at the General Debate of the 75th Session of the United Nations General Assembly (UNGA) that China would increase its nationally determined contributions (NDCs) and step up policies and initiatives to peak its CO_2 emissions by 2030 and strive to achieve carbon neutrality before 2060. This important declaration marks China's strategic decision to fulfill its responsibility in creating a community with a shared future for humanity and pursuing sustainable development. It is also a strategic arrangement of the CPC Central Committee and the State Council for coping with domestic and international situations. Internationally, the targets for carbon peak and carbon neutrality represent China's steadfast support to multilateralism. In joining hands with countries to meet the challenges of climate change and contributing Chinese wisdom to protecting Planet Earth for human survival, China lives up to its status as a responsible stakeholder. Domestically, the targets for carbon peak and carbon neutrality coincide with China's goal of building a strong socialist modern nation by the middle of this century with far-reaching significance to the sustainable development of the Chinese nation. In the foreseeable future, China will follow these targets in its broader initiatives of climate change response, green and low-carbon development, and ecological civilization.

China's climate policy targets have been consistent and reinforced. In 2009, the Chinese government made a carbon intensity commitment to "reduce CO_2 emissions per unit of GDP by 40% to 45% by 2020 on the basis of 2005". In 2015, this commitment was renewed into "reducing CO_2 emissions per unit of GDP by 60% to 65% by 2030 on the basis of 2005." In 2014, China put forth its carbon peak target, vowing to peak CO_2 emissions by around 2030 or earlier where possible. The target for carbon neutrality announced in 2020 marks a step forward in China's climate policy. After China announced its target for carbon neutrality, the Chinese leadership made a series of important speeches on various international and domestic occasions, including the United Nations Summit on Biodiversity, the Third Paris Peace Forum, the 12th BRICS Summit, the G20 Riyadh Summit, the Climate Ambition Summit, the Davos World Economic Forum, China's Central Economic Work Conference, China's Ninth Meeting of the Central Committee for Financial and Economic Affairs, and the Leaders' Summit on Climate (see Figure 1) (Wang and Zhang, 2021). The Chinese leadership mentioned carbon neutrality with increasing frequency and determination, indicating China's resolve and confidence in achieving carbon neutrality by 2060. From the carbon neutrality target by 2060 to the renewal of NDC target and tightened control on non-CO_2 greenhouse gas emissions, China has been broadening the regulatory scope for carbon neutrality and steadily implementing relevant work. Without a doubt, it is a tough battle to achieve carbon neutrality and a big test for the Party's governance capabilities. For this reason, carbon neutrality needs to be carried out in a steady manner and requires joint participation of all social members.

3. Supporting Technologies for China to Achieve Carbon Neutrality

3.1 Description of Technological System

The technological system for achieving the vision of carbon neutrality consists of four categories of technologies, including zero-carbon electric power system, low-carbon/zero-carbon end-use energy consumption technologies, negative emissions, and non-CO_2 greenhouse gas emissions reduction

二、中国碳中和目标的演进

2020年9月22日，国家主席习近平在第七十五届联合国大会一般性辩论上首次对外宣布中国将提高国家自主贡献力度，采取更加有力的政策和措施，二氧化碳排放力争于2030年前达到峰值，努力争取2060年前实现碳中和。这一重大宣示是中国基于推动构建人类命运共同体的责任担当和实现可持续发展的内在要求作出的重大战略决策，也是党中央、国务院统筹国际国内两个大局作出的重大战略部署。从国际上来看，“双碳”目标的提出体现了中国对多边主义的坚定支持，并为各国携手应对气候变化挑战，共同保护好人类赖以生存的地球家园贡献中国智慧和中国方案，充分展现了中国作为负责任大国的担当。从国内来看，“双碳”目标与我国21世纪中叶建成社会主义现代化强国目标高度契合，关乎中华民族永续发展，影响深远、意义重大，也为我国当前和今后一个时期，乃至本世纪中叶应对气候变化工作、绿色低碳发展和生态文明建设提出了更高的要求、擘画了宏伟蓝图、指明了方向和路径。

中国的气候政策目标是连贯一致且不断加强的。2009年中国首次提出“2020年单位国民生产总值二氧化碳排放较2005年下降40%～45%”的碳强度承诺，并在2015年将该承诺更新为“2030年单位国民生产总值二氧化碳排放较2005年下降60%～65%”。2014年中国提出碳达峰目标，承诺2030年左右二氧化碳排放将达到峰值并尽可能提前达峰。2020年的碳中和目标是中国气候政策的进一步强化。自我国对外宣布碳中和目标以来，国家领导人已多次在联合国生物多样性峰会、第三届巴黎和平论坛、金砖国家领导人第十二次会晤、二十国集团领导人利雅得峰会、气候雄心峰会、世界经济论坛达沃斯议程、中央经济工作会议、中央财经委员会第九次会议、领导人气候峰会等国内外重要场合就碳中和目标发表系列重要讲话（王灿和张九天，2021）（见图1）。国家领导人对碳中和的频繁提及且一次比一次更有力度，愈加表明了我国对2060年实现碳中和的坚定决心和强有力信心；从2060年碳中和目标到进一步更新国家自主贡献目标，再到加强非二氧化碳温室气体排放管控，表现出我国碳中和目标的管控范围正逐步扩大、具体工作在有序推进与落实。实现碳中和无疑是一场硬仗，也是对我们党治国理政能力的一场大考，所以碳中和工作需要稳步推进，更需要全体社会成员的共同参与。

三、实现中国碳中和目标的支撑技术体系

（一）技术体系概述

碳中和愿景的技术体系主要由零碳电力系统、低碳/零碳化终端用能系统、负排放以及非CO_2温室气体减排技术四大类技术构成。其中前三项是CO_2净零排放技术体系的重要支撑（见图2）。

其中，电力系统的快速零碳化是实现碳中和愿景的必要条件之一。其重点是以全面电气化为基础，全经济部门普及使用零碳能源技术与工艺流程，完成从碳密集型化石燃料向清洁能源的重要转变。这既需要大力发展传统可再生能源电力（如风能、光伏、水电），还要大幅度提高地热、生物质、核能、氢能等非传统可再生能源在供能系统里面的比例。为了支撑这类高比例的可再生能源供电，需要匹配上强大的储能系统和智能电

• International occasions

September 22, 2020, General Debate of the 75th Session of the United Nations General Assembly

China will increase its nationally determined contributions (NDCs) and step up policies and initiatives to peak its CO_2 emissions by 2030 and strive to achieve carbon neutrality by 2060.

September 30, 2020, the United Nations Summit on Biodiversity

Once again mentioned the "30•60" targets to make greater efforts towards and contributions to achieving the goals set forth in the Paris Agreement on climate change.

November 12, 2020, the Third Paris Peace Forum

Once again mentioned the "30•60" targets and announced that the Chinese government would draft an implementation plan

November 17, 2020, the 12th BRICS Summit

Once again mentioned the "30•60" targets and vowed that "we will keep our word!"

November 22, 2020, the G20 Riyadh Summit

Once again mentioned the "30•60" targets and declared that "China will keep its word and steadfastly fulfill its targets."

December 12, 2020, the Climate Ambition Summit

Further announced that on the basis of the "30•60" targets, China would reduce its CO_2 emissions per unit of GDP by over 65% by 2030 on the basis of 2005, increase the share of non-fossil fuels in primary energy consumption to around 25%, increase forest stock by 6 billion cubic meters on the basis of 2005, and reach a total installed wind and solar power capacity above 1200 GW.

January 25, 2021, "Davos Agenda" Dialogue at the World Economic Forum

Once again mentioned the "30•60" targets and revealed that China was formulating an action plan and had started to take specific measures to achieve the set targets

April 22, 2021, Leaders' Climate Summit

China will strictly control coal-fired power projects, curb coal consumption growth during the 14th Five-Year Plan period, and take steps to reduce coal consumption during the 15th Five-Year Plan period. In addition, China has decided to accept the Kigali Amendment to the Montreal Protocol and tighten the control of non-CO_2 greenhouse gas emissions.

• Domestic occasions

December 16-18 2020, the Central Economic Work Conference

We should work properly to achieve carbon peak and carbon neutrality. We should try to peak China's CO_2 emissions before 2030 and achieve carbon neutrality before 2060. We should race to formulate an action plan for carbon peak by 2030 and support localities with proper conditions to achieve carbon peak first.

February 19, 2021, the 18th Meeting of the Central Committee for Deepening Overall Reform

Establish a sound economic system for green and low-carbon circular development, and formulate an action plan for carbon peak before 2030.

March 15, 2021, Ninth Meeting of the Central Economic and Financial Affairs Committee

Achieving carbon peak and carbon neutrality is an extensive and profound socioeconomic transformation. We should include carbon peak and carbon neutrality into the overall plan for ecological civilization. When we clutch a piece of iron, we will leave our handprints on it. With this spirit, we should achieve carbon peak by 2030 and carbon neutrality by 2060 as planned.

On March 25, 2021, General Secretary Xi Jinping said during his inspection to Fujian Province:

"We should include carbon peak and carbon neutrality into the plan for developing an ecological province, formulate a timetable and roadmap in a science-based manner, and promote modernization with the harmonious coexistence between man and nature."

On April 30, 2021, General Secretary Xi Jinping stressed at the 29th group study session of the Political Bureau of the Central Committee of the CPC that

"In the 14th Five-Year Plan period, with decarbonization as a strategic direction, China's development of ecological civilization has entered into a critical stage of pollution abatement in coordination with decarbonization to raise efficiency, all-round green transition for socio-economic development, and qualitative improvement in the ecological environment on the basis of quantitative change."

Figure 1: Implementation of China's Carbon Neutrality Target

Source: Wang and Zhang (2021).

● 国际场合

2020年9月22日，第75届联合国一般性辩论
——中国将提高国家自主贡献力度，采取更加有力的政策和措施。二氧化碳排放力争于2030年前达到峰值，努力争取2060年前实现碳中和。

2020年9月30日，联合国生物多样性峰会
——再次提到”3060”目标，为实现应对气候变化《巴黎协定》确定的目标作出更大努力和贡献。

2020年11月12日，第三届巴黎和平论坛
——再次提到”3060”目标，并指出中方将为此制定实施规划

2020年11月17日，金砖国家领导人第十二次会晤
——再次提到”3060”目标，并指出”我们将说到做到!”

2020年11月22日，二十国集团领导人利雅得峰会
——再次提到”3060”目标，并指出”中国言出必行，将坚定不移加以落实。”

2020年12月12日，气候雄心峰会
在“3060”目标后，进一步宣布：到2030年，中国单位国内生产总值二氧化碳排放将比2005年下降65%以上，非化石能源占一次能源消费比重将达到25%左右，森林蓄积量将比2005年增加60 亿立方米，风电、太阳能发电总装机容量将达到12亿千瓦以上。

2021年1月25日，世界经济论坛”达沃斯议程”对话会
——再次提到“3060”目标，并指出中国正在制定行动方案并已开始采取具体措施，确保实现既定目标。

2021年4月22日，领导人气候峰会
———中国将严控煤电项目，”十四五”时期严控煤炭消费增长、“十五五”时期逐步减少。此外，中国已决定接受《《蒙特利尔议定书>基加利修正案》，加强非二氧化碳温室气体管控。

● 国内场合

2020年12月16日-18日，中央经济工作会议
——要做好碳达峰、碳中和工作。我国二氧化碳排放力争2030年前达到峰值，力争2060年前实现碳中和。要抓紧制定2030年前碳排放达峰行动方案，支持有条件的地方率先达峰。

2021年2月19日，中央全面深化改革委员会第十八次会议
——建立健全绿色低碳循环发展的经济体系，统筹制定2030年前碳排放达峰行动方案。

2021年3月15日，中央财经委员会第九次会议
——实现碳达峰、碳中和是一场广泛而深刻的经济社会系统性变革，要把碳达峰、碳中和纳入生态文明建设整体布局，拿出抓铁有痕的劲头，如期实现2030年前碳达峰、2060年前碳中和的目标。

2021年3月25日，习近平总书记在福建考察时指出
——要把碳达峰、碳中和纳入生态省建设布局，科学制定时间表、路线图，建设人与自然和谐共生的现代化。

2021年4月30日，习近平总书记在中共中央政治局第二十九次集体学习时强调
——”十四五”时期，我国生态文明建设进入了以降碳为重点战略方向、推动减污降碳协同增效、促进经济社会发展全面绿色转型、实现生态环境质量改善由量变到质变的关键时期。

图1 我国碳中和目标的逐步推进历程

资料来源：王灿和张九天(2021)。

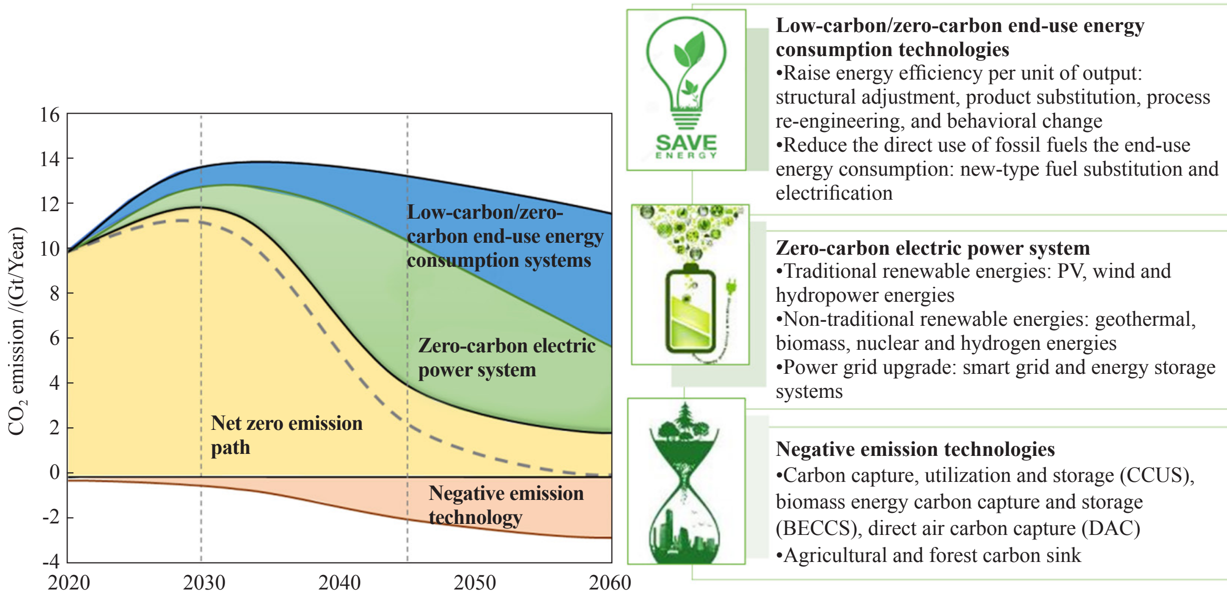

Figure 2: Net Zero Emission Technologies under the Carbon Neutrality Vision

Source: Wang and Zhang (2020); Wang *et al.* (2021).

technologies. The first three are important pillars of the CO_2 net zero emissions technology system (see Figure 2).

Rapid decarbonization is a necessary condition for achieving the carbon neutrality vision. This vision is underpinned by the important transition from carbon-intensive fossil fuels to clean energies through the penetration of zero-carbon energy technologies and processes based on complete electrification. In addition to the development of traditional renewable energies such as wind, PV and hydropower, decarbonization also requires a significant increase in non-traditional renewable energies like geothermal, biomass, nuclear and hydrogen energies. A significant proportion of power generation from intermittent renewables needs to be matched with powerful energy storage and smart grid systems to decarbonize energy use.

Low-carbon/zero-carbon end-use energy consumption technologies are concentrated at the left end of the emissions abatement cost curve, characterized by significant emissions reduction effects with low costs and even lucrative revenues. This category of technologies is applied in a wide range of key energy-consuming sectors with different processes such as industrial, construction and transportation sectors. In terms of decarbonization methods, such technologies can be divided into the following two directions: Firstly, energy consumption efficiency per unit of output can be raised through structural adjustment, product substitution, process re-engineering and behavioral change to reduce energy consumption. Secondly, carbon emissions can be cutted by reducing the direct use of fossil fuels in the end-use energy consumption process through fuel substitution and electrification. Existing estimates point to great potentials for improving energy efficiency in various sectors. For instance, energy efficiency still has the potential to increase by 50% in the transportation sector and by 10% to 20% in industrial sectors (Energy Transition Commission, 2020).

Negative emission technologies may increase flexibility for electric power systems based on renewable energies. Such technologies include agricultural and forest carbon sequestration, carbon capture, utilization and storage (CCUS), bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS), whose economic performance is subject to the feasible and

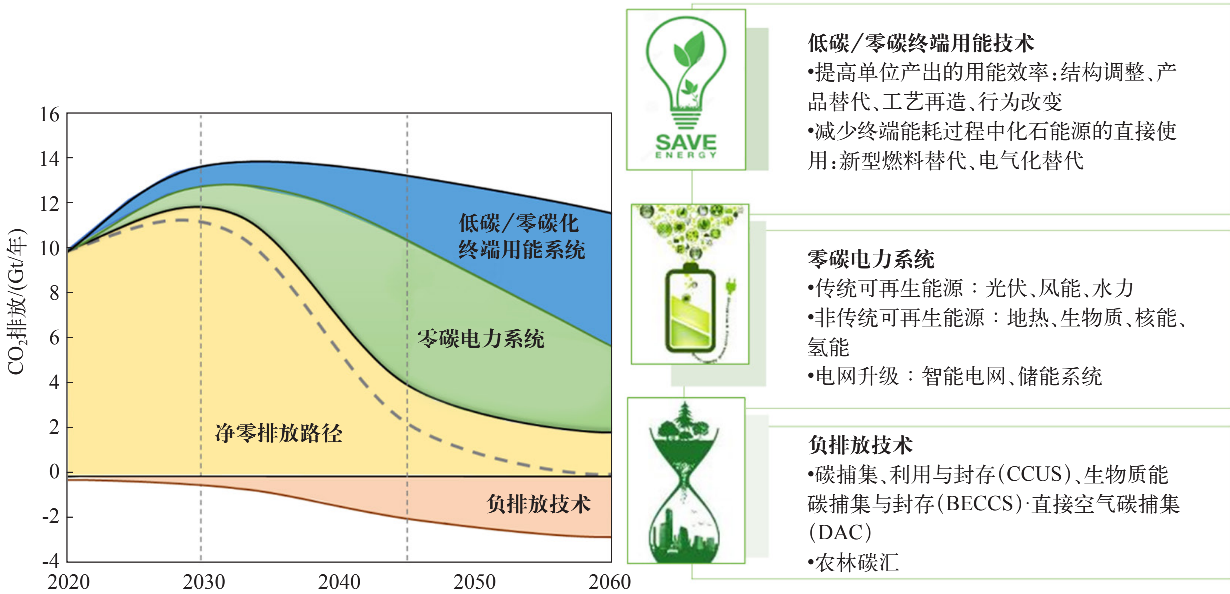

图2 碳中和愿景下的CO_2净零排放技术体系

资料来源：王灿和张雅欣（2020）；王灿等（2021）。

网，从而完成能源利用方式的零碳化。

低碳/零碳终端用能技术往往集中于减排成本曲线最左端，具有减排成效显著、减排成本较低、减排收益显著等特点。该类技术的应用领域涉及工业、建筑、交通等重要的能耗部门。其中，工业领域可细分为钢铁、水泥、化工等，因此该类技术涵盖范围较广，门类众多，工艺上存在较大差异。但从减碳方式上，该类技术可以分为两个方向：一是通过结构调整、产品替代、工艺再造、行为改变来提高单位产出的用能效率、减少能源消费；二是通过新型燃料替代、电气化替代来减少终端能耗过程中化石能源的直接使用进而减少碳排放。例如根据已有研究测算，目前各应用领域的能源效率仍有较大提升空间，例如交通部门能效仍有可能提高50%，工业部门能效提高潜力可达到10%～20%左右（能源转型委员会，2020）。

负排放技术可为以可再生能源为主的电力系统增加灵活性，这类技术主要包括农林碳汇，碳捕获、利用与封存（Carbon Capture, Utilization and Storage，CCUS），生物能源和碳捕获与封存（Bioenergy with Carbon Capture and Storage，BECCS）以及直接空气碳捕集与封存（Direct Air Carbon Capture and Storage，DACCS），其经济性将取决于各地区可行且安全的碳封存有效容量的大小（能源转型委员会，2020）。

（二）零碳电力系统

能源系统尽快实现零碳化是我国碳中和愿景的必要条件之一，这对零碳电力系统提出了更高要求。工业、交通、建筑等多部门实现碳中和均依赖零碳电力系统，在各部门全面电气化的基础上，全经济部门需要普遍使用零碳的电力，完成能源系统从碳密集型化石燃料向清洁能源的转变，从而实现能源利用方式的零碳化

secure effective capacity of carbon sequestration in various regions (Energy Transition Commission, 2020).

3.2 Zero-Carbon Electric Power Systems

As a necessary condition for China to achieve its vision of carbon neutrality, decarbonization in energy systems puts forth higher requirements on zero-carbon electric power systems. Carbon neutrality in sectors like industry, transportation and construction is dependent on zero-carbon electric power systems. On the basis of complete electrification, all sectors need to employ zero-carbon electric power for the transition from carbon-intensive fossil fuels to clean energies to decarbonize the use of energy (Wang and Zhang, 2020). In the three stages of carbon peak, plateau and neutralization, new-energy technologies will play an important role. In the carbon peak period before 2030, China needs to apply energy efficiency improvement, emission abatement and renewable energy technologies; in the plateau period before 2050, China's carbon emission abatement will focus on the rollout and commercial application of decarbonized and zero-carbon technologies, as well as the complete substitution of decarbonized fuels, raw materials and processes; in the following period, decarbonization and zero-carbon technologies will be further rolled out for achieving the neutralization target by 2060. The vision of carbon neutrality will trigger an energy revolution, reshape the energy industry, and replace fossil fuels such as coal in the energy system with new low-carbon energies. Meanwhile, China's energy system will transition towards green, low-carbon, secure and efficient performance and achieve electrification, smart and network-based operations.

The zero-carbon electric power system encompasses three components: zero-carbon power source, energy storage, and power grid. Under the carbon neutrality vision, new-type electric power systems include zero-carbon power generation based on renewable energies such as Photovoltaic (PV), wind and hydropower, zero-carbon power consumption based on mass energy storage technologies, and zero-carbon power distribution through smart grid. Furthermore, strategic emerging industries such as new energy vehicles, the internet of things (IoT) and artificial intelligence (AI) will jointly support the secure and stable operation of energy systems.

Zero-carbon power technologies lie at the heart of zero-carbon power systems. Mature technologies include wind, PV, hydropower, biomass, geothermal, tidal, and nuclear energies. Wind and PV systems are relatively mature zero-carbon power generation technologies with positive employment, regional environment and health benefits with broad public acceptance. With increasing cumulative installed capacity, wind and PV systems have become commercially competitive with conventional thermal power, offering superior cost and technological performance.

As a mature technology with high energy density and superior economic performance, hydropower plays a pivotal role in the low-carbon transition of China's energy system (Energy Transition Commission, 2020). However, China's hydropower resources are limited and uneven. With the construction of hydropower stations in downstream regions, future hydropower resources to be developed in China will be concentrated in the mid- and upstream regions of Sichuan, Yunnan, Qinghai and Tibet (CICC, 2020).

Nuclear energy technologies include heavy nuclear fission in the commercialization stage and light nuclear fission still under experiment. Compared with PV or biomass power generation, nuclear power offers greater emission reduction benefits (Zwaan, 2013; International Energy Agency, 2015) and employment dividends. On the other hand, nuclear power is faced with challenges in supply chains, economic performance, nuclear safety, political factors, and public acceptance.

Geothermal resources include hot springs, shallow geothermal energy developed with heat pump technology, geothermal fluid extracted through artificial drilling, and geothermal resources in dry-heat rock bodies. The benefits of geothermal energy include abundant geothermal reserves, broad distribution, stable and reliable performance and high energy utilization factor. Yet geothermal energy remains in the

（王灿和张雅欣，2020）。在我国实现碳中和的达峰期、平台下降期及中和期三个阶段，新能源技术均将承担重要角色。2030年前达峰期需推广节能减排技术、可再生能源技术；2050年前平台下降期主要减排手段集中为脱碳零碳技术规模化推广与商业化应用，脱碳燃料、原料和工艺全面替代；2060年前中和期中，脱碳、零碳技术将进一步推广，全面支撑碳中和目标实现。碳中和愿景将引发能源革命，重构能源产业，以低碳为核心，能源系统中的煤炭等化石能源将逐步被新能源取代，能源系统向绿色、低碳、安全、高效转型，实现电气化、智能化、网络化、低碳化。

零碳电力系统包括三个部分：零碳电源、储能和电网。碳中和愿景下的新型电力系统包括以可再生能源（光伏、风能、水力等）为核心的零碳电力生产端、以规模化储能技术为支撑的零碳电力使用端和以智能电网为核心的零碳电力分配端。同时，新能源汽车、物联网、人工智能等多个战略新兴技术产业也将共同支撑能源系统安全稳定运行。

零碳电源技术是构建零碳电力系统的核心。目前比较成熟的技术包括风力、光伏、水力、生物质能源、地热和潮汐能、核能等发电技术。风电和光伏发电是较为成熟的零碳电源技术，具有正面的就业、局地环境和健康效益，以及相对较高的技术成熟度和公众接受度，发电成本已随累积装机容量的增加而下降至与传统火电相比具有商业竞争力的水平，在经济成本和技术水平上均具有较为明显的优势。水电具有技术成熟度较高、能源密度高以及经济性优良的特点，长期以来在我国能源系统的低碳转型中发挥着重要作用（能源转型委员会，2020）。然而，水电资源相对有限，随着各流域的下游地区首先完成开发，未来可开发的水电资源主要集中在四川、云南、青海、西藏等中上游地区，开发造价成本持续提升，发展潜力有限（中金公司，2020）。核能技术包括已达到实用阶段的重核裂变和尚处于研究试验阶段的轻核聚变。与光伏或生物质发电相比，核电具有更加显著的减排效益（Zwaan，2013；国际能源署，2015）和更加积极的就业红利；但核电也面临着来自供应链建设、经济性、核安全、政治因素、公众接受度等多方面的挑战。地热资源包括温泉、通过热泵技术开采利用的浅层地热能、通过人工钻井直接开采利用的地热流体以及干热岩体中的地热资源等，具有储量丰富、分布较广、稳定可靠、能源利用系数高的优点，但是同时也受到资源分布不均衡、勘查程度较低、核心技术欠成熟和政策管理体制不成熟的制约，总体上还处于起步阶段。生物质能源的来源包括污泥、农林残留物、能源作物、多年生木质纤维素植物等（国际能源署，2017）。生物质能技术相对成熟，但废弃物生物质总量偏低，而生物质能源作物的大规模发展又可能带来占用土地资源、增加水资源压力等生态风险。

由于未来零碳新能源的分布式特性，储能系统、电网及电源结构将会发生根本性的变革。着眼于2060年碳中和愿景，氢储能、氨储能、电化学储能三种储能方式被认为是未来需要持续发展的技术。不同储能方式在储能时长、储能效率、储能规模上各有所长。对短期与低容量输电来说，电池储能系统是最快与方便的办法，但是如果要长期储电或是大规模应用，氨气储能系统可能更有效。电网的调度模式和能力将极大程度地影响能源的利用效率，催生了电网智能化调度、智慧能源服务、电网智能控制的出现。电网系统需要从传统聚焦稳定性、可靠性、坚强性的集中性网络，向更加智能、灵活的分布式网络进化。

early stage of development due to uneven resource distribution, insufficient exploration, technological immaturity, and imperfections in policy and administrative systems.

Biomass energy sources include sludge, agricultural and forest residues, energy crops, and perennial lignocellulose (International Energy Agency, 2017). Although biomass technology is more mature, the aggregate amount of waste biomass is low, and biomass crops may occupy arable land and increase water scarcity, among other ecological risks.

Given the distributed attribute of zero-carbon new energies, fundamental changes will occur in energy storage, power grid, and energy mix. As far as the carbon neutrality vision for 2060 is concerned, hydrogen, ammonia and electrochemical energy storage solutions are considered as technologies with great potentials. Different energy storage methods have distinctive advantages in terms of energy storage duration, efficiency and capacity. For short-term and low-capacity power transmission, batteries are the most efficient and convenient energy storage solution. Yet ammonia energy storage could be more effective for long-term energy storage or mass application. Power grid dispatching and capacity will greatly influence the efficiency of energy use, giving rise to smart power grid dispatching, smart energy services, and smart power grid control. Power grid system needs to evolve from traditional centralized grid focusing on stability, reliability and resiliency to smarter and more flexible distributed grid.

3.3 Low-Carbon and Zero-Carbon End-use Energy Consumption Technologies

In addition to low-carbon energy sources, carbon neutrality also requires decarbonization efforts on the end-use consumption side. Low-carbon and zero-carbon end-use energy consumption technologies fall into the five categories of energy efficiency, electrification, fuel substitution, product substitution and process re-engineering, as well as a circular carbon economy.

Energy-efficient technologies are applicable to almost all end-use energy consuming sectors. Such technologies may help achieve decarbonization by raising energy efficiency and adjusting structure and ways of life without affecting living standards. According to the International Energy Agency (IEA), the construction sector may contribute over 40% to global energy efficiency improvement (International Energy Agency, 2019). Energy efficiency in the transportation sector is achieved by using carbon-abatement technologies for traditional fuel vehicles, improving transportation structure, and promoting clean energies for transportation equipment and infrastructure. Industrial production process involves a broad range of energy efficiency technologies, most of which are related to heat exchange process optimization, equipment efficiency improvement, and digitalization.

Electrification is a key impetus and tool for achieving carbon neutrality in the energy system in coordination with low-carbon or zero-carbon energy supply. According to the estimates, about 50% of decarbonization of greenhouse gas emissions from human activity is achieved through the use of clean electric power, including the electrification of transportation system, the production of green hydrogen energy, and the electrification of various industrial processes (Sachs, 2021). The electrification of transportation offers potentials for access to frontier technologies such as 5G communication, artificial intelligence (AI), big data, and supercomputing. Such technologies, once applied in the cooperative vehicle-infrastructure system (CVIS), will become important technological trends for decarbonization in the transportation sector. With electrification basically completed for the construction sector, lighting, refrigeration and home appliances, heat pump heating will become a critical area for the early-stage deployment of electrification technologies. By 2030, the global penetration of household heat pump heating facilities will reach 22%, reducing carbon emissions in the construction sector by 50% (International Energy Agency, 2020).

New fuel substitution is an essential technology for decarbonization in end-use energy-consuming sectors. Hydrogen energy may replace fossil fuels to reduce GHG emissions by a maximum of 20%. For instance, the combination between hydrogen and fuel cells provides a solution for long-term

（三）低碳、零碳终端用能技术

实现碳中和不仅需要能源来源的低碳化，也需要终端使用侧做出脱碳努力。低碳、零碳的终端用能技术分为五大类：节能、电气化、燃料替代、产品替代与工艺再造，以及碳循环经济。

节能技术几乎适用于所有终端用能部门，这类技术可以通过提高能效、调整结构和转变生活方式，在保证人们生活水平的前提下实现脱碳。根据国际能源署的估算，建筑行业可以通过高效烹饪、高效供冷供热技术、低碳设计等方法对全球能源效率提升做出超过40%的贡献（国际能源署，2019）。交通部门的节能主要包括传统燃油载运工具的降碳技术、运输结构的优化调整、运输装备和基础设施用能清洁化等。工业生产过程中节能技术涉及范围较广，相关技术繁多，总体上是通过实现换热流程优化、设备效率提升、数字化转型来提高系统能源效率。

电气化是实现碳中和的重要推动力，是配合低碳或零碳能源供应实现能源系统碳中和的重要工具。据估算，中国当前人类活动温室气体排放量的脱碳约50%将通过使用清洁电力来实现，包括交通运输系统的电气化、生产绿色氢能和各种工业流程的电气化（Sachs，2021）。交通电气化为5G通信、人工智能、大数据、超算等前沿技术的接入提供了空间，未来这些前沿技术与车路协同系统的融合发展将成为帮助交通部门脱碳的重要技术趋势。在建筑部门，照明、制冷、家用电器等已基本实现电气化，热泵供暖将成为电气化技术早期部署的关键领域。预计到2030年，全球家庭热泵取暖使用比例将提高到22%，这将为建筑部门减少50%的碳排放（国际能源署，2020）。

新型燃料替代是终端用能领域实现零碳化必不可少的技术。氢能可以用于燃料替代以应对减排难度最大的20%温室气体排放，例如交通业可利用氢+燃料电池解决长距离运输问题，工业生产可以利用氢解决钢铁和化工业的高排放问题，建筑业可以通过在天然气网掺混氢气降低燃气供热碳排放（Renssen，2020）。生物质从全生命周期的角度看具有近零碳排放的属性，具有良好的气候效应，在北方农村清洁供暖、交通运输，以及水泥、钢铁、化工等工业领域均有广阔的应用空间。

产品替代与工艺再造是适用于工业部门的低碳终端用能技术。产品替代主要体现在混凝土和钢铁等建筑材料方面。例如，煅烧黏土和惰性填料是减少水泥熟料含量的最被广泛使用的方法，据估计，通过该种方法每年可减少水泥行业6亿吨CO_2的排放量。另外，通过智能化、新技术、新装备及具有颠覆性的节能工艺等工业流程再造技术研发，可降低工业生产的能耗，提高能源和资源利用率，有效降低碳排放。

循环经济是以再生和恢复为基础的经济模式，其目标是让经济增长不再依赖有限的资源，转而打造更加坚韧、可持续的经济社会系统。循环经济策略在工业领域有巨大的减排潜力，这类策略包括在产品设计源头避免废弃、重复使用产品和部件、材料再循环等。据测算，若在水泥、钢铁、塑料和铝四大关键工业领域运用循环经济策略，则能在2050年前减少其40%的二氧化碳排放量，约为37亿吨（能源转型委员会，2018）。循环经济策略不仅具有减排潜力，也具有较高的成本效益。通过共享商业模式、高质量回收利用、在建筑施工过程减少废弃等举措有望实现负减排成本，即在减排的同时创造收益（Material Economics，2018）。

transportation; hydrogen energy offers a solution to high GHG emissions in the steel and chemical sectors; in the construction sector, carbon emissions from fuel gas heating can be reduced by mixing hydrogen into natural gas (Renssen, 2020). From a lifecycle perspective, biomass has near-zero carbon emissions and positive climate effects with broad potentials for application in clean heating in northern rural China and industrial sectors such as transportation, cement, iron and steel, and chemical sectors.

Product substitution and process re-engineering are low-carbon end-use energy consumption technologies applicable to industrial sectors. Product substitution has broad applications in concrete, steel, and other building materials. For instance, calcined clay and inert filler are the most extensive options for reducing cement clinker content, and is estimated to reduce 600 million tons of CO_2 emissions in the cement industry each year. Moreover, smart features, new technologies, new equipment and disruptive energy-efficient processes may reduce energy consumption in industrial production, increase energy and resource efficiency, and reduce carbon emissions.

Circular economy is an economic mode based on regeneration and restoration aimed at weaning economic growth dependence from limited resources and fostering more resilient and sustainable socio-economic systems. With great emission abatement potentials in the industrial sectors, a circular economy prevents waste in product design and recycles products, components and materials. Circular economy strategies are estimated to cut CO_2 emissions by 40% or 3.7 billion tons by 2050 in the four critical industrial sectors of cement, steel, plastics, and aluminum (Energy Transition Commission, 2018). With cost-effective business modes, high-quality recycling and the reduction of waste in the construction process, circular economy strategies may also achieve negative emission abatement cost, i.e. create revenues from emissions abatement (Material Economics, 2018).

3.4 Negative Emission Technologies

Also known as carbon dioxide removal (CDR), negative emission is a critical technology for keeping global temperature rise below 1.5℃. With the proposition of the carbon neutrality concept and the broadening perspective of the Earth's carbon cycle, negative emission technologies encompass all technical pathways with negative carbon effects, primarily terrestrial carbon sinks and CCUS technologies.

As an important nature-based solution (NbS), terrestrial carbon sinks include forest, grassland, farmland and wetland carbon sinks. Forest carbon sink is achieved by increasing and improving forest stock. Specific methods include protecting forests, closing hillsides for afforestation, forest tending, improving forest stand, and promoting sustainable forests. Grassland carbon sink requires grassland protection and the prevention of overgrazing by establishing long-term mechanisms for grassland ecological compensation and returning grazing land to grassland. Farmland carbon sink is achieved by raising farmland productivity and improving soil quality for carbon absorption. In particular, GHG absorption and sequestration in soil can be enhanced by increasing the content of organic matters in farmland soil. Wetland carbon sink can be achieved by increasing wetlands and conducting ecological restoration. Specific methods include the protection, ecological recovery, restoration and expansion of wetlands.

CCUS technology has been considered as the only solution for the clean use of fossil fuels. The principal mechanism of CCUS technology is to block CO_2 emissions from fossil fuels from entering the atmosphere. Under the carbon neutrality target, fossil fuels as a share in the energy mix face a sharp decline, and only a small portion will be retained in the electric power system to stabilize generation and support sectors where decarbonization is challenging. For those fossil fuels to achieve near zero emissions, they should to be matched with CCUS technology. As a technology for the low-carbon use of fossil fuels on a mass scale, CCUS is an indispensable technology for carbon neutrality and energy security. Biomass energy, BECCS and DACCS are negative emission technologies based on traditional

（四）负排放技术

负排放技术又称为碳移除技术（Carbon Dioxide Removal, CDR），是实现"1.5℃目标"不可或缺的关键技术。随着碳中和概念的提出和地球碳循环宏观视角的扩大，负排放技术也逐渐被用来总括所有能够产生负碳效应的技术路径，主要包括陆地碳汇和CCUS技术。

陆地碳汇是重要的基于自然的解决方案（Nature-based Solutions，NbS），按照介质分为林地、草原、农田和湿地碳汇。林地碳汇主要通过提升森林蓄积量和森林改造进行提升，具体手段包括森林保护、封山育林、森林抚育、林分改造、森林可持续经营等森林减排增汇技术措施；草原碳汇提升需要保护草原和防止过度开垦放牧，包括建立草原生态补偿的长效机制、实施退牧还草工程；农田碳汇主要通过提高农田生产率和改善土壤质量实现吸收固定碳的功能。特别是提升农田土壤有机质含量，能够增强土壤对温室气体吸收和固定；湿地碳汇的增加主要通过湿地的总量增加和生态恢复实现，主要方式包括保护湿地、湿地生态恢复与重建、增加湿地面积等。

CCUS技术一直是被认为是实现化石能源真正清洁利用的唯一解决方案。CCUS技术的主要原理是阻止各类化石能源在利用中产生的CO_2进入大气层。在碳中和目标下，化石能源在能源消费体系中面临大幅度下降，最终将保留一定的占比以支持电力系统稳定、难脱碳工业部门和其他部门的应用等。这部分化石能源的利用需要匹配CCUS技术以保证其净零排放的目标。CCUS技术作为一项可以实现化石能源大规模低碳利用的技术，是未来我国实现碳中和与保障能源安全不可或缺的技术手段。生物能源、BECCS技术和DACCS技术是以传统的CCUS技术为基础发展而来的负排放技术，BECCS是通过生物能源在生长过程中的光合作用捕集和固定大气中的CO_2，DACCS则是利用人工制造的装置直接从空气中捕集CO_2。由此可见，相比传统的CCUS技术，BECCS和DACCS能够实现大气中CO_2浓度的降低，是真正实现"负排放"的技术手段，且捕集装置的分布地点可以更加灵活便捷。

无论是BECCS，还是DACCS，二者的大规模发展以CCUS技术的成熟商业化应用为基础，当前还处于示范阶段，技术成本依旧是制约其发展的重要因素。DACCS当前还处于基础研究阶段，其成本约在134~345美元/吨CO_2（国际能源署，2020），但也可能是CO_2去除潜力最高的负排放技术。相比DACCS，BECCS技术在价格上更具有落地潜力，其成本在15-85美元/吨CO_2（国际能源署，2020）。同时，广泛存在的生物能源原料也为BECCS的快速发展提供了现实可能。不过BECCS的广泛部署依然依赖于CCUS技术的大规模成熟应用，而当前制约CCUS技术的成本因素自然也成为BECCS技术快速发展的限制因素之一。

四、重点行业碳中和路径

（一）电力部门

中国电力部门的减排脱碳是中国实现2030年碳达峰和2060年碳中和目标的关键部分和重要行动抓手，也对全球气候变化温升控制目标的实现具有重要价值。

在碳中和路径下，电力系统面临着重大的结构性调整，从当前以高温室气体排放的化石燃料为基础的电

CCUS technology. While BECCS captures and sequestrates CO_2 from the atmosphere through photosynthesis, DACCS utilizes man-made devices to capture CO_2 directly from the air. Compared with traditional CCUS technology, BECCS and DACCS may reduce CO_2 concentration in the atmosphere and qualify as “negative emission” technologies in real earnest, allowing for carbon capture devices to be located more flexibly and conveniently.

For BECCS or DACCS, their mass deployment is predicated upon the commercialization of CCUS technology, which remains in the demonstration stage and too costly to be deployed on a mass scale. DACCS is in the stage of fundamental research with a cost of about 134-345 US dollars/ton of CO_2 (International Energy Agency, 2020). It is also possible to be the negative emission technology with the greatest potential for CO_2 removal. Compared with DACCS, BECCS is more feasible in terms of cost, which is 15 to 85 US dollars/ton of CO_2 (International Energy Agency, 2020). Biofuels that exist extensively also provide possibilities for rapid BECCS development. Yet the mass deployment of BECCS is dependent on that of CCUS, whose high cost poses a key barrier.

4. Carbon Neutrality Pathway for Key Sectors

4.1 Electric Power Sector

According to Wang and Zhang (2021), it takes the following three stages for the electric power sector to achieve carbon neutrality:

Stage 1 (2021-2030): The main goal is to achieve carbon peak in the electric power sector. Priorities include: On the power generation side, we should reduce renewable energy tariffs to a level below benchmark electricity tariffs by reducing the cost of renewables such as PV and wind power generation, steadily develop nuclear energy and hydropower, peak the demand and consumption of coal and other fossil fuels, and peak carbon emissions from the electric power system; remodel thermal power facilities to stabilize power generation at a lower cost; standardize renewable power generation and reduce wind and PV curtailment due to incompatibility. On the power transmission side, we should continue to build ultra-high-voltage power grid, enhance power grid transmission, develop flexible power grid technologies to match renewable energy synchronization capabilities, step up energy storage R&D, and develop smart demand-side response management systems. In this stage, non-fossil fuels as a share of China’s power generation will increase from 32% in 2020 to 46%-53% by 2030, and the installed capacity of non-fossil fuels will increase from 43% in 2020 to 65%-69% by 2030 (CICC, 2020; the Rocky Mountain Institute and Energy Transitions Commission, 2021). Prevailing research indicates that the power system is more likely to reach carbon peak before 2030 and even 2025 (the Energy Foundation, 2020; Institute for Climate Change and Sustainable Development at Tsinghua University, 2020).

Stage 2 (2031-2045): The main goal for this stage is to bring about a rapid decline in carbon emissions from the power sector. On the generation side, priority should be given to increasing renewables as a share of China’s power generation and installed capacity, generating electric power from non-fossil fuels to meet increasing power demand, and substituting the stock of fossil fuels with non-fossil fuels. On the transmission side, priority should be given to developing flexible and mature power grid technologies while increasing non-fossil fuels as a share of China’s total installed capacity, developing technologies for two-way smart generation and user demand management, and creating new business modes. In this stage, the application of energy storage technologies on the demand side will sharply reduce the cost of energy storage and keep power generation and energy storage cost for renewables below benchmark electricity tariffs (CICC, 2020) to speed up the deployment of renewables. By 2045, power generation from non-fossil fuels will increase to about 88%, and the installed capacity will reach 94% or so (CICC, 2020). Carbon emissions from the power sector will sharply decrease with the increasing share of renewables.

Stage 3 (2046-2060): The main goal for this stage is to achieve carbon neutrality in the power

力生产结构，逐渐调整为以零碳排放的可再生能源为主体，配合高灵活性的电力传输供应网络，构建现代化新型零碳电力系统。随着碳中和路径下工业、交通、建筑等能源需求部门电气化水平的不断提高，未来经济社会对零碳电力的需求将迅猛扩张，这也将成为中国电力部门低碳转型的新挑战和新机遇。

根据王灿和张九天(2021)，电力部门碳中和的三个阶段如下：

第一阶段(2021～2030年)，主要目标是实现电力部门的碳排放达峰。主要工作：在电力生产侧，光伏和风电等可再生能源成本持续下降，新能源发电低于标杆电价水平，核能、水电稳步发展，煤炭等化石能源发电需求量和使用量达峰，电力系统碳排放达峰；针对火力发电进行灵活性改造，使其具有以更低的成本为电力系统稳定提供辅助支持的能力；规范可再生能源电力生产标准，减少因规范不匹配导致的弃风弃光问题。在电力传输供应侧，持续推进特高压电网建设，增强电网的传输能力，推进灵活性电网技术的研发，与可再生能源并网能力相匹配，加大力度推进储能技术的研发，推进智能化需求侧响应管理系统的研发。在此阶段中，非化石能源发电量占比将从2020年的32%增长至2030年的46%～53%，非化石能源装机量将从2020年的43%增长至2030年的65%～69%(中金公司，2020；落基山研究所和能源转型委员会，2021)。当前主要研究认为，电力系统有较大的可能性在2030年前甚至是2025年左右实现碳达峰(能源基金会，2020；清华大学气候变化与可持续发展研究院，2020)。

第二阶段(2031～2045年)，主要目标是实现电力部门的碳排放的快速下降。主要工作：在电力生产侧，可再生能源的发电量和装机占比不断增加，通过非化石能源发电补足新增电力需求增量，并逐渐通过非化石能源发电加速替代已有化石能源产能存量；在电力传输供应侧，灵活性电网技术基本成熟，与非化石能源高比例装机发展速度相匹配，智能化的生产与用户需求双向管理技术基本成熟，新商业运营模式出现。在此阶段将实现电力需求侧储能技术的率先应用，期间储能成本将显著下降，并实现可再生能源电力生产端加储能成本低于标杆电价水平(中金公司，2020)，加速可再生能源的部署发展。到2045年，非化石能源发电量将增长至88%左右，装机量将达到94%左右(中金公司，2020)，电力部门的碳排放量随着高比例可再生能源的应用而显著下降。

第三阶段(2046～2060年)，主要目标是实现电力部门的碳中和。主要工作：通过长期发展，氢能生产技术成本达到具有竞争力的水平，随着以工业为主的电力需求侧部门对氢能使用的增加，电解制氢所需要的电力供给进一步增长。因此，从电力生产侧，非化石能源发电技术随着电力需求的增加进一步增长，并在上一阶段的基础上进一步完成必要的化石能源发电的存量替代；从电力传输供应侧，灵活性电网技术完全成熟，智能化的电力生产与消费匹配技术完全成熟并广泛应用于电力系统管理调度，电力部门完全实现碳中和。现有研究认为，电力部门有很大的可能性在2050年左右实现零碳排放(能源基金会，2020；清华大学气候变化与可持续发展研究院，2020)，并于2060年利用生物质能等技术实现电力部门的负碳排放，从而促进全经济系统于2060年实现碳中和(能源基金会，2020)。到2050年，电力部门的发电量将达到11万亿～18万亿千瓦时，其中非化石能源发电量占比约80%～94%，化石能源发电量占6%～20%。

提高能源需求部门的电气化水平，并确保电力生产来源于零碳资源，是现有研究公认的实现碳中和目标的关键。因此，电力系统的低碳转型同时面临着零碳能源替代的结构性调整、高电气化水平的电力需求扩张

sector. In this stage, priority should be given to long-term development for hydrogen production cost to reach a competitive level. On the power demand side, with increasing hydrogen consumption primarily for industrial production, electrolytic hydrogenation requires a further increase in power supply. From the power generation side, non-fossil fuel power generation technologies will further increase with rising power demand and further replace the stock of generation capacities from fossil fuels where necessary. On the supply side of power transmission, flexible power grid technologies will become fully mature and smart power production and consumption technologies will be extensively applied in power system management and dispatching for achieving carbon neutrality in the electric power sector. Studies suggest that the electric power sector is highly likely to achieve zero carbon emissions by around 2050 (the Energy Foundation, 2020; Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD), 2020). Technologies such as biomass will be deployed to achieve negative carbon emissions from the power sector in support of economy-wide carbon neutrality by 2060 (the Energy Foundation, 2020). By 2050, power generation from the power sector will reach 11 trillion-18 trillion kWh, of which non-fossil fuels account for 80% to 94% and fossil fuels make up for the rest 6% to 20%.

Studies have widely recognized the importance of electrification to carbon neutrality in energy-using

Table 1: Existing Forecasts on China's Power Generation and Structure under the Vision of Carbon Neutrality

Year	Power generation (trillion kWh)	Share of non-fossil fuels (%)	Share of coal-fired power generation (%)	Source
2050	13.1-14.3	90.7-90.9	6.3-6.5	Integrated Report Drafting Team of Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD) (2020)
2050	-	80	12	Boston Consulting Group (BCG) (2020)
2050	15	93	7	Energy Transition Commission (ETC) (2020)
2050	11.8	90	10	World Resource Institute (WRI) (2020)
2050	13	80	-	CNPC Research Institute of Economics and Technology (2020)
2050	15	-	-	Rocky Mountain Institute (RMI) and the Energy Transition Commission (ETC) (2021)
2050	16	-	-	Global Energy Interconnection Development and Cooperation Organization (GEIDCO) (2021)
2060	17	-	-	Global Energy Interconnection Development and Cooperation Organization (GEIDCO) (2021)

Source: Collected from literature and publicly available information.

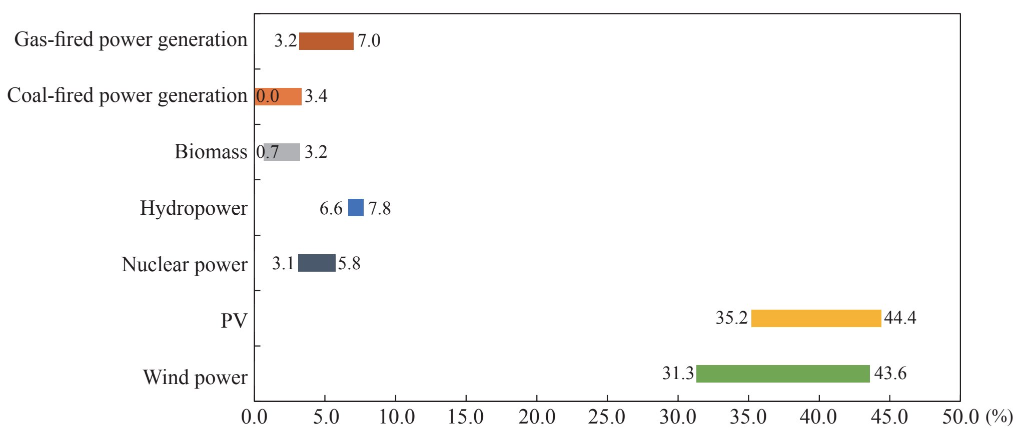

Figure 3: Proportion of Installed Capacities of Key Power Sources under the Carbon Neutrality Vision for 2050

Source: Energy Transition Commission (ETC), 2020.

两方面的挑战，而这也被全球越来越多的国家视为碳中和愿景下的新需求和新机遇。已有研究基于不同的情景假设，预测了中国碳中和路径下电力生产的规模和机构构成，如表1所示。研究结果普遍认为，中国在碳中和愿景下2050年的发电量在11万亿～18万亿千瓦时左右，相较于2020年中国总发电量7.6万亿千瓦时提高了0.4～1.4倍，而其中80%将用于建筑、轻型公路运输、铁路运输和工业等部门直接电气化的终端消费，20%用于生产氢气、合成氨等以电力为基础的燃料生产（能源转型委员会，2020）。

图3展示了已有研究在碳中和图景下各类电源装机容量的预估结果，其中风电的装机容量占比将从当前的12.8%增长至31.3%～43.6%，约为23.1万亿～27.4万亿千瓦，是当前装机容量的9倍左右。光伏发电装机占比将从当前的11.5%增长至35.2%～44.4%，为22.1万亿～35.5万亿千瓦，是当前装机容量9～14倍。核电装机容量比例将从当前的2.3%增长至3.1%～5.8%，约为2.3万亿～3.3万亿千瓦，是当前装机容量的4.6～6.6倍。水电装机将增长至6.6%～7.8%，为4.2万亿～5.8亿千瓦，是当前装机容量的1.5倍左右。在碳中和图景下，非化石能源发电装机将显著增加，具有广阔的发展前景和投资机会。

表1 已有研究对碳中和图景下发电量及其结构的预测

年份	发电量（万亿千瓦时）	非化石能源占比（%）	煤电占比（%）	数据来源
2050	13.1～14.3	90.7～90.9	6.3～6.5	清华大学气候变化与可持续发展研究院项目综合报告编写组（2020）
2050	—	80	12	波士顿咨询公司（2020）
2050	15	93	7	能源转型委员会（2020）
2050	11.8	90	10	世界资源研究所（2020）
2050	13	80	—	中国石油经济技术研究院（2020）
2050	15	—	—	落基山研究所和能源转型委员会（2021）
2050	16	—	—	全球能源互联网发展合作组织（2021）
2060	17	—	—	全球能源互联网发展合作组织（2021）

资料来源：根据文献和公开资料整理。

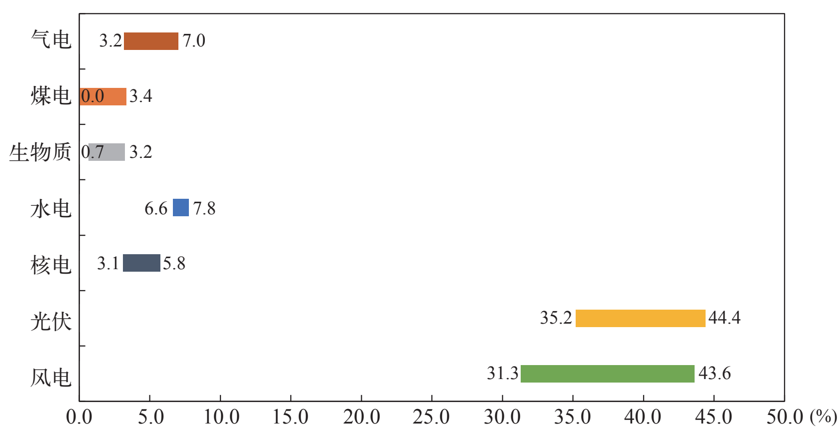

图3 2050年碳中和图景下主要电源装机容量比例

资料来源：Energy Transition Commission（2020）.

sectors and zero-carbon power generation. As such, the low-carbon transition of the power sector is faced with dual challenges of structural adjustment for zero-carbon energy substitution and rising demand for highly electrified power consumption. Those challenges are increasingly seen as new requirements and opportunities under the vision of carbon neutrality. With different scenarios, studies have forecasted the scale and composition of China's power generation under the pathway of carbon neutrality, as shown in Table 1. It is generally forecasted that China's power generation will reach 11 trillion-18 trillion kWh by 2050 under the vision of carbon neutrality, which is an increase of 0.4-1.4 times compared with China's total power generation of 7.6 trillion kWh in 2020, and 80% of such power generation will be used for electrification in construction, light road transportation, railway transportation and industrial sectors, and 20% will be used for the production of fuels such as hydrogen and synthetic ammonia (Energy Transition Commission, 2010).

Figure 3 shows the estimated installed capacities of various power sources under the carbon neutrality vision. Among them, the share of installed wind capacity will increase from the current 12.8% to 31.3%-43.6% to reach 2.31 billion to 2.74 billion kWh, which is about nine times the current installed capacity. The share of installed PV capacity is expected to rise from the current 11.5% to 35.2%-44.4% to reach 2.21 billion to 3.55 billion kW, which is nine to 14 times the current installed capacity. The share of installed nuclear capacity will rise from the current 2.3% to 3.1%-5.8% to reach 230 million to 330 million kW, which is 4.6-6.6 times the current installed capacity. The share of installed hydropower capacity will increase to 6.6%-7.8% to reach 420 million to 580 million kW, which is about 1.5 times the current installed capacity. Under the carbon neutrality vision, the installed capacity of non-fossil energies will increase sharply, giving rise to broad development potentials and investment opportunities.

Currently, the zero-carbon transition pathway for the electric power sector has become clear. However, necessary supporting technologies are still in R&D or pre-R&D stage. Achieving the carbon neutrality vision calls for technological breakthroughs. As such, attention should be focused on strategically important technologies even though they are currently immature and costly. The stability of electric power system is highly dependent on power grid, energy storage, distributed renewables and demand-side response technologies. Compared with renewables-based generation technologies that are already competitive, the cost of applying the above-mentioned technologies remains exorbitant, and some technologies are still in R&D stage without mature applications. Secure and stable power supply is vitally important to the realization of zero-carbon electric power systems and represents a priority and challenge in ongoing R&D programs.

4.2 Industrial Sector

As major carbon emitters, industrial sectors face complexities and difficulties for decarbonization with a diverse range of emission abatement technologies. Compared with developed countries, China lags behind in some critical low-carbon technologies and needs to speed up its R&D process. The share of industrial carbon emissions in China's total man-made carbon emissions increased before decreasing and currently stands at around 40%, making industrial sectors the second-largest source of carbon emissions in China. Table 2 describes China's industrial carbon emissions abatement pathways as revealed by different studies. Most studies suggest that China's industrial emissions will remain positive in target years. In the scenario of near carbon neutrality, positive industrial carbon emissions are generally believed to be around 0 to 1.5 billion tons, and cement and steel sectors will continue to be major emitters with 300 million to 400 million tons of carbon emissions, respectively. Under the condition of zero carbon emissions, industrial sectors still need to rely on negative carbon emissions from other sectors such as energy and agricultural and forest carbon sequestration to offset remaining industrial carbon emissions.

The following priorities warrant great attention for achieving industrial carbon neutrality objectives. A key step for carbon neutrality in China's industrial sectors is to adjust the energy mix. Specifically,

当前，电力部门零碳转型路径已经较为明晰，但是必要的支撑性技术仍处于研发或待研发阶段，碳中和图景的实现需要突破性技术的支持，特别需要关注当前仍不太成熟、成本较高，但发挥战略性关键作用的技术。提高电力系统稳定性高度依赖电网技术、储能技术、分布式可再生能源技术和需求侧响应技术，然而与已经具备竞争力的可再生能源发电技术相比，上述技术的应用成本仍较为高昂，部分技术仍处于研发阶段，尚未有成熟的应用案例。安全稳定的电力供应对零碳电力系统的构建至关重要，是当前面临的重要技术热点和难点。

在电源侧，以风电、太阳能发电为主的可再生能源发电技术，虽然经过多年的发展培育，其经济成本已经具备一定的竞争力，但是发电效率和经济效益仍有待进一步提高。核能、生物质能、CCUS技术作为未来零碳电力系统中重要的组成部分，在未来的碳中和路径中不可或缺，相关技术的更新换代、研发推广至关重要。此外，基于技术研发进程，兼顾能源转型的综合影响，从研究的角度合理规划现有化石能源发电产能退役路径，配合以科学的政策引导，对电力系统以更经济有效的方式进行零碳转型至关重要。

（二）工业部门

工业部门碳排放量大、机制复杂、脱碳难度高、减排技术种类繁多。与发达国家相比，我国在关键性低碳技术领域仍有一定的差距，亟须加快研发进程。工业部门碳排放占全国人为碳排放总量的比例也呈现先升后降的趋势，目前约占到40%左右，是仅次于能源行业的最大碳排放源。表2至表4展示了不同研究对未来中国

表2　不同研究报告对中国工业部门碳排放的预测汇总

行业	目标年份	情景	达峰时间	峰值（亿吨）	目标年排放（亿吨）	下降趋势	数据来源
工业	2050	政策情景	2025年左右	58	46.1	—	清华大学气候变化与可持续发展研究院项目综合报告编写组（2020）
		强化政策	2025年左右	57	34.2	—	
		2℃情景	2025年左右	53	16.7	—	
		1.5℃情景	立即达峰	—	7.1	近似线性	
工业	2050	基准情景	—	—	37–39	—	波士顿咨询公司（2020）
		2℃情景	—	—	25～27	—	
		1.5℃情景	—	—	13.65～15.6	—	
工业	2050	2℃情景	立即达峰	—	8～18	—	能源基金会（2020）
		1.5℃情景	立即达峰	—	2～10	—	
工业	2050	强化行动	立即达峰	—	29	先慢后快	世界资源研究所（2020）
工业	2060	碳中和路径	立即达峰	—	4	近似线性	高盛（2021）
工业	2050	最佳估计	立即达峰	—	4	先慢后快	DNV-GL（2019）
工业	2050	1.5℃情景	立即达峰	—	0～13	不统一	Duan *et al*.（2021）
水泥	2060	碳中和情景	立即达峰	—	4.96	先快后慢	中金公司（2020）
钢铁			立即达峰	—	4.6	先快后慢	
水泥	2060	碳中和情景	立即达峰	—	3.1	先快后慢	中金公司（2021）
钢铁			立即达峰	—	3.2	先快后慢	

资料来源：根据文献和公开资料整理。

industrial sectors such as iron and steel, cement and chemical sectors need to further raise the share of electric power and other non-fossil fuels and take steps to reduce the proportions of coal, petroleum, natural gas and other fossil fuels. For the iron and steel sector, China needs to ramp up research on hydrogen-powered steel smelting technologies. China's cement sector leads the world in terms of energy efficiency and clinker factor, and the current priority is to step up R&D on fuel and feedstock substitution. Regarding fuel substitution, biogas or biomass (solid wastes with high calorific value) may replace fossil fuels. As part of the garbage sorting system, China should develop technologies for the integrated treatment and application of multi-source alternative fuels. Meanwhile, alternative feedstocks with low carbon emissions such as desulfurized gypsum and electric furnace slag can be used to reduce carbon emissions from limestone decomposition. China should also develop technologies for the integrated application of broader alternative feedstocks such as magnesium oxide and alkali/geopolymer adhesives.

4.3 Transportation Sector

Amid rapid economic growth, China's transportation sector has entered a fast track of development. Transportation has become China's second-largest CO_2 emitter next only to industry (Huang, 2017) with an annual growth rate of CO_2 emissions above 7.5%. Emissions from the transportation sector will be

Table 2: Forecast of China's Industrial Carbon Emissions by Different Research Reports

Sector	Target year	Scenario	Target year	Peak (100 million tons)	Emissions in target year (100 million tons)	Downward trend	Data source
Industry	2050	Policy scenario	Around 2025	58	46.1	-	Integrated Project Report Drafting Team (2020) of the Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD) (2020)
		Enhanced policy	Around 2025	57	34.2	-	
		2℃ scenario	Around 2025	53	16.7	-	
		1.5℃ scenario	Immediate peak	-	7.1	Approximately linear	
Industry	2050	Benchmark scenario	-	-	37-39	-	Boston Consulting Group (BCG) (2020)
		2℃ scenario	-	-	25-27	-	
		1.5℃ scenario	-	-	13.65-15.6	-	
Industry	2050	2℃ scenario	Immediate peak	-	8-18	-	The Energy Foundation (2020)
		1.5℃ scenario	Immediate peak	-	2-10	-	
Industry	2050	Enhanced action	Immediate peak	-	29	Slow before accelerating decrease	The World Resources Institute (2020)
Industry	2060	Carbon neutrality pathway	Immediate peak	-	4	Approximately linear	Goldman Sachs (2021)
Industry	2050	Best estimate	Immediate peak	-	4	Slow before accelerating decrease	DNV-GL (2019)
Industry	2050	1.5℃ scenario	Immediate peak	-	0-13	Inconsistent	Duan *et al*. (2021)
Cement	2060	Carbon neutrality scenario	Immediate peak	-	4.96	Rapid before slowing decrease	CICC (2020)
Steel			Immediate peak	-	4.6	Rapid before slowing decrease	
Cement	2060	Carbon neutrality scenario	Immediate peak	-	3.1	Rapid before slowing decrease	CICC (2021)
Steel			Immediate peak	-	3.2	Rapid before slowing decrease	

Source: Collected from literature and publicly available information.

表3 不同研究中对钢铁、水泥产量及电钢比例的预测结果

行业	预测结果	数据来源
工业	产量逐渐下降，2050年相比2020年水泥产量下降71%（约7亿吨）	清华大学气候变化与可持续发展研究院项目综合报告编写组（2020）
钢铁	2050年钢铁产量为4.75亿吨，电炉比例为60%	能源转型委员会（2020）
水泥	2050年水泥产量为8亿吨	
钢铁	2050年钢铁产量为7.1亿吨，电炉比例为50%	IEA（2020）
水泥	2050年水泥产量大约为15亿吨	IEA（2020）
水泥	产量逐渐下降，2060年水泥产量约7.6亿吨	中金公司（2020）
钢铁	产量逐渐下降，2060年钢铁产量约6.5亿吨，电炉比例达到60%	

资料来源：根据文献和公开资料整理。

表4 不同研究中的工业部门碳中和的技术路径汇总

2050年/2060年减排技术贡献量	数据来源
能效提高16亿吨；生产结构调整4亿吨；能源结构转型5亿吨；CCS量13亿吨	刘俊玲等（2019）
优化工业生产3.62亿吨；提升工业能效3.72亿吨；改善工业用能结构0.8亿吨；跨行业减排政策（如碳价机制、CCS等）9.39亿吨	世界资源研究所（2020）
能效/循环经济13亿吨；氢能12亿吨；电气化11亿吨；生物质2.7亿吨；碳捕获15亿吨。	高盛（2021）

资料来源：根据文献和公开资料整理。

工业部门减排路线的描绘和认识。研究普遍表明，目标年份下，工业部门仍会有一定的正碳排放。在与碳中和接近的情景中，工业部门的正碳排放普遍认为在0～15亿吨左右，其中水泥和钢铁部门仍是工业部门中主要排放的子部门，分别会保留3亿～4亿吨的碳排放。这意味着整个经济社会净零排放的情况下，工业部门仍需要靠其他部门（例如能源部门和农林碳汇等）的负碳排放去抵消其难以完全脱碳的部分。

工业碳中和目标的达成需要关注以下重点。能源消费结构调整是我国工业部门实现碳中和的重要抓手。具体而言，钢铁、水泥、化工等工业部门，需要进一步提高电力及其他非化石能源的比例，逐步降低煤炭、石油、天然气等化石能源的消费比例。对于钢铁部门，我国需要加大对氢能炼钢技术的研发。对于水泥部门，我国在能源效率提高和降低熟料系数方面已走在前列，需要加大对燃料替代和原料替代技术的研发。在燃料替代方面，可利用沼气或生物质（高热值固体废物）代替化石燃料，依托国内垃圾分类制度的推进，研发多源替代燃料的综合处理与应用技术；同时可使用脱硫石膏、电炉渣等低碳排放的替代原料，降低石灰石分解带来的碳排放，研发氧化镁和碱/地质聚合物粘合剂等更广泛替代原料的综合应用技术。

研发重点工业部门的CCS技术有助于保障我国工业部门打赢碳中和目标下的"决胜战"。由于工业生产过程不可避免会释放二氧化碳，因此CCS技术将是工业部门深度脱碳的兜底技术。目前CCS技术还未能实现商业化应用，只在国际上有一些大型试点项目，我国目前研发则较为落后，应当在钢铁、水泥等重点部门开展重点研发工作。例如可采用创新的窑炉设计，将燃料燃烧的废气（低二氧化碳含量）与煅烧废气（高二氧化碳含量）分离。

Table 3: Forecasts of Steel and Cement Output and Electric Furnace Steel Smelting

Sector	Forecast result	Data source
Industry	Output gradually decreases. By 2050, cement output will decrease by 71% on the basis of 2020 (about 700 million tons).	Integrated Project Report Drafting Team (2020) of the Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD) (2020)
Steel	By 2050, steel output will reach 475 million tons, and electric furnaces will account for 60%.	Energy Transition Commission (ETC) (2020)
Cement	By 2050, cement output will reach 800 million tons.	
Steel	By 2050, steel output will be 710 million tons, and electric furnaces will account for 50%.	IEA (2020)
Cement	By 2050, cement output will reach roughly 1.5 billion tons.	IEA (2020)
Cement	Output will gradually decrease. By 2060, cement output will be some 760 million tons.	CICC (2020)
Steel	Output will gradually decrease. By 2060, steel output will be about 650 million tons, and electric furnaces will account for 60%.	

Source: Collected from literature and publicly available information.

Table 4: Technical Pathways for Industrial Carbon Neutrality in Various Studies

Contributions of carbon emission technologies by 2050/2060	Source
1.6 billion tons from energy efficiency improvement; 400 million tons from production structural adjustment; 500 million tons from energy transition; 1.3 billion tons from CCS	Liu *et al*. (2019)
362 million tons from industrial production optimization; 372 million tons from industrial energy efficiency improvement; 80 million tons from industrial energy mix improvement; 939 million tons from cross-sector emission abatement policies (such as carbon price mechanism and CCS)	World Resources Institute (2020)
1.3 billion tons from energy efficiency / circular economy; 1.2 billion tons from hydrogen energy; 1.1 billion tons from electrification; 270 million tons from biomass; 1.5 billion tons from carbon capture.	Goldman Sachs (2021)

Source: Collected from literature and publicly available information.

significant if it fails to greenize. With a strong lock-in effect and path dependence, the cost of reducing GHG emissions is higher for the transportation sector compared with other sectors. Involving myriad entities and subject to technology progress and behavioral change, the transportation sector is faced with the greatest challenges in reducing carbon emissions. Under the target of carbon neutrality by 2060, China's transportation sector should transition towards low-carbon development and achieve net zero CO_2 emissions. Carbon emissions from the transportation sector should peak as soon as possible before 2030 and decrease rapidly after the plateau period. By 2050, China should try to reduce CO_2 emissions from its transportation sector by 80% (Energy Foundation, 2020). Studies have estimated different emission pathways for China's transportation sector, and key parameters are forecasted in Table 5. Overall, it takes the following three stages to achieve carbon neutrality in China's transportation sector,

Stage 1 (2020-2030): The primary goal for this stage is to peak carbon emissions from China's transportation sector as soon as possible and strictly control the emissions peak to leave a buffer period for the decrease of carbon emissions in the subsequent stages. For this stage, an important strategy would be to upgrade traditional energies such as fuel oil and develop new energies like hydrogen at the same time. Specifically, China should improve the oil consumption structure of its transportation sector and try to peak oil consumption in transportation around 2025 (CNPC Research Institute of Economics and Technology, 2020). At the same time, traditional energy sources should be replaced with clean energies such as electric power, hydrogen, and biomass. By 2030, China should try to ensure that all new passenger vehicles are new energy vehicles powered by electric power or fuel cell, making them

（三）交通部门

随着我国经济发展水平的不断提高，交通运输业步入快速发展阶段。交通已经成为仅次于工业的第二大CO_2排放生产服务部门（黄晗，2017），且排放量年均增长率保持在7.5%以上。若交通部门无法尽快进行绿色转型，排放量不容小觑。加之交通部门的碳排放具有很强的锁定效应和路径依赖，温室气体减排成本高于其他部门；且由于涉及主体较多，受制于技术进步和行为变化，其减排难度较大，因此也被认为是碳减排最具挑战的部门之一。2060年碳中和目标下，交通部门应尽快转向低碳发展，在建设交通强国的同时，实现二氧化碳净零排放。交通行业碳排放量要在2030年前尽快达峰，在经历平台期后快速下降，力争到2050年排放量相较于2015年减少80%（能源基金会，2020）。不同研究对交通部门排放路径有不同的估计，表5列举了重要参数的预测。总体而言，交通部门的碳中和可以分为以下3个阶段：

第一阶段：2020～2030年，为达峰期。该阶段的主要目标是尽快实现交通部门碳排放达峰，严控排放峰值，为后期碳排放的下降过程留出缓冲时间。燃油等传统能源的改造升级和氢能等新能源的开发利用“双管齐下”应是这一阶段的重要战略。具体而言，加快交通用油结构优化，并争取用油量于2025年前后达峰（中国石油经济技术研究院，2020）。同时，加快电力、氢能、生物质能等清洁能源的替代使用，力争到2030年实现新上市乘用车全部转型为纯电动、燃料电池等新能源汽车，大幅降低新能源汽车的购置和使用成本，使之与传统燃油车辆相当或更为经济，实现新能源汽车总体占比达到40%的目标，并实现汽车全生命周期的碳中和。清华大学气候变化与可持续发展研究院（2020）预测，2030年中国交通运输部门能源需求约为5.83亿吨标准煤，排放量为10.37亿～10.75亿吨二氧化碳当量（Carbon Dioxide Equivalent，CO_2e）。

表5 部分研究的交通行业低碳转型情景

指标	年份		数据来源
	2030	2050	
新能源汽车占比（%）	40～50	100	中国汽车工程学会（2020）
纯电动汽车续航里程（km）	500	—	中国汽车工程学会（2016）
燃料电池汽车保有量（万辆）	100	—	
车身减重（%）	35	—	
交通行业整体减排（%）	—	80	能源基金会（2020）
公路交通减排（%）	—	61	国家发改委能源研究所“重塑能源”课题组（2016）
交通全行业用油量（亿吨）	3.7（2025）	2.5	中国石油经济技术研究院（2020）
氢能占交通用能比重（%）	—	28	
天然气占交通用能比重（%）	10	21	世界资源研究所（2020）
铁路电气化率（%）	—	100%	Energy Transition Commission（2020）
交通部门电力需求（万亿kWh）	0.42～0.56	0.79～1.59	清华大学气候变化与可持续发展研究院项目综合报告编写组（2020）
交通部门能源需求总量（亿吨标准煤）	5.83	3.46～4.02	
交通部门总排放量（亿吨CO_2e）	10.37～10.75	1.72～5.50	
2010～2050年交通转型新增投资（万亿元）	—	12.2	国家发改委能源研究所“重塑能源”课题组（2016）
投资预期收益（万亿元）		23.4	

注：投资和收益规模按2010年价计算。
资料来源：根据文献和公开资料整理。

affordable and equally or more economical compared with traditional fuel-powered vehicles. New energy vehicles should account for 40% of the total car population, and achieve carbon neutrality for full lifecycles. According to the forecast by the Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD) (2020), energy demand in China's transportation sector is projected to be 583 million tce by 2030 with 1,037 million to 1,075 million tons of CO_2 equivalent (CO_2e).

Stage 2 (2030-2015): Plateau or decarbonization period. The primary target for this stage is to accelerate decarbonization. In this stage, transportation systems will continue to improve, energy efficiency will keep rising, and major breakthroughs in low-carbon new technologies and new energy consumption modes will further drive decarbonization and energy diversification in the transportation sector. Regarding road transportation, new energy vehicles will account for over 50% by 2035 (China Society of Automotive Engineers, 2020), and the hydrogen fuel cell vehicles will exceed one million units. Except for very few fuel-efficient vehicle models, traditional fuel vehicles will be prohibited. With further development in energy storage technologies, electrically and hydrogen powered airplanes will reach a certain level of commercialization, sharply reducing carbon emissions from the aviation sector.

Stage 3 (2050-2060): Complete neutralization. After the first two stages of transition, energy demand in China's transportation sector will be transformed in this stage. In the 2050s, almost all passenger vehicles in China will be electric vehicles, and other types of vehicles based on alternative fuels will be much more efficient than traditional vehicles. Close to 100% of railways in China will be electrified, and the remainder may use hydrogen energy. Hydrogen fuel penetration will exceed 50% in the aviation sector. According to a forecast by the Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD) (2020), energy demand in China's transportation sector will decrease to somewhere between 346 million and 402 million tce with emissions reduced to somewhere between 170 million and 550 million CO_2e by 2050, down by over half compared with the peak. By 2050, energy consumption in China's transportation sector will decrease to 380 million tce, of which electric power will represent over 40% (Energy Transition Commission, 2020). While further promoting clean and low-carbon energy use in the transportation sector, China will take initiatives in coordination with other sectors and employ negative emission technologies to achieve carbon neutrality.

Regarding carbon neutrality for the transportation sector, three priorities warrant our attention: First, electrification is the fundamental solution to carbon neutrality in the transportation sector. As the most important technology for carbon neutrality, electrification contributes the most to reducing carbon emissions in the transportation sector, including road, railway, and aviation. Second, clean fuel substitution offers an important assurance for carbon neutrality. In addition to electric vehicles, hybrid vehicles and fuel cell vehicles also represent important clean energy sources to substitute petroleum in road transportation. In railway transportation, hydrogen energy holds great promise as an alternative energy source for decarbonization in railway transportation (Jiang and Feng, 2021). Solar and biofuel will also accelerate decarbonization in the railway sector. Sustainable biofuels should be adopted in the civil aviation sector on a broader scale to bring down the cost to an acceptable level as soon as possible. Third, support from relevant sectors is needed to achieve carbon neutrality in the transportation sector. This requires policy guidance on low-carbon transportation, vigorous public transportation development, and science-based urban planning.

4.4 Construction Sector

As shown in Table 6, studies have estimated decarbonization trends for the construction sector under China's carbon neutrality target. In the benchmark scenario, China's construction sector emissions will decrease by 2050 compared with the current level. Following the 1.5°C pathway, the construction sector is to reduce emissions by 50% to 95% by 2050. Considering technological and economic uncertainties, carbon emissions from China's construction sector need to reduce by 20% to 80% by 2050 under the 2°C pathway. Carbon emissions from China's construction sector will decrease from a high level

第二阶段：2030～2050年，为平台期和下降期。该阶段的主要目标是加速脱碳。此阶段中，交通体系不断优化，用能效率持续提升，更多低碳新技术的重大突破和用能新模式的出现和发展将进一步推动交通能耗的低碳化和多元化。公路交通中，到2035年，新能源汽车将占到50%以上（中国汽车工程学会，2020），氢燃料电池汽车保有量将突破100万辆，除极少部分的低油耗车型外，传统燃油车将被禁止使用。航空飞行中，随着储能技术的进一步发展，电动和氢动力飞机将实现一定程度的商用，航空碳排放大大降低。

第三阶段：2050～2060年，为全面中和期。经过之前两个阶段的转型之后，中国交通运输部门的能源需求将在本阶段实现完全重塑。到20世纪50年代，乘用车中的电动汽车比例将接近100%，其他类型车辆中替代燃料的经济性也将高于传统车辆。电气化铁路的占比将接近100%，难以实现电气化的铁路可选择氢能，航空业中氢燃料渗透率也将超过50%。清华大学气候变化与可持续发展研究院（2020）预测，2050年交通运输部门能源需求将降至3.46亿～4.02亿吨标准煤，排放量也将下降至1.72亿～5.50亿吨CO_2e，比峰值下降一半以上。2050年中国交通运输领域能源消耗将降至3.8亿吨标准煤，其中电力将占到40%以上（能源转型委员会，2020）。在进一步提高交通领域能源利用的清洁化和低碳化的同时，联合多领域行动，并利用负排放技术，最终实现碳中和目标。

交通部门碳中和目标的实现需要注意三个方面。第一，全面推进交通运输电气化是实现碳中和的根本途径。电气化是实现交通部门碳中和最为重要的技术手段，涉及公路、铁路、航空等各个领域，是最为本质、贡献最大的减排举措。第二，积极促进清洁燃料替代是实现碳中和的重要保障。公路交通领域，除纯电动汽车外，推广混合动力汽车和燃料电池汽车也是去油化和清洁化的重要方向。铁路交通领域，氢能利用也将成为铁路运输脱碳的另一条重要途径（姜克隽和冯升波，2021），太阳能和生物燃料的使用也将加快铁路部门脱碳。航空领域应加快可持续性生物燃油的推广应用，降低成本，尽快使其价格达到可接受范围。第三，交通部门碳中和需要相关领域的配套支持。这需要加强低碳交通政策引导、大力发展公共交通、科学制定城市空间规划等。

（四）建筑部门

中国建筑行业规模位居世界第一，与之相应的全过程碳排放总量为49.3亿吨，约占中国碳排放的51.3%（中国建筑节能协会，2021）。随着我国城镇化进程的持续和快速推进，城乡居民的建筑服务需求，炊事、热水、取暖、制冷、照明和电器等使用将不断增加。而城镇化，伴随着经济增长、数字化程度的提高，以及新经济增长模式下的消费转型，将给我国住宅建筑和商业建筑的碳中和带来严峻挑战。

如表6所示，已有研究测算了中国实现碳中和目标下，建筑部门不同情景下的碳减排趋势。在基准情景下，2050年建筑部门排放相较现状将降低，而在贯彻“1.5℃”目标路径下，建筑部门需在2050年前实现50%～95%的碳减排。而考虑到技术和经济的不确定性，“2℃”目标路径下，建筑部门碳排放需在2050年下降20%～80%。建筑部门的碳中和将会经历从高碳到低碳到零碳的过程，分别是现在至2035年，建筑部门的煤炭，天然气消费量达峰，碳排放在2035年左右达峰；2035～2050年建筑部门大幅度降低碳排放；2050～2060年深度脱碳，实现建筑部门的碳中和目标。

第一阶段（2021～2035年）：该阶段的主要目标是实现建筑部门的煤炭、天然气消费量达峰，实现建筑部

Table 5: Scenarios of Low-Carbon Transition for China's Transportation Sector

Indicator	Year		Source
	2030	2050	
Share of new energy vehicles (%)	40~50	100	China Society of Automotive Engineers (2020)
Range of electric vehicles (km)	500	-	China Society of Automotive Engineers (2016)
Fuel cell vehicles in stock (10,000 units)	100	-	
Vehicle weight reduction (%)	35	-	
Overall emissions reduction in the transportation sector (%)	-	80	The Energy Foundation (2020)
Emission reduction in the road transportation sector (%)	-	61	"Reshaping Energy" Research Group of the Energy Research Institute of the National Development and Reform Commission (NDRC) (2016)
Oil consumption in the transportation sector (100 million tons)	3.7 (2025)	2.5	CNPC Research Institute of Economics and Technology (2020)
Hydrogen as a share of energy consumption in transportation (%)	-	28	
Natural gas as a share of energy consumption in transportation (%)	10	21	World Resources Institute (2020)
Railway electrification rate (%)	-	100%	Energy Transition Commission（2020）
Electric power demand in the transportation sector (trillion kWh)	0.42-0.56	0.79-1.59	Integrated Project Report Drafting Team of Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD) (2020)
Total energy demand in the transportation sector (100 million tce)	5.83	3.46-4.02	
Total emissions from the transportation sector (100 million tons of CO_2e)	10.37-10.75	1.72-5.50	
New investments for transportation transition from 2010 to 2050 (trillion yuan)	-	12.2	"Reshaping Energy" Research Group of the Energy Research Institute of the National Development and Reform Commission (NDRC) (2016)
Expected investment return (trillion yuan)		23.4	

Note: Investment and return are calculated based on 2010 price.

Source: Collected from literature publicly available information.

and ultimately reach zero for carbon neutrality. In China's construction sector, coal and natural gas consumption will peak by 2035, and carbon emissions will peak by around 2035; from 2035 to 2050, the construction sector will sharply reduce carbon emissions; from 2050 to 2060, the sector is expected to decarbonize at a deeper level to achieve the carbon neutrality target.

Stage 1 (2021-2035): The primary target for this stage is to peak coal and natural gas consumption in the construction sector and peak carbon emissions from the construction sector. In this stage, the critical strategy for the carbon neutrality pathway is to increase the electrification rate, phase out household coal and natural gas consumption, and increase building energy efficiency. Specific strategies include: to raise building energy efficiency design standards and improve energy efficiency standards and label programs for home appliances; extensively renovate old buildings; and broadly apply distributed PV generation and efficient biomass technologies in rural buildings. Under this plan, coal consumption in rural dwellings will be phased out, the building materials sector will achieve carbon peak by 2025, and cement and some other sectors will achieve carbon peak by 2023. By 2025, increase in the area of assembled buildings will reach 1.069 billion square meters. Overall electrification rate in the construction sector will exceed 50%.

Stage 2 (2036-2050): The primary target for this stage is to substantially reduce carbon emissions. In this stage, priority should be given to replacing electric power demand in the construction sector with biomass, residual industrial heat without generating additional carbon emissions, solar heating. In this

门碳排放的达峰。该阶段下，碳中和路径对应的关键策略为提升电气化率，淘汰家庭煤炭和天然气使用，提高建筑物能效。具体策略主要包括：持续提高建筑节能设计标准，完善家电能效标准和标签计划；大规模翻新老旧建筑；提高分布式光伏发电和高效生物质利用技术在农村建筑中的应用。预计该阶段，农村住宅煤炭使用将逐步被禁止，建筑材料行业在2025年前全面实现碳达峰，水泥等行业在2023年前率先实现碳达峰。2030年绿色建筑面积在新建面积中的占比达90%以上。预计到2025年装配式建筑新增面积达到10.69亿平米，建筑部门整体的电气化率达到50%以上。

表6 建筑部门的碳中和路径总结

情景	排放路径				技术路径			投资路径	其他	数据来源
	达峰碳排放量（亿吨）	最终碳排放量（亿吨）	终端用能（万亿kWh）	用电量（万亿kWh）	电气化率（%）	清洁能源利用		投资规模（万亿元）		
						能源类型	占比（%）			
碳中和情景	—	0（2060年）	7.85（2050年）	2.70	65（2050年）	太阳能、地热能、氢能	22（2050）	—	能源强度为0.3吨CO_2e/吨标准油；节能和用能结构优化减排贡献：23%和73%	中国石油经济技术研究院（2020）
2050零碳情景	—	–	4.02（2050年）	3.01	75（2050年）	太阳能 工业余热 生物质	7 12 7	—	热泵技术占建筑采暖和热水的60%	Energy Transition Commission（2020）
1.5℃情景	—	0.81（2050年）	5.05（2050年）	3.66	60（2050年）	生物质和天然气	40	7.88	建筑总规模：2050年740亿平方米以内	清华大学气候变化与可持续发展研究院项目综合报告编写组（2020）
“1.5℃”目标情景	—	0（2060年）	—	—	100*	—	—	—	—	波士顿咨询公司（2020）
低碳情景	7.8（2027年）	6.15（2050年）	7.48（2050年）	—	—	—	—	0.42	能效技术和能源结构调整减排贡献：33.4%和66.6%	刘俊玲等（2019）
电气化情景	21（2030年）	5（2050年）	1.22**（2050年）	5	90（2050年）	—	—	0.7	“光储柔直”建筑面积：200亿平方米；建筑光伏累积装机容量：1000GW	能源基金会等（2020）
“1.5℃”目标情景	7（2030年）	0–3（2050年）	4.47–9.76（2050年）	3.65～5	75～85（2050年）	热能和天然气	15～30	—	农村淘汰煤炭；集中供暖脱碳	能源基金会（2020）
低碳情景	30（2030年）	10（2050年）	8.13（2050年）	—	—	—	—	—	70%的现有建筑被翻修；节能和燃料转换减排贡献：81%和19%	Zhou *et al.*（2018）

注：终端用能和用电量统一折合成万亿kWh。*表示电气化率指炊事与热水。**表示终端用能只包括一次能源。
资料来源：文献和公开资料整理。

stage, centralized heating systems in cities in northern China will complete decarbonization by 2050, and new buildings will achieve zero carbon emissions. By 2050, the overall electrification rate will reach 85%; cooking in dwellings and commercial buildings will be electrified 100%.

Stage 3 (2051-2060): The primary target is to deepen decarbonization and achieve the carbon neutrality target. The key for decarbonization lies in electric power decarbonization and negative emission technologies (CCUS, BECCS). Decarbonization in the electric power sector is subject to decarbonization technologies. Where zero carbon emissions cannot be achieved, carbon sequestration and negative emission technologies should be employed to achieve the carbon neutrality target.

Three priorities warrant great attention for the construction sector to achieve carbon neutrality: First, increasing building energy efficiency is a key step. This requires higher energy efficiency standards and penetration of existing home appliances and equipment, stricter building energy efficiency design standards, near zero/zero carbon energy consumption for new buildings, and energy efficiency retrofitting for existing buildings. Second, electrification represents an inevitable trend for carbon neutrality in the construction sector. In 2019, the overall electrification rate in China's construction sector was only 37%, and this ratio has huge reform potentials in the future. Third, China should accelerate the deployment of technologies for low-carbon building materials and construction with renewable energies, as well as other innovative technologies, to achieve carbon neutrality in the construction sector.

5. Overall Effects of Carbon Neutrality in China

The carbon neutrality target will reshape China's economic and industrial systems. Carbon neutrality offers China a major opportunity to overtake early-moving countries and increase industrial competitiveness. In such sectors as new energy, electric vehicle and zero-carbon industries, China has developed technological and market strengths and is ahead of other countries in some areas. Leadership in those industries will give China an opportunity to hold sway globally and strengthen its previously unfavorable competitive position. All in all, the global industrial landscape will transform under the carbon neutrality vision, giving rise to numerous emerging industries, jobs, new industry standards, and business opportunities in various industrial chain segments. With those changes taking place, a new world industrial landscape is on the horizon. In the long run, economic competitiveness will hinge upon emerging green and low-carbon industries.

The carbon neutrality target will reshape global energy resources and industrial layout. As an oil-poor country, China is heavily dependent on imported oil resources, which presents energy security risks. Under the carbon neutrality target, steps will be taken to phase out fossil fuels and increase the share of clean energy sources for China to become less dependent on traditional energy resources and explore a win-win situation to promote both energy security and industrial development. Second, electrification and digitalization will coordinate energy supply side and consumption side, thus changing energy consumption and supply modes. Electrification in energy-using sectors and decarbonization in the electric power sector are critical drivers of the low-carbon transition strategy in the long run. By integrating the future electric power system, the energy interconnection system holds the promise of creating more efficient and resilient energy systems. Transformations in future energy consumption and supply modes will foster more industrial growth drivers.

The carbon neutrality target will redefine China's regional economic landscape. To a great extent, carbon neutrality is contingent upon geographical conditions. With a vast expanse of territory, China may leverage resource endowments across regions, whose roles in China's economy can be redefined. China's central and western regions boast abundant clean energy resources and huge potentials for carbon sequestration, creating opportunities for local economic development.

The carbon neutrality target will transform technological and industrial innovations. Progress in science and technology holds the key for turning challenges of carbon neutrality into opportunities. In

第二阶段(2036～2050年):该阶段的主要目标是大幅度降低碳排放。此阶段下的主要工作是以生物质、不产生额外碳排放的工业余热以及太阳能热等替代建筑部门的电力需求,继续推进建筑部门电气化率的提升。具体策略包括实现因地制宜的开发高效的热泵技术提高供暖电气化率;进一步提升新建建筑中光伏一体化建筑和被动式建筑的比例;继续推广太阳能热水技术和分布式光伏技术在农村和城市建筑中的应用等。预计该阶段下,2050年北方城市集中供暖系统将实现完全脱碳,新增建筑实现零碳排放;此外,2050年,建筑部门整体的电气化率将达到85%。住宅和商用建筑的烹饪将实现100%的电气化。

第三阶段(2051～2060年):主要任务是深度脱碳,实现碳中和目标。深度脱碳的关键在于电力的脱碳和负排放技术(CCUS、BECCS)。对于无法实现零碳排放的部分,通过碳汇和负排放技术实现建筑部门的碳中和目标。

建筑部门的碳中和实现需要注意三个方面:第一,提升建筑物能效是实现碳中和的关键要素。为了达成这一点,需要提升现有电器和设备的能效标准和渗透率、设立更严格的建筑节能设计标准,实现新建建筑的近零/零碳能耗、全面实现对老旧建筑的节能改造。第二,电气化是建筑部门实现碳中和的必然趋势。2019年中国建筑部门整体的电气化率仅为37%,这一部分未来具有巨大改革潜力。第三,还应加快部署低碳建材生产技术、可再生能源建筑技术和智能支持技术等创新技术,从根本上实现建筑部门的碳中和。

五、实现中国碳中和目标的综合影响

碳中和目标将重塑我国经济和产业体系。碳中和目标给中国提供了这样一个换道超车、拓展产业竞争力的重大机遇。在新能源、电动汽车、零碳工业等领域,我国已经有了很好的技术和市场基础,部分领域已经具备领先的优势。因此,如果能够抓住机遇在这些新兴科技产业领域迅速崛起,我国就能够脱离原有落后产业竞争不利的格局,占据全球主导产业。总体而言,在碳中和愿景下全球产业格局将发生深刻调整,在产业链的细分领域将产生众多的新兴产业,创造大量的就业机会,形成新的行业标准,创造新的合作机会,构造新的世界产业格局。传统能源和重工业产业将面临较大的挑战,绿色低碳转型势在必行,新兴绿色低碳技术产业将成为未来提高长期经济竞争力的关键所在。

碳中和目标将重构全球能源资源与产业格局。首先,碳中和愿景下,能源的资源属性降低,产品属性凸显。我国石油资源相对贫乏,需要大量进口,带来了能源安全的隐患。在碳中和愿景目标下,化石能源将逐步被淘汰,清洁能源占比将大幅提升,从而帮助我国摆脱对传统能源资源的依赖局面,从而形成既能够提升能源安全又能够促进产业发展的双赢格局。其次,电气化和数字化将联动能源供应侧与消费侧,从而改变能源消费供应模式。能源系统中终端部门电气化与电力部门脱碳是长期低碳转型战略最关键的要素,能源互联网有望成功整合未来电力系统的核心要素,创建更高效和有韧性的能源体系。未来能源消费供应模式将发生巨大变革,也将催生更多的产业增长点。

碳中和目标将重新定义区域经济版图。实现碳中和的空间尺度范围不同,其实现的难易程度、战略纵深和策略空间会有极大的不同。我国具有广阔的国土空间纵深,碳中和将发挥区域间各自资源禀赋之所长,进

Table 6: Carbon Neutrality Pathways for the Construction Sector

Scenario	Emission pathway				Technology pathway			Investment pathway	Others	Data source
	Peak carbon emissions (100 million tons)	End-use carbon emissions (100 million tons)	End-use energy consumption (trillion kWh)	Power consumption (trillion kWh)	Electrification rate (%)	Clean energy utilization		Investment volume (trillion yuan)		
						Energy type	Share (%)			
Carbon neutrality scenario	2030	0 (2060)	7.85 (2050)	2.70	65 (2050)	Solar, geothermal and hydrogen energies	22 (2050)	-	Energy intensity is 0.3t CO_2/ton of oil equivalent; energy efficiency and energy mix improvement contribute to emissions abatement by 23% and 73%, respectively.	CNPC Research Institute of Economics and Technology (2020)
Zero carbon scenario for 2050	-	-	4.02 (2050)	3.01	75 (2050)	Solar power Industrial residual heat Biomass	7 12 7	-	Heat pump technology accounts for 60% of building heating and cooking	Energy Transition Commission (2020)
1.5°C scenario	2030	0.81 (2050)	5.05 (2050)	3.66	60 (2050)	Biomass and natural gas	40	7.88	Total construction area: within 74 billion square meters by 2050	Integrated Project Report Drafting Team of Institute for Climate Change and Sustainable Development at Tsinghua University (ICCSD) (2020)
1.5°C scenario	-	0 (2060)	-	-	100*	-	-	-	-	Boston Consulting Group (BCG) (2020)
Low-carbon scenario	7.8 (2027)	6.15 (2050)	7.48 (2050)	-	-	-	-	0.42	Energy efficiency technologies and energy mix adjustment contribute to emission abatement by 33.4% and 66.6%, respectively	Liu Junling *et al.* (2019)
Electrification scenario	21 (2030)	5 (2050)	1.22** (2050)	5	90 (2050)	-	-	0.7	Construction area for voltage direct current PV power generation: 20 billion square meters; cumulative installed capacity of PV generators in buildings: 1,000 GW	The Energy Foundation *et al*. (2020)
1.5°C scenario	7 (2030)	0-3 (2050)	4.47-9.76 (2050)	3.65-5	75-85 (2050)	Thermal energy and natural gas	15-30	-	Phase out coal in the countryside; centralized heating and decarbonization	The Energy Foundation (2020)
Low-carbon scenario	30 (2030)	10 (2050)	8.13 (2050)	-	-		-	-	70% of existing buildings will be renovated; energy efficiency and fuel conversion contribute to emissions abatement by 81% and 19%, respectively.	Zhou *et al*. (2018)

Note: End-use energy consumption and electric power consumption are in trillion kWh. *Electrification rate refers to cooking and water heating. **End-use energy consumption only includes primary energy.

Source: Collected from literature and publicly available information.

the absence of any step change in economic structure and technological conditions, priority should be given to improving technologies for carbon peak and carbon neutrality. China should ramp up R&D and deploy technological innovations, giving play to the strategic and pivotal role of technology in achieving vision. Driven by the carbon neutrality target, attempts have been made to explore technologies and industrial innovations in various sectors to turn advanced low-carbon, zero-carbon and negative carbon

而重新定义我国各区域在经济版图上的角色。在达成碳中和目标的过程中，中西部地区具备清洁能源资源丰富、碳封存潜力巨大的两个优势，进而为中西部地区的经济发展带来强劲的新动能。

碳中和目标将变革技术和产业创新体系。能否化碳中和的挑战为机遇，关键要依靠科技进步，一方面要在经济结构、技术条件没有明显改善条件下，促进碳达峰碳中和的技术进步，另一方面要加大科技研发力度，部署面向碳中和的科技创新体系，更好发挥科技在整个碳达峰碳中和中的战略支撑和引领作用。在碳中和目标的倡导下，各行业已开始进行相关科技与产业创新的尝试，这将引导先进低碳、零碳和负碳技术成为未来经济社会发展的战略支撑。

碳中和目标将推动气候投融资浪潮。实现碳中和既要有技术的支撑，也要有资金的投入。我国要在2060年实现碳中和目标，2020年至2050年能源系统需要新增投资约138万亿元（清华大学气候变化研究院，2020）。高盛预计我国碳中和目标意味着到2060年投资需求规模为16万亿美元。如此巨量资金的投入，需要政策的引导，也需要各利益相关方的支持和投入，目前在这两方面都已经启动了相关进程。

碳中和目标将引领生态环境的根本改善。碳达峰碳中和目标的实现需要从能源结构、经济结构等方面开展源头性变革，有助于推动污染物源头治理，协同实现降碳减污，推动高质量发展。降碳是生态环境源头治理的牛鼻子，将碳中和目标纳入生态文明建设的框架，有助于实现应对气候变化与生态环境质量改善的协同增效。一方面，碳中和目标的实现路径将为深度治理大气污染、持续改善空气质量提供强大的推力。温室气体排放和大气污染物排放存在着“同根同源”的特征，在政策目标、实施路径和治理主体方面有着诸多交叉点，可以实现协同治理。另一方面，碳中和目标的实现也会对水、土壤的污染防治以及提升生态系统服务功能、保护生物多样性间接地产生积极的影响。

六、讨论

（一）碳中和政策体系

碳中和目标的实现离不开社会的良性互动，政府、地方、企业、个人分别在迈向碳中和愿景进程中具有至关重要而又各有侧重的作用。因此面向不同主体的政策类别构成了碳中和愿景下的政策体系。在国家层面应建立健全相关法律法规。碳中和愿景下的长期深度减排是我国未来发展的必然趋势，有必要通过立法手段为减排政策的长效实施提供法律基础、增强执行力度。当前，气候立法正逐渐成为国际碳中和行动的重要组分。通过立法来保障减排政策的法律基础和效力，可以把碳中和的长期愿景转换为全社会的行动共识、全面促进低碳转型的个人行为、企业行动、资金流动、技术研发。在此基础上，我国可以进一步考虑完善应对气候变化相关制度建设，例如，持续推进以《碳排放权交易管理暂行条例》为代表的国家碳交易制度建设，以及将创新性低碳和负排放技术的长期发展纳入我国关键技术发展战略。

在地方层面，应差异化地方碳中和行动方案。地方自主探索碳中和方案是实现碳中和愿景的必然途径。一方面，碳中和愿景指引下的发展需要各地结合各自资源禀赋、发展阶段、产业结构等方面特点探索合适的转型路径。另一方面，开展碳中和行动，有利于地方因地制宜推动能源生产和消费革命、经济高质量发展和生

technologies into strategic drivers of China's future socio-economic development.

The carbon neutrality target will drive forward a wave of climate investment and financing. Carbon neutrality requires both technology and financial input. For China to achieve carbon neutrality by 2060, it needs to invest an additional 138 trillion yuan in its energy systems from 2020 to 2050 (Global Climate Change Institute (GCCI) of Tsinghua University, 2020). Goldman Sachs estimated China's investment demand for achieving carbon neutrality to be 16 trillion US dollars by 2060. Such a huge financial input requires policy guidance and support from relevant stakeholders, and work is already under way to garner both.

The carbon neutrality target will lead to a fundamental improvement in the ecological environment. To achieve the vision, China needs to transform its energy mix and economic structure, reduce pollution at the source, and promote high-quality development. Decarbonization is the key for ecological management. The inclusion of the target into the framework of ecological civilization will facilitate climate change mitigation and environmental quality improvement. Efforts to achieve this goal will provide a strong impetus for reducing air pollution and improving air quality. Greenhouse gas emissions and air pollution stem from the same sources and can be addressed simultaneously with overlapping policy targets, implementation pathways and involved entities. Carbon neutrality programs will create positive indirect effects on reducing water and soil pollution, enhancing ecosystem services, and protecting biodiversity.

6. Discussions

6.1 Carbon Neutrality Policy System

The carbon neutrality target cannot be achieved without benign social interactions. Governments, localities, enterprises and individuals play pivotal and differentiated roles in the journey towards carbon neutrality. A system of policies should be enacted for different types of entities towards the carbon neutrality vision. At the national level, we should create a complete set of laws and regulations. Commitment to emission abatement under the carbon neutrality vision represents a natural trend for China's future development. Legislation needs to be introduced for the long-term implementation of emission abatement policies. Climate legislation is becoming an important part of international carbon neutrality actions. Legislation ensures the legal basis and validity of emission abatement policies, and may convert the long-term vision of carbon neutrality into society-wide consensus to encourage individual and corporate behaviors, capital flow and R&D for the low-carbon transition. On this basis, China may further consider improving climate-related institutional development. One initiative would be to further develop a national carbon trading system based on the *Interim Regulations on the Transaction of Carbon Emission Rights* and incorporate innovative low-carbon and negative emission technologies into China's critical technology development strategies.

At the local level, differentiated carbon neutrality action plans should be formulated. Local exploration of a carbon neutrality plan is a sure path towards the carbon neutrality vision. Under the carbon neutrality vision, localities should explore appropriate transition pathways according to their resource endowment, development stage, and industrial structure. On the other hand, carbon neutrality programs help revolutionize energy production and consumption for high-quality economic development and environmental protection.

Industries and enterprises should tighten carbon neutrality constraints and incentives. In the final analysis, it takes technology to achieve carbon neutrality, and enterprises are both innovators and carbon emitters. The key, therefore, is to allow firms to adopt practical innovations and actions for carbon neutrality. To encourage carbon neutrality actions at the firm level, China needs to fully leverage market-based instruments to reduce the cost of zero-carbon development for firms. In addition, we should protect and support low-carbon/zero-carbon technologies, enhance intellectual property rights (IPR) protection and offer tax credits for low-carbon/zero-carbon technologies, conduct government procurement and

态环境高水平保护。

对行业和企业，应强化碳中和约束与激励。实现碳中和最终要靠技术，而企业既是技术创新的主体，又是碳排放的直接来源，因此，能否让企业采取切实可行的创新和行动是实现碳中和的关键。为推动企业层面的碳中和行动，首先我国应充分利用市场化工具，降低企业零碳化发展成本。此外，需要加强低碳/零碳技术保护和扶持，通过完善低碳/零碳知识产权保护，对于新技术给予税收抵免，进行政府采购以及技术授权等，提高企业碳中和发展收益。

（二）碳达峰与碳中和的关系

碳减排与碳中和有着根本性的逻辑差别（王灿和张九天，2021）。一是内涵逻辑不同。碳达峰是落在传统意义的碳减排概念中，而碳减排是对现有排放和发展路径的改进与优化，仅以排放现状作为基线。碳中和的参考基线是净零排放，需要在最大可能减排的基础上，对能源、经济甚至社会体系进行深度重构。二是概念范围不同。碳中和对经济社会发展会产生全方位的影响，传统产业和新兴产业、供给侧和需求侧都需要做出响应，需要建立全面适用、科学精准的概念体系。三是方法路径不同。碳中和要求在发展理念和方式上有根本的转变，实现碳中和需要在基础设施、市场规则和供应链体系、技术体系等诸多方面采取全新的方法和路径。

努力提前达峰和降低峰值水平有利于减缓碳中和压力。我国在达峰后不可能像发达国家一样有较长的平台期，而是需要迅速进入深度脱碳期，容不得丝毫懈怠。曾经有一种声音认为碳达峰比较容易达到，在达峰前继续大量排放，将碳排放推高上去，之后再退出一些高碳项目就能轻松实现碳达峰。这种“摸高式”的碳达峰或者“数字意义”上的碳达峰完全不可取，完全违背了我国实现碳达峰的初衷，而且会造成大量的资源浪费。我国2030年前实现碳达峰后还要实现碳中和，两者之间紧密关联，碳达峰的峰值年和峰值水平都会对碳中和路径的难易程度产生影响，碳达峰时间往后延迟意味着压缩了碳达峰到碳中和的时间，峰值水平越高意味着同样的时间内减排工作的强度越大，简单说就是前松则后紧，前紧则后松。因此，努力实现早达峰和降低峰值水平都会有利于减缓碳中和过程中的压力。

（三）企业行动需求及驱动手段

企业的碳中和关系到绿色产品的制造与创新、行业链条的传递等方方面面，作为生产制造和创新的主体，积极探索实践碳中和之路非常重要。在碳中和愿景下，企业面临来自多方面的碳中和要求，包括落实国家碳达峰碳中和战略的要求、产业链传导而来的碳中和要求、欧盟“碳关税”等市场准入要求、消费者环保偏好要求、投资者对低碳企业青睐的要求等（罗荟霖等，2021）。因此，企业自身的碳中和转型受到多方面的激励，而成功的转型也会给企业带来多重利好。为了完成这一目标，企业需要开展碳核算与盘查，摸清家底，在此基础上制定企业面向碳中和目标的战略规划，进而采取行动策略、强化品牌影响力。深化对碳中和概念和边界等的认知、减少对碳抵消的过度依赖将帮助企业更好地完成碳中和转型。政府需在其中加强标准规范引领、加速低碳/零碳基础设施建设、加快绿色低碳技术供给。

technology authorizations, and raise firm revenues from carbon neutrality.

6.2 Relationship between Carbon Peak and Carbon Neutrality

There is a fundamental logical difference between carbon emissions and carbon neutrality (Wang and Zhang, 2021). The first difference lies in the underlying logic. While carbon peak is a concept of carbon emission abatement in the traditional sense, carbon emission abatement requires optimizing existing emission and development pathways with the current status of emissions as the baseline. The reference baseline for carbon neutrality is net zero emissions and requires an in-depth reorganization of the energy, economic and social systems on the basis of the maximum possible emission abatement. The second difference lies in the concept of range. The socio-economic effects of carbon neutrality require both traditional and emerging industries and supply and demand sides to respond. A comprehensive system of applicable, science-based and accurate concepts should be put into place. The third difference lies in methodologies and pathways. Carbon neutrality entails a fundamental transformation in development concepts and methods. Brand-new methodologies and pathways should be adopted regarding infrastructure, market rules, supply chains, and technological systems.

Pressures for carbon neutrality can be mitigated by reaching an early carbon peak and reducing the peak level. After reaching the carbon peak, China is unlikely to experience a protracted plateau period as did developed countries. Instead, China must embark upon in-depth decarbonization without hesitation. Some believed that carbon peak was relatively easy to attain. Even though emissions continue to rise, they argue, the carbon peak can be easily achieved by phasing out some carbon-intensive projects. This notion of setting a high carbon peak to make things easier is inadvisable and goes against the intention of China's carbon peak. It will only cause a wasteful use of resources. After the carbon peak by 2030, China will need to achieve carbon neutrality. The year and level of carbon peak will both influence the pathway and difficulty of carbon neutrality. Delay in the carbon peak means a shorter interval from carbon peak to carbon neutrality. A higher peak means more intensive emission abatement work in the same timeframe. More work in the early stage means less work in the late stage, and vice versa. Hence, efforts to bring an early and low carbon peak will ease pressures for achieving carbon neutrality in a later stage. That is to say, more work in the early stage means less work in the late stage, and vice versa. Hence, efforts to bring an early and low carbon peak will ease pressures for carbon neutrality in a later stage.

6.3 Demand and Incentives for Corporate Action

Carbon neutrality concerns every aspect of green manufacturing, innovation, and industrial chains. As manufacturers and innovators, it is of great importance for firms to explore carbon neutrality pathways. Under the carbon neutrality vision, firms face various carbon neutrality requirements, including the implementation of national carbon peak and carbon neutrality strategies, carbon neutrality criteria from supply chains, market access thresholds such as the “carbon tariffs” imposed by the European Union, consumer preferences for environmental protection, and investors' preferences for low-carbon firms (Luo, 2021). Firms are motivated in many ways to go carbon neutral and expect to be rewarded if their low-carbon transition is successful. Firms need to conduct carbon accounting and stock-taking before setting their carbon neutrality targets and making strategic plans. Commitment to carbon neutrality will contribute to their brand influence. Firms should be more aware about the concept and boundary of carbon neutrality and less dependent on carbon consumption to complete their carbon neutrality transition. The government should enhance standardization, low-carbon/zero carbon infrastructure, and green and low-carbon technology supply.

6.4 Innovation as a Double-Edged Sword

Carbon neutrality is an important campaign in China’s development of ecological civilization, and is closely related to clean production and environmental technologies. Yet differences also exit. The

（四）技术创新的双刃剑

碳中和目标是我国生态文明建设的重要战役，与清洁生产、环保技术的发展密不可分。然而，两者之间也存在着差异，清洁技术的创新并不一定必然促进碳中和，甚至有可能会起到相反作用。例如，清洁燃煤发电技术提升了燃煤效率，减少了燃煤发电的末端空气污染物排放，却增强了能源部门对化石能源的路径依赖。再比如，继续提高燃煤电厂末端处理标准将增大煤电退役的沉没成本。在碳中和愿景下，这些技术创新和环境政策都将在一定程度上影响或阻碍碳中和所需的新能源体系的快速形成。因此，需要将碳中和纳入生态环境保护整体布局，准确识别气候友好的清洁技术，让碳中和目标成为形成生态文明建设合力的重要推动力。

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innovation of clean technologies may not always contribute to carbon neutrality. Despite its effects of raising coal combustion efficiency and reducing air pollution from coal-fired power plants, clean coal technology reinforces the energy sector's dependence on fossil fuels. For another example, further raising end-of-pipe treatment standards for coal-fired power plants will increase the sunk cost for decommissioning coal-fired power plants. Under the carbon neutrality vision, these innovations and policies will impede the fast deployment of new energy systems essential for carbon neutrality. By incorporating carbon neutrality into the environmental protection framework and identifying climate-friendly clean technologies, the carbon neutrality target should serve as an impetus and rallying force for ecological civilization.

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China will aim to have CO2 emissions peak before 2030
and achieve carbon neutrality before 2060