China Council for International Cooperation on Environment and Development

Technology Innovation for Green and Low-Carbon Transition

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【Research Significance】

The *Opinions on Accelerating the Comprehensive Green Transition of Economic and Social Development* issued by the CPC Central Committee and the State Council in July 2024 emphasized the need to adhere to innovative transformation. The document highlights the importance of technological innovation, policy system innovation, and business model innovation that support green transition, as well as advancing a green, low-carbon technological revolution. This requires the development of new quality productive forces tailored to local conditions, improvement of the ecological civilization system, and enhanced innovative momentum and institutional support to facilitate green transition.

This report aims to conduct a preliminary exploratory study on green and low-carbon transition technological innovation from a policy perspective, providing support for the deployment of subsequent research tasks by CCICED.

【Research Focus】

First, the report reveals the critical importance of technological innovation for green and low-carbon transition, pointing out that it is not only key to achieving carbon neutrality but also provides new momentum for the comprehensive green transition of economic and social development. Second, the report analyzes key areas and directions in the technological innovation for green and low-carbon transition in developed countries and summarizes the successful experiences in policy design and implementation in these nations.

Under the framework of policy research, the study focuses on how to accelerate green and low-carbon technological innovation through policy guidance to enhance new quality productive forces. The report emphasizes the key role of policy systems in promoting green and low-carbon technological innovation, noting that countries need to balance ecological and environmental sustainability with economic and social development in policy design. A systemic policy support framework is essential, involving a series of interrelated policy tools—such as fiscal policies, financial policies, green and low-carbon standards, carbon markets, and strategic planning—allowing countries to effectively regulate innovative behaviors, provide economic incentives, and create a supportive environment. This approach fosters innovation momentum and establishes a complete pathway from policy formulation to innovation realization.

Additionally, the report analyzes China's strengths and challenges in technological innovation for green and low-carbon transition. It highlights China's advantages in market size, potential for economic growth, and engineering and technical capabilities, while also identifying shortcomings in areas such as the innovation environment, policy support, and financing channels. Finally, the report provides policy recommendations for accelerating green and low-carbon technological innovation and enhancing new quality productive forces in the future.

【Key Policy Recommendations】

Regarding the next steps for the CCICED in green and low-carbon technological innovation

1. Study on Green and Low-Carbon Technological Innovation Models and Policies in Developed Countries

First, review the green and low-carbon technological innovation actions and deployments of developed countries and regions (including the United States, the European Union, the United Kingdom, Germany, and Japan), analyze their technological innovation models and pathways, and summarize the next-generation green and low-carbon technological innovations and disruptive

technologies prioritized by major economies. **Second,** compare the gaps between China and developed countries in green and low-carbon technological innovation and identify areas for improvement. **Third,** assess the effectiveness of policies on green and low-carbon technological innovation in developed countries, analyze the applicability of different policies, summarize lessons learned, and provide insights for China's policy formulation.

2. Roadmap for China's Near-, Mid-, and Long-Term Green and Low-Carbon Technological Innovation

First, organize multidisciplinary experts to develop a roadmap for China's green and low-carbon technological innovation, setting clear objectives for the near term (5-10 years), mid-term (10-20 years), and long-term (20-30 years). It is recommended that the roadmap be divided by sectors, including energy transition, industry, transportation, construction, agriculture and land use, circular economy, digital technology and green-low carbon integration, and disruptive and generational technologies. **Second,** develop technology selection criteria for various fields, considering factors such as emission reduction potential, economic and social impact, and international scientific and technological competition. Respect the uncertainties inherent in the technological innovation process and introduce a mechanism for regular evaluation and adjustment of the roadmap.

3. Research on Developing China's Green and Low-Carbon Technological Innovation Policy System in the New Era

In response to the need for building a green and low-carbon technological innovation system under China's dual carbon goals, research on the issues and deficiencies in China's current green and low-carbon technological innovation system from multiple dimensions, including the innovation environment, fiscal and tax policies, financing mechanisms, and innovation entities. Propose improvement suggestions, particularly for fostering original and disruptive innovation in the green and low-carbon technology field, to enhance China's contribution to global competitive green and low-carbon public goods.

Policy Recommendations for Promoting Green and Low-Carbon Technological Innovation in China

1. Fostering an Environment Conducive to Innovation

First, integrate national medium- and long-term science and technology development plans to ensure the long-term stability and sustainability of technology-driven carbon neutrality goals. **Second,** promote entrepreneurial spirit by fostering a social environment that encourages innovation and tolerates failure. Protect entrepreneurs' rights to innovate through legal means and encourage more entrepreneurs to participate in green and low-carbon technological innovation planning, policy, and standard formulation. Policies such as science and technology innovation vouchers and equipment leasing fee incentives should encourage enterprises to share and use research infrastructure. **Third,** increase the openness of basic research in China. Establish special funds with international third-party organizations for the research of forward-looking, disruptive, and breakthrough green and low-carbon technologies. Support domestic and international cooperation between energy companies, universities, research institutions, and industry organizations to form innovation consortia and attract top global talent to conduct green and low-carbon scientific and technological research in China.

2. Adjusting the Focus of the New Green Industry Policy

First, develop a new round of green industry policies guided by innovation. Avoid the blind expansion of production capacity, ensuring that limited fiscal resources are directed toward green and low-carbon technological innovations. **Second,** establish a public information monitoring platform for green and low-carbon industries and technologies. Timely release data and information on capacity utilization, market supply and demand, as well as technology investment and applications. **Three,** categorize green and low-carbon technologies. The classification criteria should take into account emission reduction benefits, costs, and industrial stimulation capacity. Regular evaluations should be conducted based on these standards, and a mechanism for adjusting and phasing out technologies should be established. The classification should also align with policies related to subsidies and financing. **Four,** strengthen government procurement support for green and low-carbon products. Promote the prioritization of green and low-carbon technologies and products in government and public sector procurement.

3. Strengthening Multi-Source Financial Governance to Support Financing for Leading Green and Low-Carbon Technological Innovations

First, establish a green low-carbon technological innovation financing policy system based on carbon reduction standards. By guiding diversified funds, including bank loans, equity investments, and green bonds, a multi-level, multi-channel green financial system should be formed to meet the financing needs of various types and stages of green low-carbon innovation projects. **Second,** enhance the role of venture capital in supporting original and disruptive green low-carbon technologies. Build a financial service system primarily driven by venture capital, supported by the stock market. **Three**, use revenues from carbon trading markets and other carbon reduction regulatory policies, in the form of competitive subsidies, to support green and low-carbon technological innovation.

Key words: green and low-carbon technological innovation; new quality productive forces; international experience; policy recommendations

CONTENTS

1 The Importance of Technological Innovation for Green and Low-carbon Transition

Green and low-carbon transition has become a crucial direction for sustainable global development. This transition is not only necessary for addressing climate change and solving environmental pollution but also serves as a fundamental pathway for achieving high-quality economic development. Technological innovation plays a pivotal role as the driving force behind this transition. Governments and enterprises worldwide are increasing investments in research and development (R&D) of green and low-carbon technologies and implementing a series of policy measures to support the development and application of green technologies. This innovation-driven development model is leading the world into a new phase of development. Green and low-carbon technological innovation helps reduce energy consumption, decrease greenhouse gas emissions, minimize pollutant discharge, and protect the environment and ecosystems. Besides, green technological innovation can foster the emergence of new industries and business models, such as those in the fields of renewable energy, energy efficiency, environmental protection technologies, and circular economy. These emerging industries not only stimulate economic growth but also create substantial employment opportunities and optimize economic structures.

In September 2023, during an inspection in Heilongjiang province, President Xi Jinping first mentioned the term "new quality productive forces". This was followed by the Central Economic Work Conference at the end of 2023, which called for the development of new quality productive forces. At the first collective study session of the Political Bureau of the Central Committee of the CPC in 2024, the focus was on "new quality productive forces", and the report on the work of the government (2024) listed accelerating the development of new quality productive forces as one of the top ten tasks for the year. These significant arrangements clearly signal the importance and urgency of developing new quality productive forces.

President Xi Jinping stated, "Green development is the underlying theme of high-quality development, and new quality productive forces are essentially green productive forces". This important assertion highlights the intrinsic link between new quality productive forces and green development, providing theoretical guidance for accelerating the development of new quality productive forces and promoting the comprehensive green transition of economic and social development. It holds profound theoretical and practical significance.

This study focuses on green and low-carbon innovation from a policy research perspective, analyzing how policy guidance can accelerate green and low-carbon technological innovation to empower the rise of new quality productive forces.

1.1 Achieving Carbon Neutrality Depends on the Maturity and Wide Application of Green and Low-Carbon Technologies

Achieving carbon neutrality requires global net greenhouse gas emissions to reach zero, which involves not only a fundamental transition of the energy structure but also deep emission reductions across industries such as transportation, construction, and agriculture. This goal is heavily reliant on the maturity and widespread application of green and low-carbon technologies. Firstly, the development of renewable energy technologies, such as solar, wind, and hydropower, forms the foundation for achieving carbon neutrality. The widespread adoption of these clean energy sources can gradually replace fossil fuels and reduce carbon emissions. Moreover, the development of hydrogen energy, energy storage, and smart grids ensures the stability and

reliability of energy systems, facilitating large-scale integration of clean energy. Secondly, in the industrial and transportation sectors, breakthroughs and widespread adoption of technologies like green hydrogen, electrification, and carbon dioxide capture, utilization and storage (CCUS) are critical for addressing deep decarbonization challenges. Without the maturity and large-scale application of these technologies, achieving carbon neutrality will be difficult.

Green and low-carbon technologies are playing an increasingly prominent role in addressing climate change. However, many key technologies remain in the research and testing stages and have not yet reached the level of maturity required for large-scale commercial application. They still face technological bottlenecks and market acceptance challenges. According to the latest data from the International Energy Agency (IEA) [1], as shown in Figure 1, technologies currently in the demonstration or prototype phase are expected to contribute 35% of the emission reductions needed in the 2050 net-zero emissions (NZE) scenario in energy system. Some technologies still need to be promoted and applied to support emission reduction targets. To achieve net-zero carbon emissions in the energy system by 2050, low-emission hydrogen and hydrogen-based fuels, sustainable aviation fuels (SAF), and direct air capture and storage (DACS) must see significant growth in the coming years. By 2030, low-emission hydrogen production is expected to increase from less than 1 million tons in 2022 to 70 million tons. By 2030, SAF's share of aviation final energy consumption is expected to rise from nearly zero to about 11%. By 2030, DACS is expected to contribute an annual CO_2 reduction of nearly 7 billion tons, up from almost zero today[2].

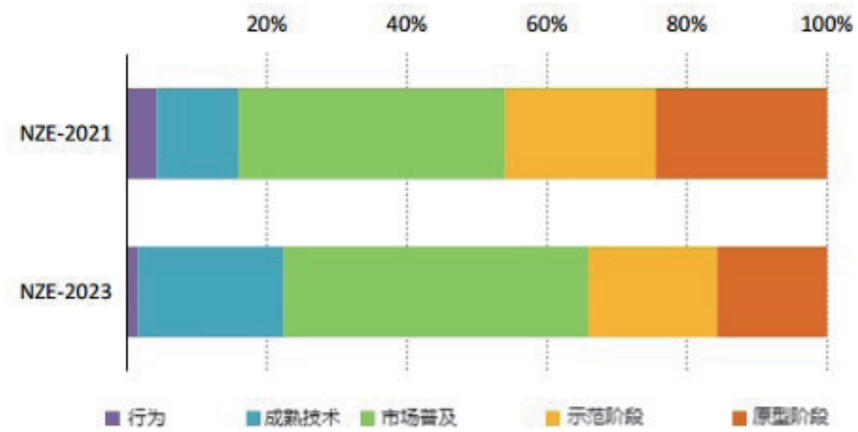

Figure 1. Global Energy Sector CO_2 Emissions Reductions by Technology Maturity in 2050 Compared to the Base Year (IEA 2021 and 2023 Net-Zero Scenarios)

Source: International Energy Agency (IEA), 2023

1.2 Technological Innovation for Green and Low-carbon Transition Will Empower the Rise of New Quality Productive Forces

Technological innovation for green and low-carbon transition will drive profound changes in production methods. Traditional productive forces depend on high energy consumption and high-emission production models, while green and low-carbon technologies introduce low-energy consumption, low-emission, and low-pollution production methods through new technologies (such as renewable energy and clean production technologies). This not only improves production efficiency but also reduces negative environmental impacts, thereby reshaping production methods. This innovation provides strong driving power for sustainable economic growth and aligns with the global trend toward green economic transition. Green total factor productivity (GTFP) is an important indicator of an economy's capacity for efficient and sustainable development under resource and environmental constraints. Research has shown that green innovation can significantly enhance GTFP (Zhao et al. 2022; Wu et al. 2022)[3][4].

Technological innovation for green and low-carbon transition will also strengthen the role of knowledge and technology in productive forces. With the rapid acceleration of technological advancement and innovation, green and low-carbon technologies have become essential components of modern productive forces. Enterprises and nations are focusing on R&D, innovative applications, and talent development, concentrating high-end technological resources to improve the competitiveness of green technologies. This knowledge-driven productivity has become a vital source of economic growth.

1.3 Technological Innovation for Green and Low-carbon Transition Will Create Numerous Emerging Industries and Market Demands

The green and low-carbon transition is driving the rise of many emerging industries globally and creating widespread market demand. This transition benefits from the combined forces of policy support, technological advancement, and market trends. First, the introduction of carbon neutrality goals and government incentive policies has created vast opportunities for the development of new fields, such as renewable energy, energy storage technologies, smart grids, and electric transportation. These policies direct capital toward green industries and stimulate market demand for low-carbon products and services.

Second, accelerated technological innovation is transforming traditional industries while creating new industrial chains and ecosystems. For instance, the widespread adoption of electric vehicles) has driven rapid growth in related industries, such as battery technology, charging infrastructure, and recycled materials, shaping a new market landscape. According to data from the International Energy Agency (IEA)[5], global sales of new energy vehicles reached approximately 14 million in 2023, accounting for 20% of total global car sales. This growth has not only accelerated the expansion of the new energy vehicle industry but also spurred the development of associated industries, such as battery production, charging infrastructure, and smart transportation systems. Notably, global battery manufacturing capacity is expanding rapidly, with 2023's capacity reaching 1,500 GWh, a 50% increase from 2022. This figure is expected to further grow to 7,500 GWh by 2030, almost five times the 2022 level. This explosive growth reflects the substantial demand for battery technologies, which is driving rapid development in materials, equipment, and recycling industries.

Additionally, the increasing environmental consciousness of consumers has made green consumption a significant market trend, driving the continued growth of green products and services. Finally, the global trend toward carbon neutrality has driven growing international demand for green technologies and products, making the green economy a crucial component of global trade. Thus, the green and low-carbon transition is not only an environmental imperative but also a new engine for economic growth, creating new industries and markets while fundamentally transforming global economic structures.

1.4 Green and Low-Carbon Transition Is Not Merely a Technological Upgrade but Also a Profound Transformation of Industrial and Social Structures

The essence of green and low-carbon transition is not simply technological iteration and upgrading. While innovative technologies are the means, the resulting deep changes in industrial and social structures are the ultimate goals. First, green transition requires systematic adjustments to traditional high-carbon industries, not just within the energy sector but across industries such as industrial manufacturing, transportation, and construction. Traditional high-carbon industries will gradually be replaced by new industries such as clean energy and green manufacturing, leading to significant changes in industrial structures. According to IEA statistics[6], in 2023, it is expected that 96% of newly installed utility-scale PV and onshore wind power generation will be cheaper than new coal and gas-fired power plants. Moreover, three-quarters of new wind and PV power plants will provide electricity at a lower cost than existing fossil fuel facilities. The cost competitiveness of wind and PV systems will continue to increase, leading to the gradual replacement of traditional high-carbon industries by clean energy.

Second, green and low-carbon transition will restructure industrial chains and upgrade value chains, promoting efficient resource allocation and circular utilization, forming a more ecological and intensive economic model. This transition will not only change production methods but will also impact employment structures and the division of labor within society, as demand for new green jobs and professions increases, while traditional occupations face pressure for transformation and upgrading. According to the IEA's 2050 Net-Zero Emissions (NZE) scenario, the energy supply sector is expected to create 14 million new jobs by 2030. During the same period, fossil fuel production may see a reduction of 5 million jobs[7].

Additionally, technological innovation for green and low-carbon transition will profoundly affect social consumption habits, lifestyles, and urban development models, promoting the development of low-carbon cities, green transportation, and sustainable communities, and shaping a new social form.

2 Key Fields and Directions in International Technological Innovation for Green and Low-carbon Transition

This study uses text mining methods to identify key fields and technologies in green and low-carbon technological innovation. As shown in Figure 2, critical areas of green and low-carbon technological innovation include energy transition, low-carbon industries, circular economy, green transportation and buildings, agriculture and land use, and digital technology, all of which exhibit strong cross-disciplinary features. From the deployment strategies of major developed countries, there are focused technological R&D efforts in these key areas, although the priority of specific breakthrough directions varies (as summarized in Table 1). Frontier technologies such as controlled nuclear fusion, green hydrogen technology, CCUS, next-generation energy storage batteries, long-duration energy storage, and industrial decarbonization are the focus of major developed countries.

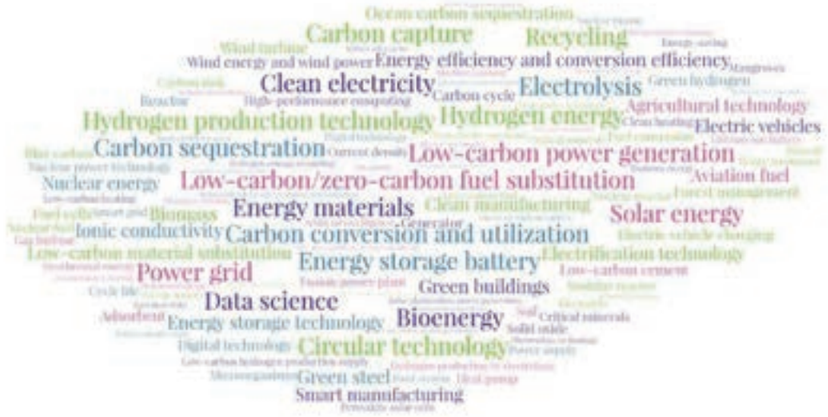

Figure 2. Key Fields and Technologies in Green and Low-carbon Technological Innovation

Note: Based on the monthly monitoring product "Intelligence Dynamics for Dual Carbon" of the The National Science Library, Chinese Academy of Sciences, more than 1,600 monitoring item data of this product from 2021 to date were collected, and a word cloud map was generated after data cleaning, word segmentation, and clustering.

The United States focuses on fostering forward-looking and disruptive technologies in the green and low-carbon sectors. Since 2021, the U.S. Department of Energy, through the Advanced Research Projects Agency-Energy (ARPA-E), has consistently supported transformative low-carbon energy technologies. These include key decarbonization technologies in electricity, renewable energy, nuclear energy, hydrogen, industry, and transportation, with a broad scope and an emphasis on disruptive technological innovations. Besides, the U.S. has deployed long-term scientific research programs, such as the "Energy Earthshots", which focuses on mobilizing national strengths in key areas of energy science and technology over the next 10 to 15 years to reduce costs, improve performance, and achieve large-scale deployment of clean energy. This plan has continuously funded projects in hydrogen energy, energy storage, negative carbon technologies, enhanced geothermal energy, clean fuels and products, industrial heating, and building decarbonization. Furthermore, in the industrial sector, the U.S. passed the *Technologies for Industrial Emissions Reduction Development Program* in 2023, outlining decarbonization technologies for key industries such as steel, cement, and chemicals, while advancing technologies with commercial potential through industrial demonstrations.

The European Union emphasizes sustainable, inclusive, and secure green transition solutions. The EU funds scientific research and technological development related to carbon neutrality through multiple programs, including the EU Research Framework Programmes, Innovation Fund, Modernisation Fund, Sustainable Europe Investment Plan, Connecting Europe Facility, and LIFE Programme. Horizon Europe, the EU's ninth research framework program (2021–2027), is the largest research program in Europe with a budget of €15.123 billion dedicated to climate, energy, and transportation research. It supports six major themes: (1) climate science and responses to climate neutrality; (2) cross-sector solutions for climate transition; (3) sustainable, secure, and competitive energy supply; (4) efficient, sustainable, and inclusive energy use; (5) clean and competitive solutions for all modes of transport; (6) secure, resilient transportation and smart transportation services.

Despite the EU's significant efforts to promote scientific research and technological development related to carbon neutrality through various funding programs, it still faces numerous challenges in the implementation process. Particularly in the clean technology sector, the EU's technological advantages have not yet fully translated into production capacity. For instance, while the EU has a technological edge in areas such as heat pumps, batteries, electrolyzers, and carbon capture technologies, it continues to struggle with limited production capacity and a reliance on imported key components[8]. The EU's lithium-ion battery production capacity remains low, electrolyzers have not yet reached large-scale manufacturing, and the expansion of carbon capture technology is hindered by inadequate infrastructure.

As a result, the EU has taken more proactive steps toward localizing production and scaling up these critical technologies to enhance its global competitiveness and reduce dependency on external supply chains. In 2024, the EU passed the Net-Zero Industry Act, identifying eight strategic net-zero technologies that are either commercially viable or soon to enter the market. These include solar photovoltaic and solar thermal technologies, onshore wind and offshore renewable energy technologies, batteries and storage technologies, heat pumps and geothermal energy technologies, electrolyzers and fuel cells, sustainable biogas/biomethane technologies, carbon capture and storage technologies, and grid technologies, all of which are supported for localized deployment.

Germany has incorporated climate change technologies into its future research and innovation strategy. In 2023, Germany released its latest top-level strategic plan for scientific and technological innovation—the Future Research and Innovation Strategy, aimed at more robustly promoting innovations related to sustainable greenhouse gas emissions reduction. Key areas of focus include developing new technologies and processes for zero-emission raw materials, promoting lightweight construction, creating innovation-friendly frameworks to tap into the potential of the bioeconomy, leveraging digital technologies to reduce resource consumption, establishing interoperable standards for a safe circular economy, leading the development of high-performance, secure, and energy-efficient communication systems such as 6G, rapidly advancing the green hydrogen economy to become a global leader in hydrogen technology, building a global battery research, production, and recycling center, continuing research on nuclear fusion, and developing novel concepts and technological pathways. Germany's goal is to create a climate-friendly, efficient, and resilient future energy system through innovation.

The United Kingdom has focused on low-carbon industrial technologies for its "Green Industrial Revolution" initiative. By setting comprehensive green innovation strategies aimed at achieving net-zero emissions, the UK has emphasized applied research on key industrial technologies, forward-looking planning, and large-scale application. The UK's primary goal in green innovation is to reduce the transition cost to net zero, cultivate better products and new business models, and prioritize key future technologies. In March 2021, the UK government launched a £1 billion Net Zero Innovation Portfolio, based on the *Ten Point Plan for a Green Industrial Revolution.* This portfolio focuses on ten priority areas, including floating offshore wind energy, bioenergy, hydrogen, flexible energy storage, advanced nuclear energy, and carbon capture, utilization, and storage (CCUS).

Japan has broadly deployed decarbonization technologies in energy, industry, and environmental sectors to drive a societal green transition. In its early 2020 Environment Innovation Strategic, Japan planned the deployment of key decarbonization technologies across five major areas—Non-fossil energy, industry, transportation, construction, and agriculture/forestry/fisheries—totaling 39 key technologies in 16 categories. By the end of 2020, under the Green Growth Strategy, Japan established a ¥2 trillion Green Innovation Fund and launched several long-term major funding programs targeting key industries such as offshore wind energy, ammonia and hydrogen fuels, next-generation batteries, novel geothermal energy, bio-based materials, and circular economy technologies. **Japan** also highly values the integration of digital technologies, such as artificial intelligence and the Internet of Things, into various sectors to achieve energy conservation and emission reduction. Moreover, Japan actively promotes the use of digital technologies in transportation, construction, energy, and other fields.

South Korea has formulated a list of emerging and core technologies to achieve carbon neutrality. In June 2022, the Korea Institute of Science and Technology Evaluation and Planning (KISTEP) identified 10 emerging technologies to assist in meeting South Korea's 2030 nationally determined contribution (NDC) targets. These include (1) carbon capture and utilization (CCU); (2) bio-based raw materials/products manufacturing technologies; (3) low-carbon steel production; (4) high-capacity and long-life secondary batteries; (5) clean hydrogen production; (6) ammonia-fueled power generation; (7) grid integration systems; (8) high-efficiency crystalline silicon solar cells; (9) large offshore wind power systems; and (10) rare earth element recycling. In October 2022, the South Korean government formally established the 2050 Carbon Neutrality Green Growth Commission, which, in addition to releasing The Strategy For Promoting Carbon Neutrality And Green Growth, also published the Carbon Neutrality And Green Growth Technology Innovation Strategy, involving 100 core technologies related to carbon neutrality. These technologies span energy, key industries, building efficiency, and transportation.

Table 1 Green and Low-carbon Key Technology Layout of Major Developed Countries

Country/region	Key Technology
US	Small modular reactors, nuclear fusion, green hydrogen, CCUS, battery energy storage, next generation low-carbon buildings, renewable energy, advanced nuclear energy, sustainable aviation fuel, industrial electrification, artificial intelligence technology in the energy field, electric vehicles, climate-smart agriculture, etc.
EU	Renewable energy, hydrogen energy, integrated energy systems, smart grids, energy storage, CCUS, industrial decarbonization and digital transformation, green buildings, sustainable and smart transportation, precision agriculture, organic agricultural ecosystems, bioeconomy, synthetic low-carbon fuels, etc.
Germany	Green hydrogen, energy storage, electric vehicles, smart grids, electrification of transportation networks, biofuels, fuel cells, low–emission industrial production technologies, climate and environmentally friendly buildings, digital energy systems, modernization of cogeneration, ecological agriculture, etc.
UK	Energy storage, hydrogen energy, offshore wind power, advanced nuclear energy, electric vehicles, electrification of transportation networks, zero–emission aircraft, sustainable transportation fuels, clean shipping, green buildings, industrial fuel transition, bioenergy, direct air capture and advanced CCUS, artificial intelligence in the energy field, etc.
Japan	Renewable energy, hydrogen and ammonia fuels, new geothermal energy, advanced nuclear energy, nuclear fusion, electric vehicles, energy storage, zero–emission ships, smart agriculture, forestry and fisheries, low–carbon semiconductors, aviation electrification, carbon resource utilization, net zero emission buildings, resource recycling and reuse, etc.
South Korea	Offshore wind power, crystalline silicon batteries, zero–energy buildings, smart grids, electric vehicles, hydrogen energy and fuel cells, resource recycling, hydrogen reduction ironmaking, low–carbon fuels, low–carbon semiconductors, bioenergy, CCUS, smart energy management systems, smart agriculture and fisheries, carbon sinks, etc.

3 Main Policies and International Experiences in Technological Innovation for Green and Low-carbon Transition

In order to promote the development of green and low-carbon technological innovation, countries must not only comprehensively consider the balance between ecological environment and economic development in policy design but also establish systematic policy support frameworks. The creation of green and low-carbon technological innovation often relies on a series of interconnected policy tools that can guide and promote innovation activities by regulating behavior, providing economic incentives, and creating supportive environments. By implementing effective regulatory tools, economic and financial tools, and "soft" tools, countries can stimulate the innovative motivation of market players while safeguarding environmental quality, gradually forming a complete pathway from policy formulation to innovation realization.

Innovation policy refers to all actions taken by public organizations to support the generation and dissemination of innovation, with the aim of influencing the innovation process to achieve predetermined political objectives through innovation. Innovation is defined as new products, services, processes, or business models used for commercial or non-commercial purposes[9].

Innovation policy tools are categorized into three main types: regulatory tools, economic and financial tools, and soft tools. These three categories are commonly referred to as "sticks", "carrots", and "sermons"[10].

Regulatory tools play a crucial role in innovation policies. They govern the interaction between society and markets through legal and institutional mechanisms. Specific measures include intellectual property protection, the management of researchers and higher education organizations, competition policies, and industry-specific regulations. These regulations are characterized by their mandatory and restrictive nature, ensuring that all stakeholders operate within a clear legal framework, thereby providing structured and institutional support for knowledge and innovation processes. This framework directly drives innovation and encourages companies to adapt to new regulations, enhancing their innovative capacity.

Economic and financial tools are key in regulating and incentivizing innovation activities. These tools mainly operate through offering economic incentives or deterrents to support specific social and economic activities. They can be categorized into positive incentives (such as cash transfers, grants, subsidies, low-interest loans, and loan guarantees) or negative incentives (such as taxes and fees). These tools are widely used to support public research organizations and corporate R&D activities. Traditionally, most of the existing financial instruments impact innovation from the supply side, but policymakers have increasingly recognized the importance of demand-side tools, such as driving innovation through public procurement.

Soft tools typically complement regulatory and economic tools. They are characterized by voluntary and non-coercive measures, achieved through providing advice, making normative appeals, or reaching voluntary or contractual agreements to achieve governance objectives. Specific soft tools include support for research infrastructure, networking and collaboration platforms, information provision, data access, and innovation promotion and public outreach. Notably, the use of soft tools reflects the shifting role of governments, moving from being providers and regulators to facilitators and coordinators, with increasingly widespread application in the field of innovation policy.

Table 2 Classification of Policy Tools for Technological Innovation for Green and Low-carbon Transition

Classification	Policy tools
Regulatory tools	Mandatory environmental regulations
	Green and low-carbon standards
	Emission trading systems
	Regulations and voluntary agreements
Economic and financial tools	Fiscal grants
	Tax incentives
	Low-interest loans, green bonds
	Venture capital, seed funds
Soft tools	Strategic planning
	Provision of public research facilities
	Technology incubator support
	Intellectual property protection

Green and low-carbon technological innovation policies have both the common characteristics of traditional innovation policies and some special policy tools. Table 2 lists the commonly used policy tools of technological innovation for green and low-carbon transition[11]-[14]. This study focuses on the role of five types of policy tools, namely fiscal policy, financial policy, green and low-carbon standards, carbon market and strategic planning, in promoting green and low-carbon transition technological innovation.

3.1 Fiscal Policies

Major countries have increased fiscal investment in green and low-carbon technological innovation and green infrastructure to provide financial support for low-carbon industries and a fair transition. The United States recently passed three pieces of legislation that can help reduce greenhouse gas emissions: the *Infrastructure Investment and Jobs Act* (IIJA, also known as the *Bipartisan Infrastructure Law*), the *Inflation Reduction Act of 2022* (IRA), and the *CHIPS and Science Act*. Compared to the average level of spending over the past decade, these laws have more than tripled U.S. government spending on energy transition, making the U.S. a global leader in climate change and clean energy investment[15]. In 2019, the European Union established the world's largest low-carbon technology demonstration program—Innovation Fund—with plans to allocate €10 billion between 2020 and 2030 to support the commercialization of innovative low-carbon technologies. In 2021, Japan's government established a ¥2 trillion "Green Innovation Fund" to support decarbonization technology R&D and deployment in key industrial sectors. That same year, the United Kingdom announced a £1 billion Net Zero Innovation Portfolio over the next decade to leverage £3.5 billion from industrial and academic institutions, accelerating low-carbon technology innovation and creating new business models.

Many countries have utilized subsidies and tax incentives to create a favorable policy environment for green and low-carbon technological innovation. Since 2021, the European Union has revised the Guidelines on

State aid for environmental protection and energy, the Trans-European Networks for Energy (TEN-E), the Energy Taxation Directive, the Alternative Fuels Infrastructure, and the Renewable Energy Directive. These revisions support low-carbon technology R&D and demonstrations, address unfavorable factors hindering the development of low-carbon technologies, reduce investment risks for low-carbon projects, and ensure the sustainability of project financing. Japan's 2021 tax reforms established the "Carbon neutral investment incentive", allowing companies to obtain a certain percentage of tax deductions for purchasing equipment with decarbonization effects as stipulated by law.

Japan's Green Growth Strategy serves as a typical example of a green economy that promotes the coordinated development of the environment and the economy, aiming to facilitate low-carbon transformation through government spending, tax incentives, and national subsidies to achieve the goal of carbon neutrality by 2050.

First, Japan has established a ¥20 trillion Green Innovation Fund to support the development of key green technologies, such as hydrogen supply chains, large-scale electrolyzers, and the research and development of next-generation ships and aircraft. This funding will continue to support technology development, demonstration, and commercialization over the next decade. Additionally, Japan provides special funding support for certain industries, particularly projects utilizing hydrogen technology in steel production and initiatives to reduce offshore wind energy costs.

Secondly, regarding tax incentives, Japan offers tax benefits for investments in carbon-neutral facilities, allowing companies to enjoy up to a 10% tax reduction or 50% special depreciation for qualifying investments, applicable to facilities such as power semiconductors, lithium-ion batteries, and fuel cells. Moreover, the research and development tax credit has been extended to companies that increased their R&D investments during the pandemic, with credits reaching up to 30%.

Finally, Japan directly supports low-carbon technologies and renewable energy projects through national subsidies, especially in high-emission industries, assisting companies in transitioning to low-carbon production methods through financial support. These measures not only advance the development of low-carbon technologies like hydrogen and wind energy but also lay a solid foundation for achieving carbon neutrality goals..

3.2 Financial Policies

Diverse financial support policies have provided funding for green and low-carbon technological and industrial innovation. Developed countries are using a variety of financing mechanisms to strongly support the development and market application of related technologies. These mechanisms include traditional financial instruments—such as credit, bonds, stocks, trusts, and financial leasing—which provide enterprises with abundant financial support. They also include venture capital and hybrid financing methods, which offer necessary financial backing for innovation projects at different stages of development.

For traditional financial tools, they provide diverse and ample funding support for companies, ensuring that green and low-carbon projects receive the necessary financial backing. For example, the **European Union (EU)** supports small and medium-sized enterprises (SMEs) through the European Investment Fund (EIF) and the European Investment Bank (EIB)[18]. The EIF designs innovative financial products and cooperates with banks, guarantee institutions, leasing and microfinance institutions, and private equity and venture capital funds to meet SMEs' financing needs. In terms of equity tools, the EIF invests in venture capital and growth funds, supporting technology transfer and business incubators, and increasing the availability of venture capital for high-growth and innovative SMEs. Regarding debt tools, the EIF enhances the lending capacity of financial intermediaries by providing guarantees and credit enhancements through securitization. Additionally, EIF also has an established track record of supporting both established and first-time entrepreneurial teams, promoting best market practices and corporate governance. Its equity activities are primarily supported by resources from the EIB and the European Commission. By cooperating with numerous financial intermediaries, EIF provides two main guarantee tools: credit enhancement/securitization and guarantees/counter-guarantees for microcredit, SME loans or leasing portfolios, providing strong protection for SME financing. **Japan**'s financial measures focus on enhancing sustainability disclosure, supporting public-private partnerships among financial institutions, and revitalizing the green bond market[19]. First, through the revised 2021 Corporate Governance Code, Japan has promoted companies to improve the quality of sustainability disclosures based on international frameworks such as the Task Force on Climate-Related Financial Disclosures (TCFD), thereby attracting more green investments. Second, regulatory authorities encourage financial institutions and local entities to develop business models that address climate change issues by providing support and knowledge sharing, which not only promotes local financial innovation but also strengthens the overall flexibility of the financial system. Moreover, Japan has revised its Green Bond Principles and developed a climate transition finance roadmap for high-emission sectors to ensure capital supply and stimulate the green bond market's prosperity. Additionally, Japan is committed to establishing an international green financial center, offering convenient information platforms and certification mechanisms, driving the development of the ESG bond market, and further incentivizing financial innovation and green investments.

For venture capital and hybrid financing, these innovative financing methods are more focused on helping startups bridge the gap between R&D and market entry. Venture capital can provide pilot and demonstration funds for innovative ideas and future technologies, especially for small companies aiming to scale up in the market. Supported by comprehensive financial regulations and a mature venture capital system, as shown in figure 3, North American investors in 2022 invested $7 billion in clean energy startups, accounting for 57% of global venture capital in clean energy[20].

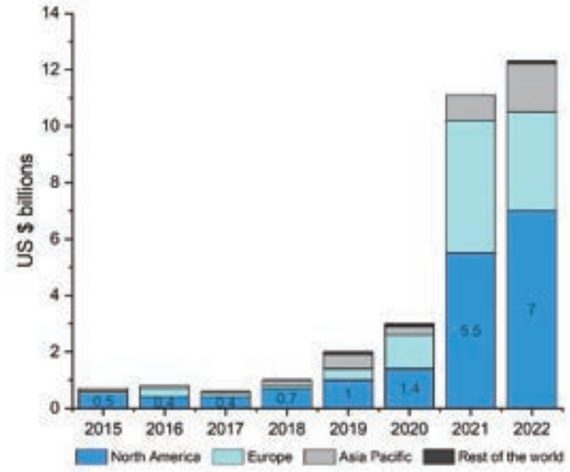

Figure 3. Venture Capital Investment in Clean Energy Startups by Region

Source: Oliver Wyman, 2024

Clean energy technologies are not always well-suited to venture capital's typical investment model. Most venture capital funds sign buyback agreements, committing to return capital to investors within approximately five years. However, this short-term investment horizon often mismatches with the longer time frames and substantial upfront investments required by energy technology developers, especially those in the hardware domain. Additionally, energy technology developers typically need to overcome numerous technical, commercial, and regulatory hurdles before becoming sustainable businesses.

Hybrid financing, as an innovative financial tool, combines public and private funds through debt and equity financing and risk mitigation tools. It helps companies overcome the "valley of death" between technology development and large-scale deployment and commercialization. For example, the Breakthrough Energy Ventures-Europe fund, a collaboration between the European Commission and the European Investment Bank, uses equity investment to support energy technology development, leveraging private investment in R&D and innovation[21](see case 1). This financing approach helps address the challenges of sustainable development, especially supporting the R&D of "public goods".

Box 3-1: European Breakthrough Energy Ventures (BEV-E)

The European Commission, the European Investment Bank, and Breakthrough Energy Ventures (BEV) have jointly established a new €100 million investment fund called the European Breakthrough Energy Ventures (BEV-E). The fund aims to invest in innovative European companies and bring cutting-edge clean energy technologies to market. The funds include a €50 million contribution from the European Investment Bank, backed by financial instruments from the EU's research and innovation program, Horizon 2020, under the InnovFin Guarantee, and an additional €50 million from Breakthrough Energy Ventures. This combination of long-term risk capital from the European Investment Bank and Horizon 2020's guarantee funding is intended to accelerate global decarbonization and support faster, more efficient market entry for clean energy innovations across Europe.

Investment Project 1:

H2SITE received €12.5 million in financing to scale up its breakthrough membrane reactor technology. This financing will accelerate the commercialization of H2SITE's integrated membrane reactor and membrane separation technology, enabling the extraction of fuel cell-grade hydrogen from ammonia or methanol cracking, or facilitating the transport of hydrogen within existing natural gas infrastructure. H2SITE will also increase its membrane manufacturing capacity by operating a globally unique membrane manufacturing plant in northern Spain.

H2SITE has demonstrated strong commercial appeal in 2022, securing projects to convert ammonia into hydrogen for Birmingham's bus fleet in the UK and to transform biogas into hydrogen for hydrogen stations in Spain and France. The company is also involved in several projects for separating hydrogen/natural gas mixtures within existing natural gas transportation infrastructure.

Investment Project 2:

Blue World Technologies Receives Investment from Breakthrough Energy Ventures Europe (BEV-E)

Blue World Technologies secured investment from BEV-E and other existing shareholders, such as the Danish Growth Fund (Vækstfonden), bringing the company's total Series B financing to around €37 million. The Series B funds will be used to scale up the company's fuel cell production and invest in developing methanol-driven fuel cell applications for the maritime sector.

Blue World Technologies develops and produces methanol fuel cells, as shown in Figure 5. As a green alternative to traditional internal combustion engines and generators, it is currently in the pre-mass production stage. Blue World Technologies will start mass production, and as the scale is further expanded, the company expects to reach a production capacity of 500MW within a few years.

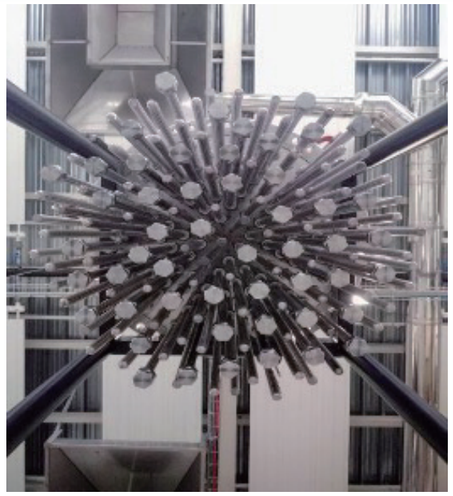

Figure 4 Membrane Bundle of Ammonia Cracking Reactor

Figure 5 Methanol Fuel Cell

3.3 Green and Low-Carbon Standards

Standards play a critical role in shaping the path of green and low-carbon technological innovation by regulating market behavior and creating demand for low-carbon innovations. Different types of standards, such as technical standards and emissions-based standards, not only set targets for controlling emissions but also specify methods and equipment requirements, promoting the development of clean technologies. For instance, Japan's Green Transformation Technology Inventory (GXTI) provides a comprehensive tool for identifying green technology trends through patent searches[22]. In the U.S., the voluntary carbon market (VCM) integrates protocols and methodologies for sectors like energy, while the Department of Energy's carbon dioxide removal (CDR) procurement initiative supports the application of standards[23].

The European Union has implemented a series of forward-looking green and low-carbon standards, such as the Ecodesign for Sustainable Products Regulation, which significantly expands the scope of the Ecodesign Directive to cover nearly all physical products. This regulation requires products to consider their entire lifecycle environmental impact, including durability, reparability, recyclability, and resource efficiency. The regulation also introduces a digital product passport, allowing consumers and regulators to make more informed environmental decisions based on product sustainability data[24].

Box 3-2: EU Battery Regulation

Background and Purpose

As global battery demand grows rapidly, particularly in sectors like electric vehicles, renewable energy storage, and portable electronics, the environmental impact of battery production, use, and recycling is increasingly significant. By 2030, global battery demand is expected to increase 14-fold, with the EU likely accounting for 17% of that demand. This growth, mainly driven by the electrification of transportation, will lead to an equivalent increase in demand for raw materials, requiring efforts to minimize their environmental impact. In response to these challenges, the EU passed the Battery Regulation in 2023, becoming the first legislation globally to cover

the entire lifecycle of batteries. This regulation aims to promote the sustainable development of the battery industry by imposing stringent environmental requirements.

Key Requirements

Carbon Footprint and Digital Battery Passport: Starting in 2025, electric vehicle and industrial batteries will be required to introduce carbon footprint declarations, performance rating labels, and carbon emission limits. From 2027, all batteries with capacities exceeding 2 kWh must be equipped with a digital battery passport, providing detailed information on the battery's chemical composition, capacity, and carbon footprint. This measure will not only help consumers make informed purchasing decisions but also provide regulatory authorities with effective compliance monitoring tools.

Material Recycling and Sustainability: The regulation sets stringent targets for recycling efficiency and material recovery. From 2028 onwards, industrial and electric vehicle batteries must contain a certain proportion of recycled materials, such as cobalt, lithium, and nickel. This requirement is aimed at reducing reliance on virgin resources and fostering the development of a circular economy.

Removable and Replaceable Batteries: To extend product lifespans and reduce waste, from 2027 onwards, all portable devices must have batteries designed to be user-removable and replaceable. This rule will have significant implications for manufacturers of mobile phones, tablets, and other portable devices.

Impact and Significance

The EU Battery Regulation (EU 2023/1542) will have a profound impact on the global battery industry, setting new benchmarks through a series of stringent environmental requirements and innovation standards. The regulation pushes the battery industry towards sustainability, driving technological innovations in battery design and manufacturing. The carbon footprint declarations, digital battery passports, and user-replaceable battery requirements will foster innovation throughout the battery lifecycle. Additionally, mandatory recycling and the use of recycled materials will accelerate advancements in material technologies, helping the EU enhance its strategic autonomy, reduce reliance on external supply chains, and contribute to global climate goals. As the world's first regulation covering the full lifecycle of batteries, this legislation not only lays the foundation for the EU's own green transition but also sets new global standards for the battery market.

3.4 Carbon Markets

Carbon markets are an effective policy tool for accelerating emission reductions and promoting investment in low-carbon technologies. By controlling financial flows and establishing constraint mechanisms, they expedite the global transition to a low-carbon economy. The European Union launched its carbon market EU-ETS in 2005, which is now in its fourth phase. The EU-ETS initially controlled the total issuance of allowances in the primary market and then allowed regulated entities in industries subject to carbon emission regulations to trade allowances in the secondary market. This market mechanism drives companies to fulfill their emission reduction obligations. To prevent carbon leakage, the EU also introduced the Carbon Border Adjustment Mechanism (CBAM) and has proposed the scope of products and methods for calculation under this mechanism. After Brexit, the UK launched its own carbon trading scheme, UK-ETS, on January 1, 2021. The UK-ETS is a "cap-and-trade" system, a market-based pricing mechanism designed to incentivize and regulate emissions reductions cost-effectively. Japan has been developing its carbon trading system through multi-sector pilots for some time. In April 2023, Japan officially launched its GX-ETS trial carbon market, marking significant progress toward establishing a national carbon trading platform. In contrast, the United States primarily operates regional carbon trading markets, using carbon trading to push companies to adopt innovative low-carbon technologies and achieve emissions reductions.

In 2023, the European Parliament passed the EU-ETS reform plan, aiming to cut emissions in the ETS sectors by 62% by 2030 (compared to 2005 levels), an increase from the previous target of 43%. The reform achieved three key agreements: First, expansion of ETS coverage. ETS will be extended to the maritime sector for the first time, and the EU will continue to assess the feasibility of including waste incineration in the ETS. Additionally, a separate ETS II is planned to be established by 2027, covering road transport and commercial building heating fuels, with potential expansion to manufacturing sectors. Second, clarifying the transition period and the free allocation reduction schedule for the CBAM. From October 2023 to December 2025, the CBAM will be in a transition period where reporting is required but no taxes will be levied. From 2026 onwards, CBAM will be fully operational, with free emission allowances for EU industries gradually phased out by 2034. Third, improving green transition financing. All revenues from ETS auctions will be used for climate-related activities, including increasing funding for innovation and modernization. Starting in 2026, a Social Climate Fund will be established to support vulnerable groups affected by the climate transition, with funding primarily sourced from ETS II revenues, estimated to reach up to €65 billion ($68.9 trillion).

3.5 Strategic Planning

Strategic planning is a crucial tool for supporting the implementation of technological innovation outcomes for green and low-carbon transition, enhancing technological competitiveness, and establishing leadership in future green technologies. In the United States, the Biden administration has formulated a comprehensive green and low-carbon innovation strategy. This includes[25]:First, strengthening top-level design for green and low-carbon technological innovation. Through presidential executive orders, the U.S. government has outlined the ten critical green and low-carbon technology fields that need breakthroughs. The administration has also laid out the basic pathways for achieving carbon neutrality through cutting-edge science and technology innovation. Second, enhancing governmental leadership and coordination in climate technological innovation. Under the framework of the National Climate Task Force, the Climate Innovation Working Group has been established. This group, co-chaired by the White House Office of Domestic Climate Policy, the Office of Science and Technology Policy, and the Office of Management and Budget, is responsible for coordinating and organizing technological forces across federal government agencies to define and implement a unified innovation agenda. Third, building a multi-departmental collaborative R&D and innovation organizational model. The U.S. Department of Energy (DOE) leads in designing and organizing the core tasks of the innovation chain, from basic research to technological breakthroughs, early-stage demonstrations, and deployment. The DOE coordinates with agencies such as the National Science Foundation, Department of Transportation, Department of Agriculture, and Department of the Interior in joint R&D efforts. Four, optimizing the mechanism for the transformation and implementation of scientific and technological achievements. The DOE has been reformed and reorganized to address weak links in the lifecycle of innovative technologies, from R&D to commercialization. The department has established the Office of Clean Energy Demonstrations to create an innovation chain that links technology development with commercialization. The office also deploy major scientific and technological tasks with the collaboration of various stakeholders, including research institutions, industries, and universities, leveraging the strengths of these diverse entities to form new research institutions (see figure 6).

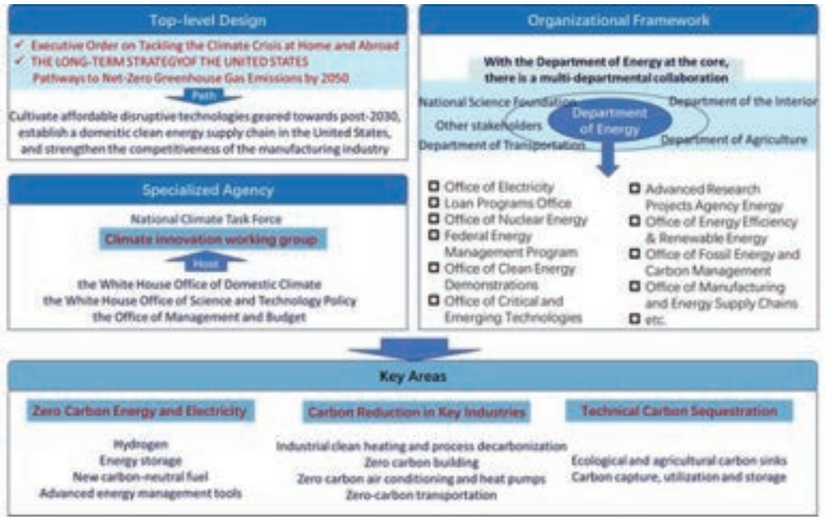

Figure 6. Carbon Neutrality Technology Deployment in the United States

3.6 International Experiences in Technological Innovation for Green and Low-carbon Transition

(1) A Renewed Focus on Industrial Policy

Major economies are increasingly adopting "new industrial policies" to foster the learning-by-doing process for low-carbon technologies, expand the learning pool, and internalize the externalities of green and low-carbon technological innovation. Since green and low-carbon technologies bring widespread societal benefits, the creators and pioneers of these technologies often do not fully capture the benefits of R&D and green gains. In response, many major economies have welcomed the return of industrial policy over the past decade, recognizing the critical role of policy intervention in effectively allocating market resources.

These new industrial policies share several characteristics: First, they emphasize broad support for R&D and technology diffusion in specific sectors to promote technological innovation and knowledge accumulation. For example, the Net-Zero Industry Act in the European Union supports a broad range of low-carbon technologies on its defined "Net-Zero Technology List". Second, they focus on overcoming market failures and constraints on new technology development through regulation and incentives, addressing issues such as the lack of niche markets, fragmented supply chains, and externalities. For example, the U.S. Inflation Reduction Act provides subsidies along the entire supply chain, from basic raw materials to manufacturing and domestic consumption. Third, these policies are integrated into broader strategic frameworks focused on creating comparative advantages. The EU's low-carbon technological innovation plan aligns with its broader strategy for global climate leadership and pursuit of low-carbon industry dominance. The basic paradigm for these "new industrial policies" can be summarized as identifying, supporting, and updating strategic sectors in a dynamic process, with technological innovation serving as the driving force.

(2) Innovation Entities

In terms of green and low-carbon innovation policy, developed countries share common goals, focusing on creating national strategic leadership, with enterprises as the main driving force, market-oriented mechanisms, and deep integration of research, industry, and application to achieve high-level outcomes and commercialization. These policies have three main features: First, they emphasize top-level design and coordination of national scientific and technological forces, with governments playing an indispensable role in leading and organizing technological innovation. This involves coordinating resources across public and private sectors, including research institutions, universities, and enterprises, to create a virtuous cycle between top-down goal-setting and bottom-up demand-driven innovation. Second, they focus on building a new innovation ecosystem that serves carbon neutrality, promotes breakthrough technological advancements, and fosters commercialization. Countries are deploying interdisciplinary and cross-agency large-scale research plans to achieve these goals. Third, they promote public-private partnerships to establish new research and development institutions that provide advanced technologies and solutions for emissions reduction. For example, the UK has proposed the Industrial Decarbonisation Research and Innovation Centre, while the U.S. is focusing on industrial electrification and decarbonization with plans to establish a Department of Defense Manufacturing Innovation Institutes. And Germany has established the Competitiveness of Energy-Intensive Industries as a one-stop platform for government, industry, academia and research, dedicated to uniting all stakeholders to provide consulting, technology and funding for energy-intensive industries.

(3) Innovation Environment

Green and low-carbon transition faces political, economic, technological, and other uncertainties and risks. Developed countries have introduced diverse environmental policy tools to eliminate obstacles to green and low-carbon technological innovation, creating a conducive regulatory and policy environment. Different countries and regions have developed three primary models in terms of policy tools and their combination: The U.S. primarily adopts supply-side policies, supplemented by environmental and demand-side policies, focusing on financial investment, infrastructure development, and technological innovation, supplemented by planning, subsidies, and tax incentives. Japan adopts a demand-side model, which is mainly based on environment and demand, supplemented by supply, emphasizing policies such as diversified financial measures, green government procurement, and carbon markets. Europe and the UK apply a balanced approach, combining financial, fiscal, carbon market, pricing, and other tools to create a comprehensive policy system that supports green and low-carbon transition.

Developed countries use a balanced approach of regulation, standard-setting, financial support, and fiscal incentives to create a favorable environment for low-carbon technological innovation. By utilizing regulation and standards to guide financial investments and technological development, they promote the scale-up of low-carbon economic activities. Financial support and tax incentives, meanwhile, reduce innovation costs and stimulate market vitality. The balanced application of these environmental policy tools has cultivated fertile ground for the rapid development and application of green and low-carbon technologies. For instance, the UK takes a short-term approach by relying on government intervention and policy incentives, stimulating investment in low-carbon technologies through research and demonstration government funds, green financing, carbon pricing, and the promotion of green products. In the medium and long term, the UK focuses on market mechanisms, gradually building a comprehensive framework that includes carbon pricing, carbon trading, energy efficiency regulations, and international trade agreements. In terms of environmental policy coordination, both the UK and Japan have proposed improving environmental regulatory frameworks to ensure that new decarbonization technologies and policies contribute to achieving environmental goals.

(4) Innovation Funding

Governments in developed countries have adopted diversified funding strategies to support different stages of development for startups. In addition to direct grants, governments also provide loans and loan guarantees to support business growth. For instance, in the European Union, small businesses can receive up to 70% of the industrial research costs or 45% of the experimental development project costs. This type of funding reduces the financial burden on startups during the technological R&D process. Governments also participate directly in the growth of startups through equity investments. An example of this is the collaboration between the European Investment Bank and the Breakthrough Energy Ventures-Europe fund (BEV-E), which provides long-term, capital-intensive project funding to support the growth of clean energy technology startups.

In providing funding to startups, governments balance risks and rewards by using reasonable funding terms and strict regulatory mechanisms. This helps mitigate risks to public funds while ensuring expected economic and social benefits. For instance, the U.S. Department of Energy provides debt financing for large energy projects based on project viability, usually targeting companies that have already secured late-stage venture capital and major customers. This approach reduces financial risk while ensuring effective use of funds. Meanwhile, the European Union has encouraged banks to offer loans to startups by sharing part of the risk through loan guarantees, facilitating more private capital flow to high-risk, high-reward clean energy technology projects.

Governments often fund startups indirectly through incubators, accelerators, and venture capital funds. These intermediaries are better equipped to identify, guide, and provide financial support to startups. For example, the European Institute of Innovation and Technology (EIT) through its InnoEnergy Highway program offers not only financial support but also acceleration services tailored to energy technology innovators. This program helps startups by providing consultation and access to market analysis, improving their chances of success even before the business is established. This model of indirect support increases funding efficiency while also offering added value in the form of technical consulting and market insight.

Developed countries also provide a variety of incentives, such as tax breaks and financial subsidies, to encourage private sector investment in startups. For example, the UK's Enterprise Investment Scheme (EIS) encourages private investors to fund high-risk startups by offering tax relief, including a 30% income tax reduction for investors and capital gains tax exemptions for investments held for more than three years. These incentives attract substantial private capital to startups, encouraging private investors to take on higher risks. In addition, developed countries have placed a strong emphasis on supporting collaboration between financial institutions and private enterprises through policies and regulations, particularly in areas such as environmental information disclosure and the development of green bond markets. Transparent environmental information disclosure standards and innovative financial products draw more private capital into green technology sectors, fostering innovation and green investments. The above policies aim to create a favorable market environment, enhance the flexibility of the financial system, provide more convenient and broader financial support for green and low-carbon transition, and jointly promote the development of clean energy technologies.

Governments also support startups through awards and competitions, which not only provide financial backing but also enhance their visibility in the market. For instance, Germany's Start Up Energy Transition Award (SET) links innovators with stakeholders in venture capital, public and private sectors, increasing the market visibility and appeal of winning companies through media coverage. This broad exposure and synergy encourage greater interest and investment in clean energy technologies, motivating more innovators to participate.

(5) International Cooperation

Developed countries actively promote international cooperation on green and low-carbon technological innovation through existing international platforms, new technical alliances, industry alliances, and bilateral or multilateral cooperation agreements. For example, the G7 *Industrial Decarbonisation Agenda* calls for strengthened cooperation on market regulation, standard-setting, investment, and procurement between governments and multilateral platforms. One initiative is the creation of a Clean Energy Buyers Alliance, designed to create markets for low-carbon industrial products. The agenda also emphasizes the role of existing multilateral platforms such as the Clean Energy Ministerial, Mission Innovation, and the CCUS Acceleration Consortium. Japan has proposed strengthening cooperation with the United States and Europe on the standardization of key technologies and rules and working with emerging economies to expand markets for green products. The United States has established various climate, energy, or green technology alliances at different levels and across regions. For example, the U.S. is forming a Transatlantic Green Technology Alliance with Europe, and within the Indo-Pacific region, it has set up a climate working group under the Quad (comprising the U.S., Japan, India, and Australia) to collaborate on future key technologies. Through these international cooperation efforts, developed countries aim to coordinate global efforts in market regulation, standard setting, investment, and procurement strategies, promoting technology export and seeking leadership in the global green transition. Simultaneously, they seek to secure key materials and resources from diverse sources, ensuring supply chain security in the face of geopolitical conflicts and resource crises.

4 China's Strengths and Challenges in Technological Innovation for Green and Low-carbon Transition

4.1 Strengths

(1) Massive Market Scale

China has a vast consumer market, providing broad application scenarios for green and low-carbon technological innovation. A large consumer market supports the large-scale application of green and low-carbon technologies, enabling these technologies and products to quickly enter the market, receive feedback, and make improvements. This facilitates rapid iteration of technologies, driving down costs and advancing technological progress. According to a recent the report Technology Outlook on Wind and Solar Power toward China's Carbon Neutrality Goal by Institute for Carbon Neutrality, Tsinghua University, China's wind and solar installed capacity is expected to reach 1,582 to 2,130 GW by 2030 and 5,496 to 7,662 GW by 2060, with wind and solar generating capacity increasing 13-fold by 2060 compared to 2020 levels. By 2060, wind and solar will account for 83% of total installed capacity for all energy sources[26]. In addition, solar PV manufacturing is the technology with the greatest regional concentration. Approximately 80% of global solar PV manufacturing capacity is concentrated in China, with the entire supply chain benefiting from lower production costs. China is expected to increase its share of solar panel production to slightly above 80%, while its share of wafer and polysilicon production may approach 95%. Due to economies of scale and technological innovation, China has been a major driver in the reduction of global solar PV and

onshore wind energy costs. As noted by the Executive Director of the International Energy Agency (IEA), Fatih Birol, China's contributions have significantly enhanced access to clean energy technologies and lowered the cost of utilizing green technologies globally[27]. According to data published by the International Renewable Energy Agency (IRENA), between 2010 and 2022, the global weighted average cost of electricity (LCOE) from utility-scale photovoltaic plants dropped by 89%, offshore wind by 59%, and onshore wind by 69%[28]. China's vast market capacity provides enterprises with broad platforms for experimentation and promotion, facilitating a complete industrial chain from R&D to commercialization. This not only accelerates technological iterations but also enhances the competitiveness of enterprises.

(2) Economic Growth Potential

China's economy has shifted from high-speed growth to high-quality growth, yet its economic growth rate remains among the highest globally, demonstrating significant potential. This continued growth will provide ample space for the application of green and low-carbon technologies. A continuously expanding economy offers sufficient funding and resources for innovation activities, fostering increased investment in R&D and driving breakthroughs in technology. In 2023, China's total GDP was 12.606 trillion yuan, a 5.2% increase from the previous year. Although this represents a slowdown compared to previous periods of rapid growth, the underlying potential of China's economy remains strong, and the long-term trend of positive development has not changed. Additionally, in the first half of 2024, China's industrial added value from enterprises above a designated size increased by 6.0% year-on-year. The green and low-carbon industries showed a particularly strong growth trend. For example, in the first half of the year, production of new energy vehicles (NEVs) increased by 34.3% year-on-year, while the output of complementary products like charging stations and lithium-ion batteries for vehicles grew by 25.4% and 16.5%, respectively[29]. Meanwhile, the combined export value of the "New Three" products—NEVs, lithium-ion batteries, and solar cells—reached 1.06 trillion yuan, breaking the trillion-yuan mark for the first time with an annual growth rate of 29.9%. Notably, one out of every three vehicles China exports is a new energy vehicle[30]. This promising economic growth potential will attract more foreign investors to participate in China's green and low-carbon industries, providing long-term capital support for innovation projects.

(3) Strong Organizational and Engineering Capabilities

China's ability to organize and implement large-scale engineering projects provides a strong foundation for green and low-carbon transition and technological innovation. First, China has a mature engineering management system and an efficient decision-making mechanism that can quickly mobilize resources and effectively advance large projects. Additionally, the Chinese government's emphasis on infrastructure construction ensures policy and financial support, facilitating the smooth implementation of large-scale green and low-carbon projects. Moreover, China possesses the most complete production supply chain network in the world, with significant economies of scale, allowing companies to reduce costs through bulk procurement and production. This extensive supply chain network fosters upstream and downstream cooperation and accelerates the diffusion and application of new technologies. In regions such as the Yangtze River Delta and the Pearl River Delta, the wind and PV industries have developed comprehensive supply chains. In the wind power sector, China has established an integrated industrial system, including wind turbine sets, special steel for wind power, hubs, towers, main shafts, flanges, gears, bearings, nacelles, special coatings, and other key components[31]. In the PV industry, 80% of China's solar panel production—equivalent to two-thirds of global output—comes from three provinces: Jiangsu (40% of production), Anhui, and Zhejiang (each contributing about 20%)[5]. Furthermore, China's robust technical expertise and a vast pool of engineering talent lay a solid foundation for the development and application of green technologies. With these strong organizational and engineering capabilities, China is well-positioned to accelerate the promotion and application of green and low-carbon technological innovations during the transition to a greener economy.

4.2 Challenges

Despite its achievements, China still faces several challenges in green and low-carbon technological innovation.

Innovation environment: Green low-carbon transition involves cross-disciplinary technological innovations. Although China has a large number of researchers, the country lacks top-tier talent with cross-disciplinary expertise in green and low-carbon fields. Furthermore, in the areas of basic research and technology development, China lacks professionals with international competitiveness. The current education and training system has not fully adapted to the rapidly evolving demands of technological innovation, limiting the cultivation and attraction of high-level talent and impeding the enhancement of innovation capabilities.

Many entrepreneurs exploring new technologies and markets are often discouraged by difficulties in obtaining financing, policy uncertainties, and insufficient market demand. Additionally, the high risk of innovation failures and the lack of a robust tolerance mechanism suppress entrepreneurial initiatives.

Although China actively promotes international cooperation in the field of green and low-carbon technologies, the depth and breadth of such collaboration are still limited due to geopolitical tensions and trade restrictions. These limitations hinder technological exchange and transfer and make it harder for China to access cutting-edge global technologies and resources.

Industrial policy: Current policies are more focused on supporting mature industries, with relatively less emphasis on emerging green technologies. Policy stability, continuity, and enforcement still need to be strengthened. Moreover, the issue of inefficient subsidies is prevalent, and the fairness and consistency of regional industrial policies need to be improved. The lack of coordination between regional and industrial policies also hampers the progress of industrial transformation and upgrading. Meanwhile, the support and coordination for corporate restructuring and exit are insufficient, and the policy effect evaluation and adjustment mechanism is missing, which affects the accuracy and effectiveness of the policy. Finally, the connection between the old and new policies is not close enough, and the restrictive policy benefits of high-energy-consuming industries need to be transformed into support for emerging green industries to promote the green transition of the industrial structure.

Financing channels: The development of green and low-carbon industries requires substantial long-term investment, but China's green financial system is still in its nascent stage. Small and medium-sized enterprises (SMEs) in green technology innovation have limited access to capital and often struggle to obtain long-term, stable funding. Venture capital models are not fully developed, and the current models provide insufficient support for green and low-carbon projects. As a result, many promising innovation projects fail to scale due to a lack of funding. In terms of carbon trading, the auction mechanism, as a way of allocating carbon quotas, can provide price signals and promote market competition, but there is still room for improvement in its design and implementation. The price signal problem is a key challenge in the carbon market. If the carbon price is too low, it may not be enough to motivate companies to invest in emission reduction; while too high a carbon price may increase the operating costs of companies. In addition, with the continuous expansion of the carbon market, the complexity of the market mechanism has increased, which

has put forward higher requirements for supervision and information disclosure. The existing supervision system and information disclosure mechanism are not yet sound, which may lead to inefficient use of funds and difficulty in achieving the expected emission reduction effect.

Consumer demand: Although public environmental awareness has gradually increased, market demand for green products and services has not been fully unleashed. Price sensitivity and consumption habits have prevented the green consumer market from reaching scale, limiting companies' market expansion and technological promotion. Existing incentive measures, such as tax breaks and subsidies, are mainly directed at production and companies, with few direct incentives for consumers. This reduces consumers' economic motivation to purchase green products.

Coordination mechanisms: Green and low-carbon transition involves multiple sectors and industries, but there is insufficient cross-departmental collaboration and policy coordination. Different departments often have inconsistent policy goals and implementation pathways, lacking a unified action framework and standards. This results in inefficient resource allocation and hampers the effective promotion and application of green low-carbon technologies.

5 Policy Recommendations for China's Green and Low-Carbon Technological Innovation

5.1 Next Steps for the China Council for CCICED in Green and Low-Carbon Technological Innovation

(1) Research on the Green and Low-Carbon Technological Innovation Models and Policies of Developed Countries

First, a comprehensive review of green and low-carbon technological innovation actions and deployments in developed countries and regions (including the United States, the European Union, the United Kingdom, Germany, Japan, etc.) should be conducted. This includes analyzing their innovation models and pathways, as well as compiling lists of next-generation green and low-carbon technologies and disruptive innovations prioritized by these economies. Second, comparisons should be made between China and developed countries in terms of technological innovation for green and low-carbon transitions, identifying areas where China needs to improve. Third, a classification-based evaluation of the policy effects of green and low-carbon technological innovation in developed countries should be undertaken, analyzing the conditions under which different policies are effective. Lessons learned from these experiences can then be used to inform China's policy formulation.

(2) Research on China's Near-, Mid-, and Long-Term Roadmaps for Green and Low-Carbon Technological Innovation

First, organize multidisciplinary experts and scholars to draft a roadmap for China's green and low-carbon technological innovation, with clear goals for the near term (5-10 years), mid-term (10-20 years), and long term (20-30 years). This roadmap can be divided into several sectors, such as energy transition, industry, transportation, construction, agriculture and land use, circular economy, digital technologies and their integration with green and low-carbon innovations, as well as disruptive and intergenerational technologies. Second, develop selection criteria for technologies in each sector, considering factors such as emission reduction potential, economic and social impacts, and international scientific and technological competition. It is also essential to respect the uncertainties of the innovation process and introduce regular evaluations and adjustment mechanisms for the roadmap.

(3) Research on the Development of China's Green and Low-Carbon Technological Innovation Policy System in the New Era

Given China's dual carbon goals, there is a need to build a green and low-carbon technological innovation system that aligns with these objectives. Research should focus on the challenges and shortcomings of the current system, examining dimensions such as the innovation environment, fiscal and tax policies, financing mechanisms, and innovation entities. Recommendations should be made to improve the system, particularly in fostering original and disruptive innovations in the green and low-carbon technology field. These efforts aim to enhance China's capacity to provide globally competitive green and low-carbon public goods.

5.2 Policy Recommendations for Accelerating China's Green and Low-Carbon Technological Innovation

(1) Cultivating an Environment Conducive to Innovation

First, a coordinated layout for China's medium- and long-term science and technology development plans should be implemented to ensure the long-term stability and consistency of technology-driven carbon neutrality goals. Second, entrepreneurial spirit should be promoted. A social environment that encourages innovation and tolerates failure must be created. It is essential to protect the innovation rights of entrepreneurs through legal means and involve them in planning, policy-making, and setting standards for green and low-carbon technological innovations. Policies such as science and technology innovation vouchers and equipment rental incentives should open up scientific infrastructure to enterprises, fostering shared use of resources. Third, China's basic research should be more open. Cooperation with international third-party organizations in establishing dedicated funds for forward-looking, breakthrough, and disruptive green and low-carbon technologies should be encouraged. Partnerships between domestic and international energy companies, universities, research institutions, and industry organizations should be fostered to form innovation consortia, with the goal of attracting global talent to China for green and low-carbon research and collaboration.

(2) Adjusting the Focus of China's New Round of Green Industrial Policies

First, the next round of green industrial policies should be innovation-driven, avoiding over-expansion of production capacity, and ensuring that limited fiscal resources are more directed toward green and low-carbon technological innovation. Second, a public information monitoring platform for the green and low-carbon industry and technologies should be established. This platform should periodically release data and information on capacity utilization, market supply and demand, and technological investment and application. Third, green and low-carbon technologies should be categorized based on their emission reduction benefits, cost, and industrial impact. Regular evaluations should be conducted to adjust and update technology lists, which can then be linked with subsidies, financing, and other policies. Fourth, government procurement of green and low-carbon products should be strengthened, with government agencies and public institutions prioritizing the purchase of green and low-carbon technologies and products.

(3) Strengthening Multi-Source Financial Governance to Provide Financing Support for Leading Green and Low-Carbon Technological Innovations

First, a financing policy system should be developed based on carbon emissions reductions. Multiple sources of funding, including bank loans, equity investments, and green bonds, should be mobilized to create a multi-tiered, multi-channel green financial system that meets the diverse financing needs of different types and stages of green and low-carbon innovation projects. Second, venture capital should play a more significant role in supporting original and disruptive innovations in green and low-carbon technologies. A financial services system based on venture capital and backed by stock markets should be established. Third, revenues from carbon trading markets, as well as fines and penalties from other carbon reduction regulatory policies, should be used to provide competitive subsidies to support green and low-carbon technological innovations.

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