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The Second Year of the Tsinghua University – Harvard University Project on Technological Systems and Innovation Policy for Climate Neutrality

Synthesis report

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Executive Summary

This report provides a synthesis of the work in the second year of the "China-US Deep Decarbonization Technology Innovation and Policy" project. It summarizes the research findings of the 2022-2023 academic workshops on key decarbonization technologies, which focused on building heating; green hydrogen; carbon capture, utilization, and storage (CCUS); and hard-to-abate transportation modes. As summarized here, the work of the three teams separately and in the joint seminars provided up-to-date assessments on the status of these key technologies in both countries, including their current and projected costs and possible policies for accelerating progress toward widespread implementation.

The Foundation Provided in the Project's First Year

The first year of the joint study was summarized in a report produced jointly by key members of the three teams, provided to the two countries' national Climate Envoys at the time of the Glasgow Conference of Parties to the UN Framework Conference on Climate Change, and made public shortly thereafter, in January 2022 (https://www.belfercenter.org/publication/harvard-tsinghua-joint-statement-carbon-neutrality-pathways-china-and-united-states).

The report pointed out that, despite the many nuanced differences between the Chinese and American contexts, there exists a noteworthy similarity in the list of low- and zero-carbon technologies poised to play important roles in the countries' net-zero pathways. That list includes solar and wind power, smart grids, CCUS for fossil fuel facilities, hydrogen from renewable sources, electric and hydrogen-fueled vehicles, and improvement of end-use energy efficiency across all sectors.

From this list, the US side elected to focus in the first year on (i) an expanded and modernized electricity grid; (ii) CCUS; (iii) electrolytic hydrogen production; and (iv) electricity and hydrogen for space heating and water heating in buildings. The Chinese side focused, similarly on (i) electrification and the electricity grid, (ii) CCUS for coal power plants, (iii) the transport sector, and (iv) end-use efficiency in industry and building. At the end of the first year's work, the two sides agreed that in the second year both would pursue deeper dives on decarbonization of building heating, hydrogen from renewable sources, and CCUS.

Building Heating

A notable distinction between China and the United States in building sector is the prevalence of district heating in northern China, contrasting with the predominant use of distributed heating systems in households and commercial spaces in the United States. Therefore, the technical solutions considered in the U.S. study tend to be simpler. Challenges in the United States include the need for large-scale energy-saving retrofits in existing buildings, the high cost of clean heating technologies such as heat pumps, and the imperative to decarbonize power systems due to the electrification of the building sector.

In northern China, the discussion around the decarbonization of urban district heating is ongoing. The research conducted by the Tsinghua team suggests that combined heat and power units (CHP) heating is a feasible solution in the early stage towards carbon neutrality. It will remain necessary for some time to maintain an appropriate number of coal-fired CHP units with CCS to meet building-heating needs. Both countries face the challenge of high capital costs when promoting heat pumps for heating and cooling, and there is a need for technological advancement and supportive policies to facilitate the application of the technology.

Hydrogen From Renewable Sources

The transition to a global low-carbon economy will significantly reshape the existing energy supply, production, and consumption patterns. Hydrogen, which is receiving much attention in this context, might well become a focus of both competition and cooperation among major powers. China and the United States are encountering similar challenges in the development of clean hydrogen: technological maturity disparities along the value chain, high cost, limited demand and market presence, and insufficient infrastructure. The massive subsidies in the United States have significantly boosted investment and production of clean hydrogen, while policy enhancement is needed to channel investment towards green hydrogen projects.

In contrast, despite China’s obvious cost advantages for hydrogen production, the country's hydrogen policy remains fragmented, with inadequate support measures. Looking ahead, both China and the United States need to proactively create a domestic market for green hydrogen application, focusing on the demonstration and application of clean hydrogen in the industrial sector. For China, a reframing of its hydrogen strategy is imperative, in the context of the evolving global energy geopolitical landscape and domestic long-term carbon neutrality and energy system transition strategies. Actively participating in international cooperation and standard certification is crucial to ensure the competitiveness of industrial products in the future.

Carbon Capture, Utilization, and Storage (CCUS)

China and the United States are two of the three countries in the world, alongside India, with the greatest imperative to develop and deploy CCUS technologies. The majority of global and national-level modelling results indicate that by the middle of this century, all three countries will need to deploy CCUS, along with conventional and breakthrough emission reduction technologies, to achieve net-zero emissions. CCUS serves as the sole technological option for achieving near-zero emissions from fossil fuels, a feasible technological solution for deep decarbonization of hard-to-abate sectors such as steel, cement and others, and a main technical measure to support carbon recycling in the future.

In general, the CCUS technology and infrastructure development in China significantly lags behind that of the U.S. While the CCUS technology in the United States has progressed to the stage of commercial application, China’s capture technology is still in the demonstration phase while its CCUS system integration optimization is in the pilot stage and its infrastructure development is comparatively delayed. Given the urgent demands of China’s domestic carbon peaking and carbon neutrality strategy and further consolidating cost advantages in equipment manufacturing, China needs to upgrade the orientation of CCUS from a strategic reserve technology to a practical solution.

Cross-Cutting Policy Issues

While both China and the United States have made significant progress in climate policymaking, they face challenges in the effective implementation and enforcement of these policies. The U.S. policy relies heavily on incentives such as large-scale investments, tax incentives, and subsidies; policy consistency remains challenging. China's "1+N" policy package primarily relies on a “top-down” approach, underscoring the need to strengthen the "bottom-up" participation of the whole society. In terms of time frame, both countries’ climate policies focus on the period before 2030, with long-term climate measures still lacking in robustness. Moving forward, the two countries still need to continuously refine their climate policy systems while strengthening measures and implementation to achieve multiple goals, including emission reduction, justice and equality, public health, employment, and public participation.

The pathways and technologies required to achieve global net-zero goals are becoming increasingly clear. The innovation of deep decarbonization technology is highly concentrated in a few economies, however, posing challenges to the commercialization and global diffusion of these technologies. Simultaneously, the current rate of deployment of low-carbon and deep decarbonization technologies falls short of meeting the imperative to "keep 1.5-degree target within reach". The decarbonization pathways and technology demands in China and the U.S. are remarkably similar, presenting an opportunity for the two countries to collaborate in ways that are mutually beneficial for meeting their respective climate goals, advancing research, and identifying best practices in ways that may also be helpful to other countries.

Recommendations

Based on the research in the second year of our joint project, we recommend the following specific steps for the two governments:

(1) Clarify the strategy and goals of developing and deploying major decarbonization technologies such as heat pumps, green hydrogen, and CCUS. Align these technologies with global energy geopolitical shifts and domestic long-term strategies of carbon neutrality and the energy transition.

(2) Strengthen climate policymaking by releasing clear and consistent policy signals. Actively cultivate domestic market demand for deep decarbonization technologies to encourage private sector investment and promote economies of scale.

(3) Enhance international cooperation in innovation to accelerate the commercialization of deep decarbonization technologies. Facilitate rapid reductions in technology costs and increased market penetration through global collaboration.

(4) Consider a comprehensive approach to unify the different technologies, infrastructures, and applications in the energy transition; examples include co-production of thermal and electrical energy for building-sector decarbonization, integrating green hydrogen production with end-use-sector applications, and fitting industrial clusters with CCUS infrastructure.

(5) Consider infrastructure investments in parallel with policies to enhance innovative clean technologies for both energy supply and end use. Recognize that infrastructure has become both a driver and constraint in the development of green hydrogen, CCUS, and other technologies.

(6) Promote the effective implementation of climate policies, improve long-term measures and climate policy packages to guard against economic and social risks associated with the transition.

Finally, as noted in our first-year report, it will be critical to mobilize increased energy-climate finance for developing countries—not only for clean-energy technology and infrastructure but also for adaptation to climate change—and to strengthen institutions and mechanisms for technology transfer. Research indicates that developing countries will need to increase their climate investments by at least four to eight times by 2030. The international community will need to work collectively on both financing and technology transfer if such levels are to be achieved.

Acknowledgements

In September 2020, former Special Envoy for Climate Change of China, Mr. Xie Zhenhua, launched a trilateral research project focusing on comparative study of Chinese and U.S. deep decarbonization technologies and policies. The three project teams are: the Institute for Climate Change and Sustainable Development team led by Professor He Jiankun and Professor Li Zheng at Tsinghua University; the Global Energy Technology Innovation Initiative (GETI) team led by Professor John Holdren from the Kennedy School at Harvard University; and the Harvard-China Project on Energy, Economy and Environment (HCP) team led by Professor Michael McElroy from Harvard's Paulson School of Engineering and Applied Sciences (SEAS). The project, designed to span three years, received strong support from the Ministry of Ecology and Environment of China, among other institutions. Energy Foundation China generously sponsored the project's research and academic activities.

A series of seminars organized under this project were well attended by members of the three teams, as well as by a number of experts from other universities and research organizations. We would like to express our special thanks to Professor Baolong Wang from the School of Architecture at Tsinghua University, Professor Jin Lin from the Department of Electrical Engineering at Tsinghua University, Professor Huan Liu from the School of Environment at Tsinghua University, Professor Jingli Fan from China University of Mining and Technology, Dr. Xian Zhang from the Administrative Center for China's Agenda 21 at the Ministry of Science and Technology, and Dr. Dong Xu from the National Energy Group. On the Harvard side, we are grateful for the participation of Dr. Alan Krupnick from Resources for the Future, Professor Andrew Waxman from the University of Texas at Austin, and Dr. Nicola De Blasio from the Harvard Kennedy School.

These experts shared cutting-edge research and practical insights in deep decarbonization technology and policies to accelerate its implementation. We appreciate the support provided by Yuxuan Huang, Canyang Xie, and Yuezhang He from Tsinghua University and Amanda Sardonis and Karin Vander Schaaf for their contributions to the organizing the research and the seminars. Special thanks to Tsinghua's Canyang Xie and Harvard's Rachel Mural for meticulous proofreading and editing of the report. Our gratitude extends to Fang Zhang and Jieqiong Tong for their unwavering support on project coordination, and Chunliu Mao, Zhihui Li, Yi Hong and Congyu Wang for their robust support in the early stages of the project and its smooth implementation. In addition, we would like to acknowledge the valuable assistance from numerous colleagues and peers in the research and publication of this report.

Content

1. Background and research scope

1.1 Background

In September 2020, former Special Envoy for Climate Change of China, Mr. Xie Zhenhua, launched a trilateral research project focusing on deep decarbonization technologies between China and the United States (U.S.). The three project teams are: the Institute for Climate Change and Sustainable Development team led by Professor He Jiankun and Professor Li Zheng at Tsinghua University; the Global Energy Technology Innovation Initiative (GETI) team led by Professor John Holdren from the Kennedy School at Harvard University; and the Harvard-China Project on Energy, Economy and Environment (HCP) team led by Professor Michael McElroy from the Department of Earth and Planetary Sciences and the John A. Paulson School of Engineering and Applied Sciences (SEAS) at Harvard University. Despite challenges posed by the COVID-19 pandemic, the three teams have diligently advanced research, fostered academic exchange, and maintained a strong cooperative relationship between leading universities in China and the U.S., yielding results that serve as important references for both the Chinese and American governments.

In November 2014, President Obama and President Xi Jinping issued a joint statement on climate change, demonstrating the significance of consistent and cooperative China-U.S. leadership on climate issues. This joint statement played a pivotal role in laying the groundwork for the Paris Agreement, which was finalized a year later. During the 2021 the United Nations Framework Convention on Climate Change (UNFCCC) 26th Conference of the Parties (COP26), China and the U.S. issued the Glasgow Joint Declaration on Strengthening Climate Action in the 2020s; the Declaration played a significant role in shaping the conference's outcomes, reflecting not only a determination for action but also a practical and respectful guide for all Parties. Despite differences on numerous issues, the two governments have maintained longstanding willingness to cooperate on climate change at many levels.

The pathways and technologies required to achieve net-zero emissions around mid-century exhibit similarities across China and the U.S., highlighting the value of collaboration in research, technology innovation and development, and related policies. Through the 2023 China-U.S. Sunnylands Statement on

Enhancing Cooperation to Address the Climate Crisis, China and the U.S. not only reaffirmed their commitment to international climate cooperation but also decided to operationalize the Working Group on Enhancing Climate Action in the 2020s. This Working Group engages in climate dialogue and cooperation; exchanges information on policies, measures, and technical knowledge around emission reduction technologies; and identifies and implements cooperative projects. The joint efforts of Tsinghua and Harvard University on this project demonstrate the value of continuing and strengthening China-U.S. climate cooperation; the work accomplished thus far exemplifies the importance of future cooperation between the two countries.

1.2 Research scope

To achieve the net-zero by mid-century, as announced by both China and the U.S., all feasible pathways require a rapid and substantial scale-up of low- and zero-carbon energy supply technologies, accompanied by the deployment of energy transmission infrastructure to reflect new supply and growing demand; in addition, new technologies and practices to dramatically improve end-use energy efficiency and electrification will be needed. In the pursuit of these goals, diversification of both energy supply and end-use technologies emerges as a key strategy for both countries. However, neither country is in a position to confidently and accurately identify which combinations of technologies are most likely to achieve net-zero emissions.

Some of the most practical and useful approaches include:

- Identifying technologies with the greatest potential to make a significant contribution based on existing knowledge;
- Identifying and describing obstacles that hinder the full realization of their emission reduction potential; and
- Identifying and promoting near-term regulations, policies, and agreements that can be implemented to maintain the likelihood of achieving net-zero emissions around mid-century, based on continued advancements in technology and research from now until 2030.

These are the goals of our joint project, which also include exploring insights and lessons from each other's national development pathways. Through collaborative efforts, we aim to communicate our interim and final findings directly to national climate policymakers and the Conference of the Parties (COP) to the United

Nations Framework Convention on Climate Change (UNFCCC).

1.3 Research progress

During the first year, the Tsinghua team focused on mapping China's decarbonization pathway towards carbon neutrality before 2060, while two Harvard teams delved into key technologies and policies necessary for the U.S. to achieve net-zero. The joint study found that despite each country's circumstances, the low- and zero-emission energy technologies most likely to play pivotal roles in decarbonization are similar in China and the U.S.

In the Chinese context, these key technologies encompass solar and wind power generation, smart grids, CCUS for fossil fuel power plants and industries, hydrogen produced from renewable energy, electric and hydrogen-fueled vehicles, and energy efficiency improvements across all end-use sectors. Next-generation nuclear power technologies, biofuels, energy storage, and hydropower are other potential contributors. In addition to taking full advantage of existing cost-effective emission reduction measures, there is a need to advance non-CO_2 greenhouse gas reduction technologies and to increase agricultural and forest carbon sinks in order to offset residual emissions from hard-to-abate sectors[1].

Building upon these findings, the Harvard and Tsinghua teams coauthored the "Joint Report on the Pathway to Carbon Neutrality between China and the United States", which was published on the website of the Belfer Center for Science and International Affairs at the Harvard Kennedy School of Government.[2] This report was supplemented by three "Research Briefs for Non-Specialists" on narrower technology topics disseminated by HCP, enhancing media coverage in both countries of specific Harvard-Tsinghua studies[3]. The Tsinghua team's dedicated work on China's decarbonization pathway has laid a robust foundation for the follow-up flagship project "Research on China's 2035 and medium- and long-term low-carbon development strategy in the context of carbon neutrality".

In the second year, the Harvard Kennedy School team focused on policy research related to three key

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[1] He J, Zhang X, Li Z, et al. Comprehensive Report on China's Long-Term Low-Carbon Development Strategies and Pathways[J]. Chinese Journal of Population Resources and Environment. 2020, 18(4): 263–295. DOI:10.1016/j.cjpre.2021.04.004.

[2] Harvard-Tsinghua Joint Statement on Carbon-Neutrality Pathways for China and the United States. Harvard Kennedy School Belfer Center. January 2022. https://www.belfercenter.org/publication/harvard-tsinghua-joint-statement-carbon-neutrality-pathways-china-and-united-states.

[3] See https://chinaproject.harvard.edu/news/hcp-research-briefs-non-specialists

technologies: 1) the decarbonization of heating, 2) green hydrogen, and 3) carbon dioxide capture, utilization, and storage (CCUS). Simultaneously, the Harvard-China Project team conducted an in-depth case study on the potential of green hydrogen technology in Texas (a U.S. state with rich renewable energy resources and expansive existing hydrogen infrastructure) and led a supplemental workshop on decarbonizing hard-to-abate transportation modes.

Concurrently, the Tsinghua research team focused on the key technological potentials and obstacles to achieving carbon neutrality, designing a comprehensive framework comprising five distinct topics: 1) decarbonization of building heating, 2) technology potential of hydrogen in the transportation sector, 3) CCUS, 4) costs and risks of a zero-carbon power grid, and 4) assessment on China's climate policy, as well as a synthesis report. At COP28 in Dubai, the Tsinghua team unveiled the major findings of its synthesis report and policy briefs, each focusing on specific topics. The team also invited scholars from the U.S., the United Kingdom (U.K.), India, and other countries to conduct in-depth discussions on deep decarbonization technologies and international cooperation.

This report is the summary of the second project year; it draws on research and findings from a series of workshops under this project. To provide a holistic perspective and deeper insights, the report also incorporates global progress and offers a comparative analysis between China and the U.S. The report is structured as follows: Chapter 1 introduces the background and progress of the project; Chapter 2 provides an overview of global innovation and application of deep decarbonization technologies; Chapter 3 synthesizes the research on the decarbonization of building heating, hydrogen production and application, and CCUS deployment in China and the U.S.; Chapter 4 provides a preliminary assessment on climate policies in both countries; and Chapter 5 presents conclusions and policy recommendations.

2. Innovation and application of deep decarbonization technology: an overview

A carbon-neutral economy will be both capital- and technology-intensive, relying on a combination of conventional and breakthrough technologies. The International Energy Agency (IEA) underscores that more than half of the technologies needed for carbon neutrality by 2050 are still in the research and development (R&D) and demonstration stages. Active development and deployment of these technologies within the next decade is imperative to meet ambitious climate targets[4]. However, the landscape is characterized by intense competition in technological innovation and commercialization among major global powers, while the imperative for green and low-carbon development has added an additional challenge for developing countries seeking to catch up. This unbalanced international pattern is gradually expanding.

2.1 Highly concentrated global innovation

A small number of economies have been dominating the global R&D and deployment of low-carbon energy technologies; simultaneously, the competition among major economies is escalating. Since 2016, there has been a notable surge in the global public budget for low-carbon energy technology R&D and demonstrations, with an average annual growth rate of 7.6% (see figure 2-1). Despite this growth, a concentrated group of economies (including North America, Europe, Japan, South Korea, Australia, New Zealand, and China) accounted for a staggering 97.5% of the global public budget for low-carbon energy technology R&D in 2021. China has become the second largest government supporter of energy R&D. Meanwhile, India has outpaced France, Germany, and Japan to become the third largest. The competition around government R&D spending in the clean energy sector between China and the U.S. is particularly intense. Depending on the definition of clean energy, both countries have the potential to be the world's largest clean energy investor[5].

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[4] IEA, 2021. Net zero by 2050: a roadmap for the global energy sector.

[5] Zhang F, Gallagher K S, Myslikova Z, et al. 2021. From fossil to low carbon: The evolution of global public energy innovation//Wiley Interdisciplinary Reviews: Climate Change. DOI:10.1002/wcc.734.

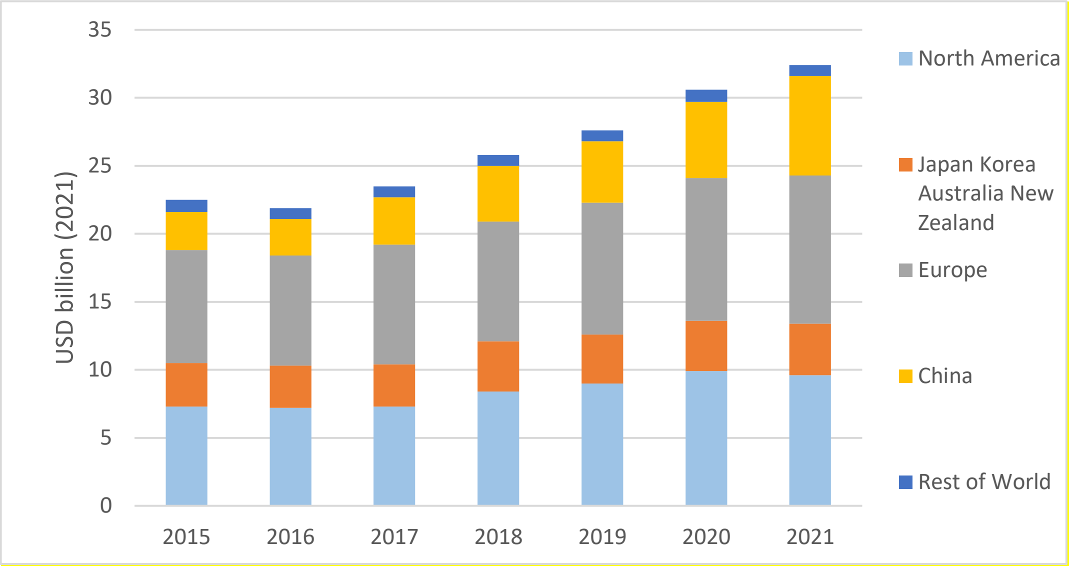

Figure 2-1 Global public budget for low-carbon technology R&D areas by region (2015-2021)
Source: Created by ICCSD, based on Energy Technology RD&D Budgets (IEA, 2023 edition).

The output of low-carbon technology innovation also exhibits a substantial imbalance. According to WIPO, green energy technologies patents are highly concentrated in a small number of countries. Between 2005 and 2015, five major countries—Japan, the United States, Germany, China, and South Korea—accounted for nearly 90% of green energy technology patent family applications, followed by other developed countries such as France, the Netherlands, and the United Kingdom[6] . In contrast, the share of developing countries is much smaller, with India, Brazil and South Africa each accounting for less than 1%, and most African countries having almost no patent applications[7] . Since 2012, global patents for low-carbon technologies have gradually shifted from energy supply technologies to end-use and enabling technologies (i.e., hydrogen, cross-cutting technologies, etc.) as well as technologies with both low-carbon and broader applications (i.e., information and communication technologies and artificial intelligence)[8].

In the realm of international standards development, about 78% of published standards come from three international bodies: the International Standards Organization (ISO), the International Electrotechnical Commission (IEC), and the Society of Automotive Engineers (SAE). The majority of the remaining standards

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[6] Rivera León, L., Bergquist, K., Wunsch-Vincent, S. A., Xu, N., & Fushim, K. 2023. Measuring Innovation in Energy Technologies: Green Patents As Captured by WIPO's IPC Green Inventory. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4429912

[7] World Intellectual Property Organization (WIPO). 2023. World Intellectual Property Indicators 2023. https://doi.org/10.34667/TIND.48541

[8] European Patent Office (EPO) & International Energy Agency (IEA). 2021. Patents and the energy transition. Paris. https://www.iea.org/reports/innovation-in-batteries-and-electricity-storage.

come from the European Committee for Standardization (CEN) and the American Society of Mechanical Engineers (ASME).

The concentration of global innovation hubs is another striking feature, primarily residing in a handful of economies. Out of the 120 innovation clusters worldwide, 98 are located in Europe, with Munich (Germany), the Ruhr area (Germany), and Paris (France) comprising the three largest innovation clusters. The U.S. maintains its position as the center for cutting-edge and conventional energy technologies and has established collaborative R&D links with 21 other countries in the field of green hydrogen technology. In east Asia, China, Japan, and South Korea have cultivated innovation clusters focusing on batteries, hydrogen, and communication technology. An analysis by Elsevier indicates that China has ascended to the world's second largest patent holder and the largest paper publisher in the field of green patents, especially regarding information and communication technology and green transportation[9]. Taken together, the highly unbalanced global innovation landscape poses a significant challenge for the widespread diffusion and transfer of deep decarbonization technology on a global scale.

2.2 Slow progress on technology deployment

By comparing different sectors, it is evident that certain sectors will decarbonize earlier than others due to differing characteristics and varying levels of technological maturity. The power sector is poised to decarbonize through the development of clean electricity generation and, through electrification, this sector will play a crucial role in partially decarbonizing additional end-use sectors such as land transport (i.e., roads and railways), buildings, and certain industries. Despite a variety of technical options for industrial decarbonization, large-scale deployment of these technologies has faltered due to insufficient technological maturity and high costs. Hard-to-abate sectors (such as agriculture, aviation, and shipping) will rely heavily on breakthrough technologies and changes in consumer behavior to decarbonize.

Although the speed of technological iteration in the ongoing scientific and technological revolution and industrial transformation has accelerated, it is still far from the scale required by net-zero pathways. The IEA's Global Energy Transition Stocktake highlights that only a handful of technologies (such as

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[9] ELSEVIER’S ANALYTICAL SERVICES. Pathways to Net Zero: The Impact of Clean Energy Research. (2021). https://www.elsevier.com/__data/assets/pdf_file/0006/1214979/net-zero-2021.pdf.

photovoltaics, electric vehicles, and lighting) currently align with the pace of net-zero scenarios. More than half of technologies will require additional policy support and accelerated development, while over one-third are not on track, seriously lagging the level of deployment required for achieving net-zero[10]. Notable inadequacies exist in low- and zero-emission technology development in the industrial sector, methane emission abatement technologies, heavy and long-haul transport, infrastructure-related district heating, and CCS (see figure 2-2). Addressing these gaps necessitate not only increased investment and collaboration in scientific and technological innovation on an international scale, but also the acceleration low-carbon technology deployment and rapid reduction of technology costs, so as to promote the global clean and low-carbon transition.

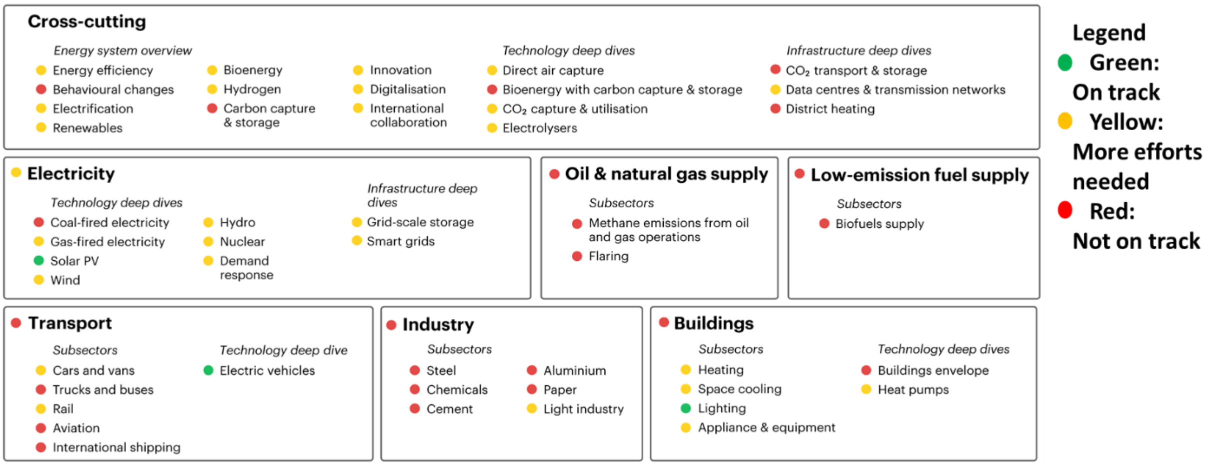

Figure 2-2 Technology landscape and progress assessment in the net-zero emission scenario
Source: IEA, 2023. Tracking Clean Energy Progress 2023.

3. Progress and challenges of deep decarbonization technologies in China and the United States

3.1 Decarbonization of building heating

In 2022, heating and hot water accounted for nearly half of global building energy consumption, resulting in direct emissions of 2.4 billion tons of CO_2 and indirect emissions of 1.7 billion tons of CO_2. Globally, 60% of

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[10] IEA. 2023.Tracking Clean Energy Progress 2023. Paris.
https://www.iea.org/reports/tracking-clean-energy-progress-2023#overview

heating energy still originates from fossil fuels and about 40% of households need space heating for part of the year. Additionally, heating costs are a major component of household energy bills. Under the IEA's 2050 net-zero scenario, carbon emissions associated with building heating must be halved by 2030 through a combination of building envelope efficiency improvements, alternate fuels and technologies, and power sector decarbonization. In general, the net-zero scenario entails reducing the average energy intensity of global heating by about 4% per year before 2030, or double the average rate observed over the last decade[11].

Decarbonizing the building sector faces significant challenges due to the diverse and dispersed nature of thermal energy supply and utilization. The low-carbon transition requires not only investments in new technologies and infrastructure renewal, but also the transformation of heating facilities in hundreds of millions of homes. A potential solution to these challenges is to reduce energy consumption by improving energy efficiency, improving thermal insulation, and recycling waste heat. Additional solutions include more efficient utilization of thermal energy, the adoption of specific zero- or low-carbon heating technologies, and the adoption of new technologies for heat storage and transmission. Countries are deploying key technologies including heat pumps, electric boilers, renewable thermal energy storage, and hydrogen.

The challenges are even greater in the field of district heating, due to the large-scale energy supply required. One approach is to continue using fossil fuels while eliminating some CO_2 emissions through CCUS. Another approach involves using alternative fuels, such as low-carbon electricity, biomass, and other sustainable heat sources. In addition, innovative technologies are constantly emerging that will shape the future landscape of thermal energy storage, transportation, and distribution. This dynamic environment is shaping new thermal energy supply chains and business models[12].

While gas boilers still dominate global household heating markets, efficient and low-carbon heating technologies are emerging. At present, over 30 countries have introduced subsidies for heat pumps; heat pump sales accounted for 10% of the global heating market share in 2021, and global sales of heat pumps grew by 11% in 2022. Under the IEA’s net-zero scenario, the global heat pump stock would almost triple by 2030, covering at least 20% of global heating needs. Therefore, further policy support and technical

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[11] IEA, 2023. Energy system/ Buildings/Heat pumps. https://www.iea.org/energy-system/buildings/heating

[12] The Royal Society, 2021. Low-carbon heating and cooling: what science and technology can do to tackle the world’s largest source of carbon emissions. https://royalsociety.org/climate-science-solution

innovation are required to meet this goal[13].

(1) Decarbonization of building heating in the United States

Direct energy use of fossil fuels accounts for 13% of U.S. greenhouse gas emissions in the building sector. About 110 million U.S. households use distributed systems for space heating. Of the total fuel used for heating, natural gas accounts for about half, electricity accounts for about one-third, and other fuels (such as oil, propane, firewood, and kerosene) account for a relatively small share. Regional variations are significant. In the south, the heating supply is dominated by electricity, accounting for two-thirds of the total share. In the central and western regions, natural gas comprises up to three-quarters of heating energy. Natural gas also holds a majority share in both the west and northeast. In the southeast, heat pumps have become common heating appliances. In 2015, around 10% of U.S. homes used air-source heat pumps for heating; in 2020 this proportion grew to 13%[14].

Since the Biden administration took office, the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) have provided substantial support for clean energy research, development, manufacturing, and infrastructure construction. Reducing the costs of the energy transition for U.S. homes is one of the IRA's key goals, with $8.5 billion in tax rebates allocated to support home electrification and energy conservation retrofits and another $837 million to improve energy efficiency in affordable housing accompanied with subsidized loans for low-income properties. In addition, tax credits are provided to consumers to support home electrification, energy-efficient retrofits, and clean vehicle purchases. According to estimates by the U.S. Department of Energy (DOE), these measures could reduce the costs of energy conservation retrofits and renewable installations by as much as 30 percent per household[15].

Heat pumps play an important role, reducing greenhouse gas emissions by 50% compared to gas boilers. The main advantage of heat pumps lies in their high efficiency, producing more energy in the form of heat as

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[13] IEA. 2023.Tracking Clean Energy Progress 2023. Paris.
https://www.iea.org/reports/tracking-clean-energy-progress-2023#overview

[14] U.S. Energy Information Administration. 2023. Highlights for space heating in U.S. homes by state, 2020.
https://www.eia.gov/consumption/residential/data/2020/state/pdf/State%20Space%20Heating.pdf

[15] FACT SHEET: One Year In, President Biden's Inflation Reduction Act is Driving Historic Climate Action and Investing in America to Create Good Paying Jobs and Reduce Costs. White House. August 16,2023.
Https://www.whitehouse.gov/briefing-room/statements-releases/2023/08/16/fact-sheet-one-year-in-president-bidens-inflation-reduction-act-is-driving-historic-climate-action-and-investing-in-america-to-create-good-paying-jobs-and-reduce-costs/

compared to the amount of electricity needed to operate the pump. While heat pumps demonstrate remarkable efficiency, it's important to note that their performance is influenced by various factors, including the specific heat pump model, the temperature at which heat is produced, and the outdoor temperature. As the latter decrease, the heat pump's efficiency will also decrease. In extremely cold weather conditions, using heat pumps for indoor heating remains challenging.

According to a Princeton University study on the U.S. net-zero pathway, electricity will almost completely replace natural gas for heating and cooking in the U.S. by 2050; furthermore, air-source heat pumps are projected to become the dominant heating technology. Since heat pump efficiency is correlated with ambient temperature, heat pump penetration is higher in the Southern US than in the North, reaching 83% in Florida and 76% in Wisconsin and Minnesota[16]. However, the Harvard team argues that there are challenges associated with achieving such high penetration rates. Particularly in colder climates, where winter temperatures are very low, the switch from natural gas to heat pumps could lead to an increase in household energy costs.

A soon to be published study on U.S. heating from the Harvard team indicates that using heat pumps to replace natural gas heating would significantly increase heating costs (excluding capital costs)[17]. These costs would rise in almost all states, with an increase of approximately 1.5-2 times in cold northern regions. Without either a carbon tax or significant subsidies the rate of heat pump adoption in northern climates will remain slow.

Possible technological solutions to decarbonize the U.S. heating systems include:

-- Use alternative energy sources, such as hydrogen or biomass; however, the cost and scalability of these technologies remain challenging.

-- Replace air source heat pumps with ground source heat pumps, which can improve the performance coefficient. However, the capital investment for ground source heat pumps is extremely high, with the current prices around $20,000 per household.

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[16] Larson Eric, Chris Greig, Jesse Jenkins, Erin Mayfield, Andrew Pascale, Chuan Zhang, Joshua Drossman, et al. 2021. "Net-Zero America: Potential Pathways, Infrastructure, and Impacts." https://netzeroamerica.princeton.edu.

[17] Daniel Schrag. 2022. Challenges to electrification of heating in the Northern U.S. Harvard-Tsinghua Workshop on Heating and Cooling Buildings in a low-carbon world. May 24, 2022. (Unpublished)

-- Store heat energy when electricity prices are low and release it during high-price periods, which are most viable. An example would be storing power from solar power at midday and discharging the electricity in the early evening. However, this option would be difficult to achieve without real-time pricing in the electricity market. Furthermore, low-grade heat storage technology is not mature, necessitating the development of materials that can absorb and store low-grade thermal energy.

Case study: Building Decarbonization in Massachusetts

Massachusetts has set a goal of reducing greenhouse gas emissions by 50% by 2030 and achieving net-zero emissions by 2050. At present, the state's power sector has nearly achieved its target of 50% clean power, with current clean power penetration at 48.2%[18]; additionally, building sector emissions stem mainly from natural gas, propane, and other heating fuels. In terms of heating decarbonization, it is necessary to improve building airtightness, which involves renovating existing buildings with effective insulation. In the next 20-30 years, new buildings in Massachusetts and the Northeast will represent only 20-30% of building stock, and most of the investment in additional savings will have to come from retrofitting existing buildings. Investments in air source heat pumps and geothermal energy (more expensive) will increase. Finally, there is a need for deep decarbonization of the power grid. While the current power system will be able to cope with demand increases by 2030, modifications to the system will be required after 2030 to meet peak demand during the summer months. To decarbonize the building sector by 2050, 60%-70% of households will need to rely solely on air-source heat pumps for heating. To meet the state's 2050 targets, the emissions reduction curve will be very steep, and likely quite costly.

(2) Decarbonization of the building sector in China

According to the Building Energy Conservation Research Center at Tsinghua University, in 2021, China's building sector carbon emissions reached 2.2 billion tons, with direct carbon emissions of 510 million tons (23%), electricity-related indirect carbon emissions of 1.24 billion tons (57%), and heat-related indirect carbon emissions of 430 million tons (20%)[19]. District heating and energy demand in the northern region

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[18] State of Massachusetts. 2023. “Massachusetts Climate Report Card – Power Decarbonization.” https://www.mass.gov/info-details/massachusetts-climate-report-card-power-decarbonization

[19] Building Energy Conservation Research Center at Tsinghua University, Annual report on building energy conservation in China 2023 (Special topic on urban energy system). Beijing: China Architecture and Building Press.

have continued to grow, while the heating energy consumption and carbon emissions per unit area have continued to decline.

In the 15 northern provinces' urban heating sector, coal remains the dominant energy source, accounting for 58% of heating energy consumption. Other sources include natural gas (14%), biomass (15%), electricity (8%), and less-utilized sources, such as geothermal and industrial waste heat (5%). Co-generation units for heat and power and coal-fired boilers are the most common ways to provide heat. The climatic transition zone in southern China and some alpine regions also exhibit a demand for heating through distributed electric heating, household air conditioners, and small electric heaters. In addition, China has the world's largest central heating ring network, with 426,000 kilometers of heating network pipelines in 2020[20].

In 2006, China began to install meters to measure the heat energy consumed by buildings. The National Energy Administration's 11th Five-Year Plan for Energy Development, issued in 2007, not only outlined a shift from distributed boilers to district heating, but also introduced new energy-saving standards for combined heat and power. The 12th Five-Year Plan for Energy Development, issued in 2013, required the development of natural gas cogeneration and the construction of heat networks. The 13th Five-Year Plan for Energy Development, released in 2017, proposed to promote combined heat and power and cooling, biomass combined heat and power, geothermal heating, and low-grade waste heat heating. Since the 12th Five-Year Plan (FYP) period, clean heating in northern China emerged as a policy priority, leading to a series of policies to promote clean heating and pollution control. Notably, clean heating sources in northern China have become predominantly characterized by ultra-low emission[21] coal-fired cogeneration, supplemented by natural gas and other heat sources.

Research on low-carbon transition of combined heat and power in Northeast China

In 2019, 72% of China's electricity supply came from thermal power, and 65% of its heat supply came from cogeneration units. In the northern regions (notably the northeast), where the winter heating season spans

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[20] Hongchun Zhou, 2022. China Clean Heating Industry Development Report 2022. Beijing: China Economic Press.

[21] Flue gas ultra-low emission engineering of coal-fired power plant: under the condition of 6% benchmark oxygen content, the mass concentrations of particulate matter SO2 and NOx emissions in the standard dry flue gas of coal-fired power plants are not higher than 10 mg/m3, 35 mg/m3 and 50 mg/m3, respectively, referred to as ultra-low emissions (National Environment Protection Standard HJ 2053-2018).

six months, approximately 70% of coal-fired power units are cogeneration units[22]. The Chinese government's 2022 Clean Heating Plan for Northern China encourages the conversion of existing coal-fired power units into cogeneration units. Therefore, any examination of China's power system transformation, particularly the transformation of coal-fired power generation units in northern China, must consider both power supply and heat supply.

Compared with other heating methods, coal-fired cogeneration units present significant advantages. The heating cost of cogeneration units is quite low, standing at only 82% of the heating cost of coal-fired boilers, 21% of the cost of electric heating, and 35% of the cost of natural gas heating[23]. Additionally, the controllability of cogeneration units, coupled with the simultaneous supply of heat and power, enhances overall efficiency. The simultaneous supply of heat and electricity supply in the form of combined heat and power CHP, with heat and electricity storage, can protect the energy system against systematic shocks caused by the integration of intermittent renewable energy. The challenge lies in increasing the system's complexity and deploying new technologies.

The Tsinghua team demonstrated that wind power will play a crucial role in Northeast China's energy transition and underscored the need to integrate power and heating systems when planning for low-carbon energy system transitions. The CHP unit is a key technology to achieve clean heating in China and should be prioritized in the early stage of the energy transition. Different processing modes for coal-fired units could lead to huge cost variations in the energy transition of Northeast China. However, attaching CHP units to coal-fired units could reduce the total transition cost by around 16% and avoid stranding coal assets. Additionally, allowing new coal-fired units to be built could reduce the total transition cost by about 20%. Therefore, achieving carbon neutrality within 30 years in Northeast China entails retaining a portion of coal-fired units by retrofitting them as CHP units and adding carbon capture technologies, thereby ensuring a cost-effective low-carbon transition. A comprehensive and integrated energy system planning approach holds promise for realizing a sustainable and low-carbon energy transition in the Northeast.

The potential of heat pumps in the decarbonization of building sector in China

China is the world's largest heat pump manufacturer and exporter, producing about 40% of the world's heat

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[22] Zheng, W., Zhang, Y., Xia, J., Jiang Y. "Cleaner heating in Northern China: potentials and regional balances." Resources, Conservation and Recycling, Vol. 160, September 2020, p.104897. doi: 10.1016/j.resconrec.2020.104897.

[23] Xu, L., Li, J. "Cost analysis of several commonly used heating methods." Heating and cooling, vol.2, 2019, p.23-24.

pumps in 2022 and selling about one million heat pumps in the domestic market. In northern urban areas, district heating remains prevalent; on the other hand, due to milder winters, air source heat pumps are commonly used for space heating in southern China[24]. The adoption of heat pumps is currently below 10%, with coal-fired and gas-fired boilers accounting for about 40% and the combined heat and power units comprising about 50%. In addition, less than 2% of heat pumps are used as water heaters. According to the research of Building Energy Conservation Research Center at Tsinghua University, there is still a great potential for heat pumps tapped for space heating and hot water. By 2060, replacing fossil fuel boilers with heat pumps at a high growth rate could reduce about 795 million tons of CO_2e, constituting 67% of all building heating emissions[25].

Heat pumps exhibit a huge potential to reduce emissions in China's building sector, thereby necessitating a concerted effort to drive technology innovation and deployment. Innovation needs span four key dimensions: 1) improving the energy efficiency of heat pumps, 2) exploring alternatives to fluoride refrigerants, 3) enhancing the interaction between heat pumps and the grid to facilitate demand-side response, 4) and incorporating more sustainable renewable energy sources. Air-source heat pump technology innovation can benefit from high-efficiency compressors (e.g., scroll compressors), advanced defrost technology, and new cycle technology of azeotropic refrigerants. For mixed-source heat pumps, combining air, geothermal, and solar energy should be considered to improve performance. The efficiency of ground source heat pumps can be increased by 50% compared to ordinary heat pumps, and pipeline depths can reach 2000-3000 meters[26]. In addition, there is ample room for enhancing the cooling efficiency of heat pumps.

While large central heating systems are prevalent in northern China, the vast majority of residential and commercial buildings in the U.S. use separate heating systems, spurring unique problems for building decarbonization. As a result, the technological challenges are relatively straightforward and include the scale of energy-efficient retrofits in existing buildings, the high cost of clean heating technologies (such as heat pumps), and the decarbonization of power systems. From a policy perspective, the IRA provides considerable subsidies that can reduce the cost of energy-efficiency renovation and building electrification

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[24] IEA (2023), Global heat pump sales continue double-digit growth, IEA, Paris. https://www.iea.org/commentaries/global-heat-pump-sales-continue-double-digit-growth, License: CC BY 4.0

[25] Building Energy Conservation Research Center at Tsinghua University. 2021. Annual report on building energy conservation in China 2021. Beijing: China Architecture and Building Press.

[26] Ibid.

by 5-30%. On the other hand, decarbonization options for urban district heating in northern China, especially in the frigid Northeast region, are still under discussion. According to research from the Tsinghua team, cogeneration unit heating with carbon capture facilities is the most economical and feasible technology to reduce emissions from heating. This pathway will require China to retain a portion of its coal-fired units for heating. Both countries grapple with the challenge of high costs in promoting heat pump heating technology, relying on technology and policy advancements to foster the use of heat pump technology.

3.2 Hydrogen from renewable sources

Since the Japanese government released the world's first national hydrogen strategy in 2017, more than 40 countries have issued hydrogen energy strategies (as of July 2023). The era of carbon neutrality has fostered new opportunities for the production and application of hydrogen. As the global technological pathway to carbon neutrality becomes clearer, clean hydrogen is emerging as an option to advance electrification and serve as an energy source to support decarbonization efforts. Current hydrogen production emphasizes low-carbon hydrogen (hereafter referred to as clean hydrogen) in the short-to-medium term with a transition to green hydrogen in the longer term. Hydrogen applications are gradually narrowing – focusing on hard-to-abate sectors that cannot be electrified, such as industrial high-temperature thermal processes, carbon-based fuel and feedstock substitution, and zero-emission aviation and shipping. The storage and transportation of hydrogen using existing infrastructure is being considered in several countries; for example, Europe has identified pipeline transportation and focuses on retrofitting existing gas pipelines to accommodate hydrogen transportation.

Hydrogen is expected to play an important role in transitioning towards global carbon neutrality, but a large gap remains between current clean hydrogen production and projected future demand. Despite optimistic forecasts for future hydrogen supply and demand, 2022 total global clean hydrogen production was less than 1 million tons[27]. Projections for China's 2060 hydrogen consumption range from 90 million tons to 130 million tons[28]. Clean hydrogen by 2050 could reduce U.S. economy-wide emissions by 10% from 2005

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[27] IEA (2023), Global Hydrogen Review 2023. IEA, Paris.
https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf

[28] China Hydrogen Association. 2021. Report on hydrogen and fuel cell development in China (2021).

levels[29].

At present, hydrogen production predominantly relies on fossil fuels, with consumption primarily concentrated in traditional industrial applications; however, infrastructure development is accelerating. In 2022, global hydrogen production was around 95 million tons (see Figure 3-1). Of this figure, clean hydrogen production accounted for less than 1% of total supply while hydrogen as a by-product of petrochemical production represented about 14.8%. The remaining 84.3% was sourced from fossil fuels, of which 70% was produced from natural gas and about 30% from coal.

On the demand side, in 2022 global hydrogen demand increased by nearly 3% compared with 2021, driven primarily by traditional industrial applications such as refining, synthetic ammonia, methanol, and steel industries. New applications, such as road transportation, accounted for only 0.1% of the demand[30]. In the context of manufacturing and infrastructure, by the end of 2022, global electrolyzer capacity stood at about 700MW with approximately 1,070 hydrogen refueling stations in operation and around 4,600 kilometers of hydrogen pipelines worldwide.

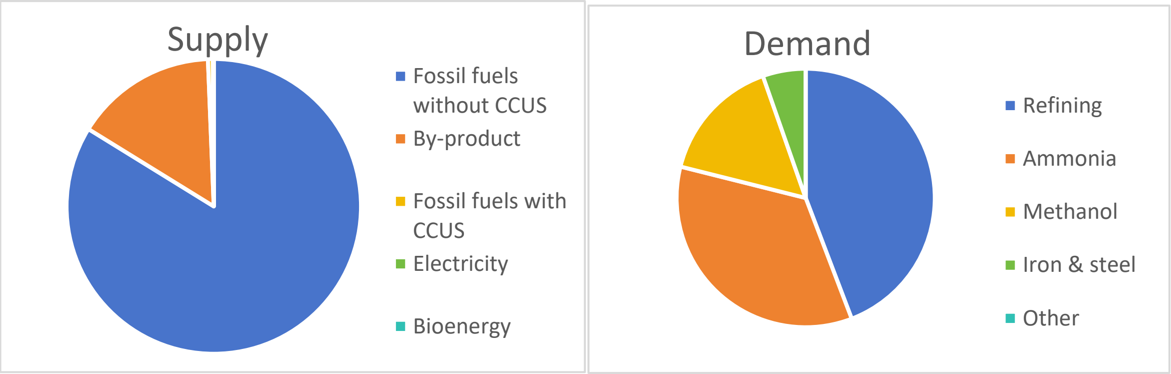

Figure 3-1 Global hydrogen production and demand (2022)
Source: Created by ICCSD, based on IEA data.

Clean hydrogen is already dominating proposed new investment projects. Proposals to invest in green hydrogen investments rose from $240 billion to $320 billion over an eight-month period, ending in January 2023, with 1,046 hydrogen projects announced. About 50% of the new projects focus on large-scale industrial hydrogen applications and about 20% are related to transportation. There are 112 GW-scale

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[29] U.S. National Clean Hydrogen Strategy and Roadmap, 2023. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

[30] IEA, 2023. Hydrogen, https://www.iea.org/energy-system/low-emission-fuels/hydrogen

hydrogen production projects, of which 91 are green hydrogen projects and 21 are blue hydrogen projects[31]. Even if all these proposals became real facilities, there remains a considerable gap between the scale of announced investments and the necessary demand in the net-zero scenario. To align with net zero, hydrogen demand will need to reach more than 150 million tons by 2030, with about 30% of that demand arising from new applications. As such, the ratio of clean hydrogen production to total hydrogen production will need to exceed 50%, which in turn requires the massive deployment of new renewable electricity capacity to serve green hydrogen production[32].

(1) The future geopolitical landscape of hydrogen

The global transition towards a low-carbon economy will significantly reshape existing energy supply and demand dynamics. The Harvard team's research on hydrogen's geopolitical landscape concludes that hydrogen's geopolitics and markets will bear resemblance to those of natural gas. Specifically, the geopolitical landscape for green hydrogen will be determined by factors related to hydrogen electrolysis: 1) renewable energy resource endowment, 2) freshwater availability, and 3) potential infrastructure development. The study suggests that the U.S., Canada, and Australia will become global champions in hydrogen exports due to their favorable conditions for renewable energy, water, and infrastructure. Although China possesses abundant renewable energy, its potential for hydrogen export is constrained by its uneven distribution of water resources. The U.S. is positioned to emerge as an export leader in the global green hydrogen industry value chain, provided it focuses on value chain development in areas such as green ammonia, ethanol, and steel production; the U.S. must also effectively overcome cost and infrastructure accessibility challenges[33].

When considering both green hydrogen production and industrial applications, the geopolitical landscape is uneven. The Harvard team applies three key criteria (resource endowment, scale and level of existing industries, and economic relevance) to predict the role that countries may play in future hydrogen markets. The analysis shows that the potential for the leadership in green hydrogen production and industrial applications is unevenly distributed across the globe. The evolving landscape may include frontrunners,

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[31] Hydrogen Council, McKinsey & Company. Hydrogen Insights 2023.

[32] IEA. 2023. Hydrogen, https://www.iea.org/energy-system/low-emission-fuels/hydrogen

[33] De Blasio, Nicola, Fridolin Pflugmann, Henry Lee, Charles Hua, Alejandro Nuñez-Jimenez, and Phoebe Fallon. "Mission Hydrogen: Accelerating the Transition to a Low Carbon Economy." Belfer Center for Science and International Affairs, Harvard Kennedy School, October 29, 2021.

upgraders, exporters, importers, and outsiders. As leaders in both green hydrogen production and industrial applications, the U.S. and China are positioned to become frontrunners in the future green hydrogen economy; they also lead in industrial applications such as ammonia, methanol, and steel production. Other resource-rich countries, such as Mexico and Thailand, have the opportunity to ascend along the value chain and compete with import-dependent industrial powerhouses for jobs and market share[34].

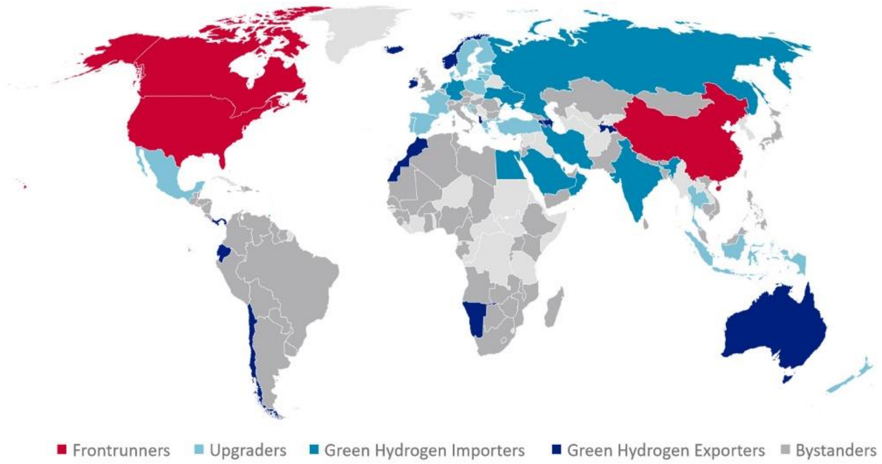

Figure 3-2 Global green hydrogen geopolitics and market landscape in consideration of production and industrial applications

Note: Industrial applications of green hydrogen include ammonia, methanol, and steel production.

Source：Laima Eicke, Nicola De Blasio. Green hydrogen value chains in the industrial sector—Geopolitical and market implications, Energy Research & Social Science, Volume 93, 2022, 102847, https://doi.org/10.1016/j.erss.2022.102847.

(2) Hydrogen development and policies in the United States

North America (i.e. the U.S. and Canada) houses the world's second-largest hydrogen market, with the U.S. currently contributing about 10% of global production, all of which is grey hydrogen produced through natural gas-methanol reforming. The primary U.S. sectors utilizing hydrogen include ammonia and methanol production (35%), oil refining (55%) and metallurgy (2%). Furthermore, the U.S. is implementing various new end-use applications, including “more than 50,000 fuel cell forklifts, nearly 50 retail hydrogen refueling stations, over 80 fuel cell buses, more than 15,000 fuel cell vehicles, and over 500 megawatts (MW) of fuel

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[34] Eicke, Laima and Nicola De Blasio. “The Future of Green Hydrogen Value Chains: Geopolitical and Market Implications in the Industrial Sector.” Belfer Center for Science and International Affairs, Harvard Kennedy School, October 5, 2022.

cells for stationery and backup power”[35].

Operating at the forefront of hydrogen technology research and development, the U.S. released an early hydrogen roadmap in 2002. However, from 2011 to 2020, the number of relevant patent applications filed in the U.S. gradually fell behind that of Europe and Japan. In 2020, the DOE issued the "Hydrogen Energy Development Plan," outlining a strategic framework for hydrogen R&D demonstrations over the following 10 years. Benefitting from supportive policies such as BIL and IRA, the U.S. is poised to increase hydrogen investment, with the scale of announced hydrogen projects surpassing that of any other country.

In 2023, the DOE unveiled the National Clean Hydrogen Strategy and Roadmap, defining hydrogen as a diversified energy carrier and chemical feedstock. The Roadmap focuses on accelerating the commercialization of clean hydrogen production, fostering the development of the entire hydrogen supply chain, cultivating new industries, and creating jobs. The proposed strategy emphasizes clean hydrogen as a preferred technology route, proposing a stringent carbon intensity standard (carbon intensity ≤ 2 $kgCO_2e/kgH_2$, on site) and cost target ($2/$kgH_2$) by 2026. Clean hydrogen penetration in various end-use sectors will be impacted by market dynamics, alternative technological solutions, policy support, and the cost of market entry. If all of the proposed initiatives were successful, clean hydrogen could reduce U.S. economy-wide emissions by 10% relative to 2005 levels[36].

Moreover, the National Clean Hydrogen Strategy and Roadmap, a part of the BIL enacted in 2022, meticulously addresses features of hydrogen development, including supply, demand, emissions, jobs, infrastructure, policies, and investments. The BIL emphasizes bolstering Research, Demonstration, and Development (RD&D). The legislation includes support for clean hydrogen standards, the establishment of seven regional clean hydrogen hubs (valued at US$7 billion), electrolysis technology RD&D (US$1 billion), and manufacturing and recycling RD&D (US$500 million). Meanwhile, the IRA promotes mass manufacturing and applications through industrial project demonstrations, port infrastructure decarbonization (US$2.25 billion), and clean heavy-duty truck manufacturing (US$1 billion). The IRA also introduces tax credits for infrastructure construction, CCUS technology, clean hydrogen production, aviation fuel production, and other areas. In summary, the current supportive measures encompass R&D

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[35] U.S. National Clean Hydrogen Strategy and Roadmap, 2023. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

[36] Ibid.

investments for cleaner manufacturing, supply-side incentives (i.e. tax credits), and demand-side incentives (i.e. government green procurement and infrastructure development).

U.S. clean hydrogen development faces several key challenges, including the effectiveness of utilizing of R&D investments; the need for industries and enterprises to prepare projects that attract capital inflows; public resistance to pipeline construction; and increasing renewable energy penetration into the power grid. Furthermore, some complex supportive policies, such as application and bidding processes, have slowed policy implementation. For the U.S., the primary short-term low-hanging fruit lies in hydrogen used for steel and ammonia production, in which traditional hydrogen can be transitioned to green hydrogen. Ammonia, in particular, holds promise for applications in the marine transportation industry.

(3) Hydrogen development and policies in China

China is the world's largest producer and consumer of hydrogen, producing about 33 million tons in 2021. China is also the largest market for hydrogen production equipment and hydrogen fuel cell vehicles. Currently, hydrogen production relies predominantly on fossil fuel, with coal-to-hydrogen, oil-to-hydrogen, and natural-gas-to-hydrogen accounting for more than 70% of all production; industrial by-product hydrogen comprises about 28%. On the demand side, hydrogen is mainly used as a raw material for oil refining (25%), methanol production (27%), and ammonia synthesis (32%), with limited fuel applications[37]. The development of China’s clean hydrogen industry is gaining momentum, with new projects concentrated in the transportation and industrial sectors.

The supply and applications of clean hydrogen are not yet cost-competitive. Notably, the economics of renewable-based hydrogen require improvement. Presently, the cost of green hydrogen (particularly photovoltaic hydrogen production) remains considerably higher than that of gray hydrogen. The levelized cost of green hydrogen production can reach 60 yuan/kgH_2, which is about 2-3 times the cost of coal-to-hydrogen production[38]. The characteristics of hydrogen supply systems differ due to variations in production devices, storage facilities, and regional transportation modes. On the other hand, blue hydrogen

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[37] China Hydrogen Energy and Fuel Cell Industry Innovation Strategic Alliance. 2021. China Hydrogen Energy and Fuel Cell Industry Development Report 2020- A low-carbon and clean hydrogen supply system under the carbon neutrality strategy. Beijing: People’s Daily Publishing House.

[38] Wang Y., Zhou S., Zhou X., Ou X. 2021. Cost analysis of different hydrogen production methods in China. China Energy. Vol(5): 29-37.

enjoys more centralized production facilities and greater storage capacity. Furthermore, the initial deployment of blue hydrogen, at scale, can lead to a smoother transition to green hydrogen in certain sectors. However, this strategy risks creating mismatched infrastructure connections, asset stranding, and unstable hydrogen supply in the future. Therefore, the strategic design for China’s hydrogen development should begin with green hydrogen considerations and emphasize the production of hydrogen from renewable energy sources.

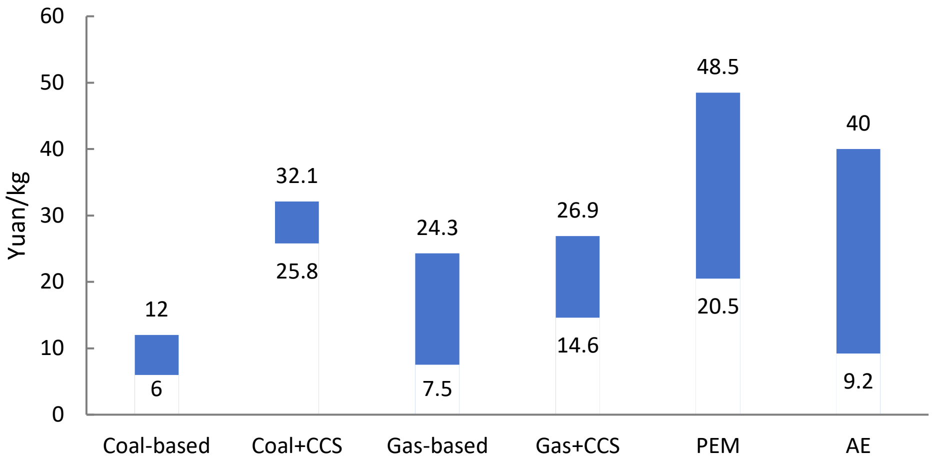

Figure 3-3 Cost of hydrogen production for different methods in China

Notes：(1) Data from EV 100 and China Hydrogen Association；NG price：1~5 yuan/Nm3; electricity price: 0.1~0.6 yuan/kWh ; Coal price：200~1000 yuan/t.

(2) PEM: Proton Exchange Membrane electrolyzer; AE: Alkaline Electrolyzer.

Currently, there are three standard modes of hydrogen transportation in China: 1) high-pressure gaseous trailers, 2) liquid hydrogen tankers, and 3) pipelines. Of these, high-pressure gaseous storage and transportation dominates, commonly utilizing 20MPa gaseous high-pressure hydrogen storage and cluster tube trucks. The development of storage and transportation at 30MPa gaseous and higher is currently underway. While liquid hydrogen tankers have been used, they are more suitable for long-distance transportation exceeding 200km due to their high costs (see figure 3-4). While China has explored the feasibility of hydrogen transportation via natural gas pipelines, pipeline construction still faces challenges including high investment costs and insufficient application scenarios. At present, China's hydrogen transportation relies on high-pressure gaseous trailers for short-distance hydrogen distribution.

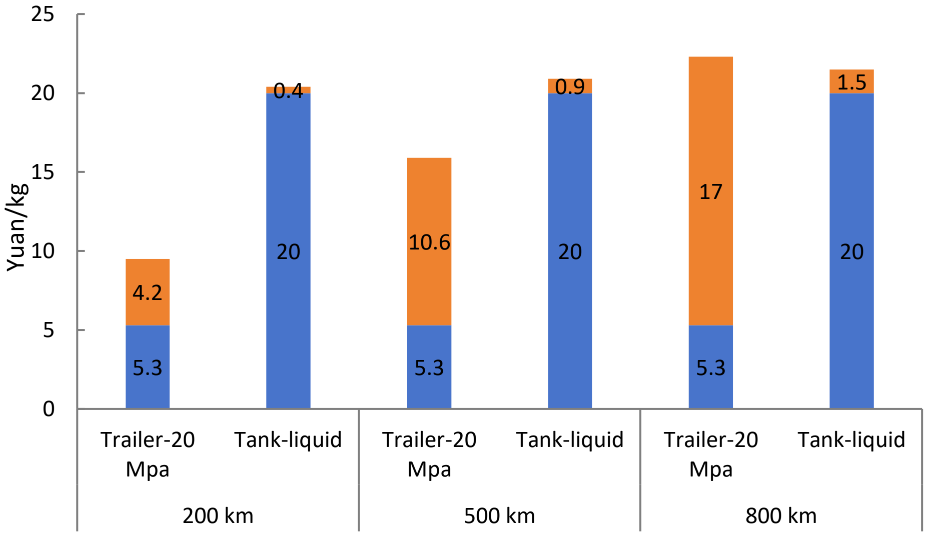

Figure 3-4 Cost of hydrogen storage and transportation by category in China

Notes：(1) Data from Tsinghua University & China Automotive Technology and Research Center (CATARC), 2021. (2) Fixed costs include depreciation, personnel costs, vehicle insurance premiums, and liquefaction process costs; Variable costs are highly correlated with transportation distances, including vehicle maintenance costs, tolls, fuel costs, etc.

The industrial sector may be a significant customer for green hydrogen. In 2020, China's major industrial sectors (steel, cement, petrochemicals, industrial heating, industrial boilers, and building materials) accounted for about half of national carbon emissions. According to the China Hydrogen Alliance, by 2060, 60% of China's hydrogen demand will come from industry and 31% from transportation[39]. Replacing gray hydrogen with green hydrogen in the chemical industry could substantially reduce industrial carbon emissions; several demonstration projects are already underway. At present, green hydrogen applications within the chemical industry still face challenges in the forms of high costs and limited supplies. In steel production, two technology routes for green steel exist—partial and complete hydrogen usage. Currently, most demonstration projects in China partially use hydrogen, utilizing hydrogen-rich gas for direct emission reductions.

Transportation represents a crucial sector for potential large-scale hydrogen application, with fuel cell vehicles representing a core technological route. Hydrogen fuel cells are mainly deployed for medium- and heavy-duty vehicles as well as long-distance road transportation, thereby replacing diesel-based heavy-duty trucks and buses. This transition will aim to decarbonize road transportation through the complementary use

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[39] China Hydrogen Energy and Fuel Cell Industry Innovation Strategic Alliance. 2021. China Hydrogen Energy and Fuel Cell Industry Development Report 2020--A low-carbon and clean hydrogen supply system under the carbon neutrality strategy. Beijing: People’s Daily Publishing House.

of hydrogen and electricity. It is estimated that by 2030, the overall cost of hydrogen-fueled heavy-duty trucks (including the costs of hydrogen energy, vehicles, and maintenance) will be roughly equivalent to that of their diesel-fueled counterparts. Hydrogen fuel cell technology is also expected to find applications in other transportation areas, including ships for inland shipping (catering to inland waterway freight), fixed-line ferries, offshore vessels, cruise ships, and more. Experimental applications of hydrogen fuel cells in rail vehicles, aircraft, drones, and other fields are underway. Furthermore, hydrogen fuel cell storage and power generation methods are in the demonstration stages, primarily in off-grid scenarios such as base stations.

China entered the global hydrogen development arena relatively late. For example, the "Energy Science and Technology Innovation Strategy" first highlighted "hydrogen energy and fuel cell" as a strategic direction for energy science and technological innovation in 2014. In 2019, the central government incorporated hydrogen development into the Government Work Report for the first time.

The "Medium and Long-term Plan for the Hydrogen Energy Industry (2021-2035)", issued in 2022, highlighted hydrogen as an integral component of the future national energy system. It identified hydrogen as an important carrier for the green and low-carbon transformation of end-use sectors and as an alternative energy source for strategic and emerging industries, with a focus on the development of green hydrogen and industrial by-product hydrogen. The targets established for the hydrogen industry included developing core technologies and manufacturing process by 2025, delivering approximately 50,000 fuel cell vehicles, increasing green hydrogen production capacity to 100,000-200,000 tons/year, and reducing CO_2 emissions by 1-2 million tons/year. Looking ahead to 2035, the Plan calls for the completion of a technological innovation system, significantly increasing the consumption of green hydrogen in end-use sectors[40].

The Chinese central government has issued about 50 policies on hydrogen development, covering such areas as scientific and technological RD&D, clean production, industry development, fuel cell vehicle demonstration, and standardization[41]. In terms of financial support policies, city clusters demonstrating fuel cell vehicles can receive four consecutive years of support. The subsidy cap for a single city cluster is estimated to be about 1.7 billion yuan.

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[40] National Development and Reform Commission, National Energy Bureau. 2022. Medium and Long-term Plan for the Hydrogen Energy Industry (2021-2035).

[41] Zhang, Y.W., Zhang Z. (2022). Diversified Incentive System Drives Sustainable Development of the Hydrogen Energy Industry. China Energy, No. 9, 2022.(in Chinese)

As of the end of 2022, 21 provinces and 69 cities have proposed hydrogen development targets, accompanied by corresponding policies. An in-depth study analyzing 122 policy documents from 39 cities in China found that cities could be pivotal early contributors to the switch to hydrogen fuels by driving technological innovation and laying the groundwork for future transitions. However, city-level support is focused on infrastructure development, and only half of the cities have enacted policies to support technological innovation. Additionally, current uses of hydrogen are concentrated primarily on the transport sector. Overall, city-level initiatives need to more effectively steer the transition towards clean hydrogen[42].

China's hydrogen development faces multiple challenges, including limited water availability for large-scale production; regional mismatch between green hydrogen production and consumption; and lack of strategic design for production infrastructure, storage, and transportation. While the industrial sector is a crucial source of green hydrogen demand, current policies emphasize hydrogen as a transportation fuel. Insufficient policy support for the development of blue and green hydrogen persists. There is a misalignment between the optimal technological route and governmental goals for hydrogen development. Therefore, new business models and international cooperation mechanisms must be further developed.

Case study: A grid-friendly new energy hydrogen production pathway for decarbonization in the chemical industry

In 2020, China’s chemical industry accounted for about 13.4% of total carbon emissions. Hydrogen is used in reaction processes such as hydroprocessing, hydrocracking, and desulfurization in petroleum refining, ammonia synthesis, methanol synthesis, and modern coal chemical processes. Green hydrogen is poised to play a vital role in the decarbonization of the chemical industry. The intermittent nature of wind and solar power coupled with the need for precise temperature and pressure conditions in chemical manufacturing suggests that "Green flexible chemical electrification" (GFCE) may be a viable option. Technical advances will involve balancing production and consumption through grid exchange, employing advanced process control equipment in the chemical industry to respond to fluctuations in the production of power, and enhancing system flexibility with larger electrolyzers and longer-lasting hydrogen buffer tanks. This topic is the subject of a collaborative study by Tsinghua and Harvard resulting from a presentation in one of our

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[42] Peng, Y., Bai, X. (2022). Cities leading hydrogen energy development: the pledges and strategies of 39 Chinese cities. npj Urban Sustainability, 2(1), 22. https://doi.org/10.1038/s42949-022-00067-9

workshops.[43]

In most Chinese regions, GFCE technology offers advantages over CCS technology based on the levelized cost of emission reductions, with costs turning negative in Inner Mongolia and Xinjiang. While CCS applies primarily to the power or chemical sectors, GFCE offers the flexibility to connect the power and chemical industries. Even without carbon pricing, green ammonia proves economically viable in some provinces, such as Hebei. In other regions, green ammonia will need to be supported by carbon pricing. Thus, greater amounts of investment remain necessary, supported by government subsidies and carbon pricing incentives[44].

Hydrogen challenges faced by China and the U.S. share similar challenges, such as technology immaturity, high costs, limited market demand, and insufficient infrastructure. As a result, both countries are implementing targeted measures to address these challenges, such as supporting greater amounts of RD&D to accelerate technology commercialization, encouraging mass production, stimulating market demand through subsidies, supporting infrastructure development, and fostering international cooperation. While the U.S has experienced increased clean hydrogen development thanks to large-scale subsidies, there is a need to more effectively direct these efforts to enhance both the demand and supply of green hydrogen. In contrast, China's hydrogen policy remains fragmented and underfunded, despite the country’s clear cost advantages in electrolyzer manufacturing. Going forward, both China and the U.S. need to actively create a domestic market for green hydrogen, focusing on supporting demonstrations and applications in the industrial sector. For China, it is imperative to align the national hydrogen strategy with both the evolving international energy geopolitical landscape and the domestic long-term strategy for carbon neutrality. Furthermore, active participation in international research cooperation and standard certification is crucial for ensuring the competitiveness of industrial products.

3.3 Carbon capture, utilization, and storage (CCUS)

Since 2022, notable progress has been made on commercial CCUS deployment worldwide. As of July 31,

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[43] Li, J.R., Lin J., Wang, J.X., Lu, X., Nielsen, C.P., McElroy, M.B., Song, Y.H., Song, J., Lyu, S.F., Yu, M.K., Wu, S.R., Yu, Z.P. In review (2024). Redesigning Electrification of China’s Chemical Industry to Mitigate Carbon and Security Impacts on the Power System. Nature Energy.

[44] Qiu Y.W et al. 2023. Research Status of Green Hydrogen-Based Chemical Engineering Technology and Prospect of Key Supporting Technologies for Large-Scale Utilization of New Energies[J/OL]. Proceedings of the CSEE: 1-20 (in Chinese). https://doi.org/10.13334/j.0258-8013.pcsee.230233.

2023, there were 392 announcements for proposed CCUS projects globally. Of these, 41 projects are in operation (representing a capture capacity of 49 million tons CO_2/year), 26 projects are under construction, and 325 projects are under development; successful completion of these projects could result in a capture capacity exceeding 360 million tons of CO_2 annually.[45] CCUS facilities have been deployed across various sectors, including ethanol, power generation, heating, hydrogen, ammonia, fertilizer, natural gas processing, and cement. There are also six Direct Air Capture (DAC) projects that are either operational or in development.[46] Additionally, the world is witnessing ， significant growth in CO_2 transportation and storage projects. More than 210 million tons of CO_2 storage capacity was announced in 2022, reflecting an increase of 110 million tons from the year prior.[47] With over 140 CCUS hubs in progress,[48] a global "CO_2 transportation and storage" industry is emerging.

Although 45 countries now have plans to develop CCUS technology,[49] a significant gap exists between current capacities and future demand under the net-zero scenario. As the two largest emitters, China and the United States are crucial players in large-scale CCUS facility deployment. Research from Princeton University projects that in order to achieve net zero, the scale of U.S. CO_2 capture must reach 0.9-1.7 billion tons of CO_2 per year.[50] Various studies on China's carbon neutrality suggest that the country's annual carbon capture capacity will need to reach 1-2.5 billion tons of CO_2 by 2060[51，52，53].In November 2023, China and the United States jointly released the aforementioned Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis; as part of it, the two countries committed to promoting at least

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[45] Global CCS Institute (GCCSI), 2023. Global status of CCS 2023: scaling up through 2030.

[46] Ibid.

[47] Fajarday M., Greenfield C., Moore R., 2023. How new business models are boosting momentum on CCUS. IEA Commentary, March 24, 2023.

[48] Ibid.

[49] Ibid.

[50] Larson Eric, Chris Greig, Jesse Jenkins, Erin Mayfield, Andrew Pascale, Chuan Zhang, Joshua Drossman, et al. 2021. "Net-Zero America: Potential Pathways, Infrastructure, and Impacts."

[51] Global Energy Interconnection Development and Cooperation Organization. 2021. China Carbon Neutrality Before 2060. (in Chinese)

[52] Zhang X., Huang X., Zhang D., et al. 2022. Research on energy economy transition pathway and policy under the goal of carbon neutrality.Management World. 38(01):35-66. DOI:10.19744/j.cnki.11-1235/f.2022.0005.（In Chinese）

[53] Zhang X., Yang X.L., Lu X. 2023. CCUS Progress in China- A Status Report (2023). China Agenda 21 Management Center, Global Institute of Carbon Capture and Storage, Tsinghua University.

five large-scale CCUS cooperation projects in their industrial and energy sectors.[54] The following sections address recent research and policy progress on CCUS development in the United States and China, respectively.

(1) CCUS technology progress and policies in the United States

The United States enjoys a carbon storage potential of between 2.6-22 trillion metric tons of CO_2 (8.3 trillion tons in a "moderate" scenario).[55] In previous publications, the Harvard Kennedy School team highlighted numerous long- and short-term benefits and applications of CCUS deployment in the United States, such as enhancing power-system flexibility, reusing captured CO_2 for manufacturing or industrial processes, delivering “net-negative emissions when combined with electricity generation from biofuels (BECCS)”, and enabling natural-gas-based, low-carbon hydrogen production.[56] Enhanced oil recovery (EOR) remains a key application as well, in as much as sequestering CO_2 in oil-bearing geological formations allows oil production that defrays carbon capture and sequestration costs .[57]

In a recent report (Galeazzi et al. (2023)), the Harvard Kennedy School team found that “adequately sized regional or national networks, where capture sites organically connect to shared CO_2 transportation and storage networks, are achievable in the next decades given the right policies and associated market conditions.”[58] Several policies have been passed with the aim of creating the necessary conditions for network expansion. For example, the Inflation Reduction Act (IRA) strengthened the CO_2 sequestration tax credit in Section 45Q of the Internal Revenue Code — increasing the credit amounts by 70%-260% (depending on end use)—as well as lowering the CO_2 capture threshold for credit qualification and easing monetization of the credit [59] . Table 3-1 (below) outlines the 45Q changes between the BIL and IRA.

Table 3-1 45Q credits under the Bipartisan Budget Act and the Inflation Reduction Act

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[54] U.S. Department of State, 2023. The Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis. https://www.state.gov/sunnylands-statement-on-enhancing-cooperation-to-address-the-climate-crisis/

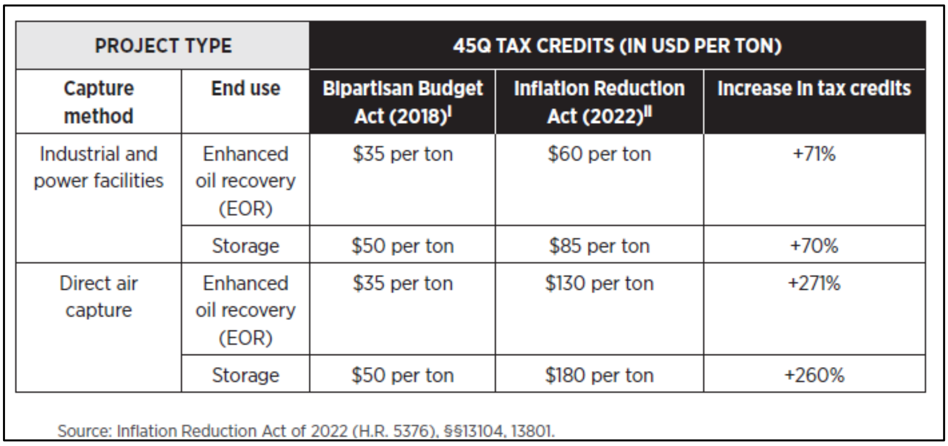
[55] Clara Galeazzi, Grace Lam, John P. Holdren, 2023. Carbon capture, utilization, and storage: CO2 transport costs and network infrastructure considerations for a net-zero United States. Belfer Center for Science and International Affairs.

[56] Ibid.

[57] USGS, 2023. “Using Petroleum Reservoirs to Store Carbon.” https://www.usgs.gov/news/featured-story/using-petroleum-reservoirs-store-carbon

[58] Clara Galeazzi, Grace Lam, John P. Holdren, 2023. Carbon capture, utilization, and storage: CO2 transport costs and network infrastructure considerations for a net-zero United States. Belfer Center for Science and International Affairs.

[59] Ibid.



PROJECT TYPE		45Q TAX CREDITS (IN USD PER TON)		
Capture method	**End use**	**Bipartisan Budget Act (2018)**[I]	**Inflation Reduction Act (2022)**[II]	**Increase in tax credits**
Industrial and power facilities	Enhanced oil recovery (EOR)	$35 per ton	$60 per ton	+71%
	Storage	$50 per ton	$85 per ton	+70%
Direct air capture	Enhanced oil recovery (EOR)	$35 per ton	$130 per ton	+271%
	Storage	$50 per ton	$180 per ton	+260%

Source: Inflation Reduction Act of 2022 (H.R. 5376), §§13104, 13801.

Source: Clara Galeazzi, Grace Lam, John P. Holdren, 2023.

Infrastructure for CO_2 transportation must also be considered in CCUS policy. In 2018, the United States had 5,012 miles (8,066 kilometers) of CO_2 pipelines, most of which was used for EOR. This figure represented only about 2% of all non-gas pipelines,[60] but expanding it rapidly to handle a large increase in CCUS would be inhibited by multi-layered permitting requirements. For example, projects crossing a combination of federal, state, and private lands, may need up to 30 permitting reviews and approvals before construction begins.[61] To address these challenges, the 2021 Infrastructure Investment and Jobs Act included several provisions to facilitate CO_2 infrastructure expansion, such as its CO_2 Infrastructure and Finance Innovation Act.[62]

Notwithstanding the policy interventions to date, U.S. CCUS development faces considerable challenges. CCUS remains economically uncompetitive in most applications, despite current subsidy and tax credit structures.[63] While EOR can offset CCUS project costs where it's an option, low oil prices threaten EOR's commercial viability.[64] There is considerable opposition to CCUS, moreover, based on the argument that its use would extend reliance on fossil fuels and, in the case of the EOR option, would enable increased oil production. The logic underlying these propositions is debatable, but they do continue to complicate both public acceptance of CCUS and policy development.

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[60] Clara Galeazzi, Grace Lam, John P. Holdren, 2023. Carbon capture, utilization, and storage: CO2 transport costs and network infrastructure considerations for a net-zero United States. Belfer Center for Science and International Affairs.

[61] Ibid.

[62] Ibid.

[63] Moch, Jonathan M., Xue, William, & John P. Holdren. 2022. Carbon Capture, Utilization, and Storage: Technologies and Costs in the U.S. Context. Belfer Center for Science and International Affairs.

[64] Ibid.

(2) CCUS technology progress and policies in China

China's theoretical CO_2 storage capacity estimates range from 1.21 to 4.13 trillion tons. The Songliao Basin has a storage capacity of 695.4 billion tons, the Tarim Basin of 552.8 billion tons of CO_2, and the Bohai Bay Basin holds about 50% of the total storage capacity[65]. Since the announcement of the national carbon peaking and carbon neutrality goals in September 2020, the number of CCUS demonstration projects in China has increased rapidly from 42 to 100. Nearly half of these projects have been operationalized with a capture capacity of more than 4 million tons of CO_2 per year and an injection capacity of more than 2 million tons CO_2 per year. At present, China's CCUS demonstration projects span multiple industries including electric power, oil and gas, chemicals, cement, and steel. The power sector alone features over 20 demonstration projects[66]. Industrial cluster projects such as the Xinjiang CCUS cluster, the Daya Bay Area CCUS cluster project, and the East China CCUS cluster project are currently in preparation.

From a value chain perspective, technology advancements and demonstration projects are propelling the development of a new generation of low-cost, low-energy carbon capture technologies. These investments are transitioning from pilot testing to industrial demonstration. CCUS demonstration projects are evolving from single technology applications to comprehensive, whole-process applications. In terms of CO_2 transportation, road tanker trucks and inland waterway shipping technologies have been commercialized at a scale of less than 100,000 tCO_2/year[67]. CO_2 pipeline transportation has seen breakthroughs, while submarine pipeline transportation is still in the research phase. While system optimization has entered commercial applications in the U.S., China has limited experience in large-scale and whole value chain CCUS operations, particularly in pipeline network optimization and cluster hub development.

CO_2 utilization is the focus of China's CCUS industry. Utilization objectives include EOR, dry ice production, and chemical production (methanol, fertilizer, etc.). At present, EOR is the predominant approach for CO_2 utilization in CCUS demonstration projects. That said, the number of chemical and biological utilization projects is increasing. Over 30 carbon capture projects use CO_2 for EOR, while a few projects utilize CO_2 for intensive coalbed methane extraction. However, only a handful of projects sequester the collected CO_2 for

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[65] Cai B.F., Li Q., Zhang X. Annual report on carbon capture, utilization, and storage (2021). (in Chinese)

[66] Zhang X., Yang X.L., Lu X. 2023. CCUS Progress in China- A Status Report (2023). China Agenda 21 Management Center, Global Institute of Carbon Capture and Storage, Tsinghua University.

[67] Ibid.

geological storage.

To meet China's 2060 carbon neutrality target, the scale of CO_2 captured must reach 1-2.5 billion tons per year[68,69,70]. China's current capture capacity equals only about 0.16%-4% of the projected demand under the carbon neutrality goal. Moreover, the spatial mismatch between China's emission sources and sinks creates additional challenges, and there is a lack of onshore storage sites in eastern, central, and southern China. These regions will need to rely on seabed storage. Collectively, these factors create a huge gap between carbon capture capacity and future demand.

Among the four major industries, the cost of CCUS in the coal chemical industry is the lowest. The cement industry presents additional low-cost emission reduction opportunities due to its small scale and wide distribution. CCUS installation in coal-fired power plants could avoid asset stranding, promote a just transition, and significantly reduce the cost of achieving carbon neutrality in the power system. It is estimated that by 2050, CCUS technology will be widely deployed in the energy and industrial sectors. The cost of second-generation capture technology is expected to decrease by more than 50%, leading to a substantial overall cost reduction[71]. China holds a cost advantage as compared to other countries. Based on current demonstration projects, costs are declining yearly as a result of "learning by doing".

Case study: China National Energy Group CCS post-capture technology demonstration project

In June 2021, the China National Energy Group's 150,000 tons/year coal-fired power CCS post-capture technology demonstration project, initiated as a national key R&D project in 2018, commenced formal operations. This project utilizes captured CO_2 for enhanced oil recovery (EOR) in nearby oilfields and high value-added chemicals production, such as sodium bicarbonate and dimethyl carbonate production. The technical performance parameters are impressive, with a CO_2 capture rate of >90%, CO_2 concentration of >99%, absorbent regeneration energy consumption of $< 2.4GJ/tCO_2$, and power consumption of $<90kWh/tCO_2$. Furthermore, the pilot’s operational cost is 40% lower than similar international projects, and

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[68] Global Energy Interconnection Development and Cooperation Organization. 2021. China Carbon Neutrality Before 2060. (in Chinese)

[69] Zhang X., Huang X., Zhang D., et al. 2022. Research on energy economy transition pathway and policy under the goal of carbon neutrality.Management World. 38(01):35-66. DOI:10.19744/j.cnki.11-1235/f.2022.0005.

[70] Zhang X., Yang X.L., Lu X. 2023. CCUS Progress in China- A Status Report (2023). China Agenda 21 Management Center, Global Institute of Carbon Capture and Storage, Tsinghua University.

[71] Ibid.

its unit construction cost is the lowest globally, at US$40/t$CO_2$. Another 500,000 tons/year CO_2 capture demonstration project was developed to optimize the selection of absorbents, materials, and equipment, leading to costs as low as US$35/tCO2[72].

The Chinese government has introduced various measures to support CCUS, including policies targeting R&D demonstrations, tax incentives, subsidies, and capacity building. However, widespread policy dissemination has been hindered by factors including varying stages of technological maturity, diverse regional fiscal conditions, and challenges in adapting policies at the national level.

China's CCUS policies primarily provide guidance without outlining specific regulations on aspects such as market access, construction, operation, supervision, and termination of CCUS projects. The preferential tax policies for CCUS are dispersed across categories including environmental protection, energy conservation, water conservation, and comprehensive resource utilization. These tax incentives encompass value-added taxes, resource taxes, and the enterprise income tax, with exemptions and reductions granted in certain cases.

In terms of regional financial subsidies, some cities, including Shenzhen and Beijing, provide grants or awards for CCUS project investments, with maximum caps of 10 million yuan and 30 million yuan, respectively[73]，[74]. Financial policies supporting CCUS include the People's Bank of China's carbon emission reduction supporting tool and the Green Bond Taxonomy.

However, technical standards and guidelines remain scarce. In 2018, the Ministry of Industry and Information Technology issued a standard for CO_2 transportation pipelines, while the Ministry of Housing and Urban-Rural Development released the "Design Standard for Flue Gas Carbon Dioxide Capture and Purification Engineering". Some industry associations and academic institutions are proactively developing standards for environmental risk assessments and the measurement and verification of greenhouse gas emissions reductions.

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[72] Cui, Q., et al., A 150 000 t·a−1 Post-Combustion Carbon Capture and Storage Demonstration Project for Coal-Fired Power Plants. Engineering, 2022. 14: p. 22-26

[73] Shenzhen Municipal Development and Reform Commission. 2023. Guidelines for the Application of Special Fund Projects for Strategic Emerging Industries (First Batch).

[74] Beijing Municipal Bureau of Economy and Information Technology, Beijing Municipal Bureau of Finance. 2022. Beijing Municipal High-tech Industry Development Fund Implementation Guide.

Regarding project life cycle management, 13 government departments are currently involved in the pre-project approval and supervision processes, reflecting a fragmented regulatory landscape. There is also a lack of clarity regarding regulatory responsibilities for CCUS storage projects after the wells are sealed.

Overall, China's CCUS technology and infrastructure development lag behind that of the U.S. The capture technology is still in the demonstration stage, and the CCUS system integration and optimization are only in the pilot stage; meanwhile, the U.S. has advanced to the commercial application stage. With the expansion of application scenarios, CCUS technology may emerge as an integral component of China's deep decarbonization technology system. It is the only choice for near-zero emission from fossil fuels; along with green hydrogen, it is one of the feasible solutions for the deep decarbonization of hard-to-abate industries (such as steel and cement); and it is the main technical measure to support future carbon recycling in the future. Considering the international geopolitical landscape and domestic imperatives for meeting carbon peaking and carbon neutrality goals, China urgently needs to elevate CCUS from a strategic reserve technology to a realistic solution, thereby necessitating further study on its targets, development strategy, and applications.

4. Progress and preliminary assessment of climate policy in the United States and China

4.1 Climate policy progress in the federal government of the United States

Although the U.S. is the world's second-largest emitter of greenhouse gases, its CO_2 emissions peaked in 2007 and have been trending downward, falling by 19.9% from 2007 to 2020. However, there was a notable increase of 370 million tons of CO_2 emissions in both 2021 and 2022. According to the U.S. Environmental Protection Agency (EPA), the country’s greenhouse gas emissions in 2022 amounted to 6.34 billion tons of CO_2e (excluding LULUCF), with the transportation, power, and industrial sectors accounting for 28%, 25% and 23% respectively. The building (commercial and residential) and agricultural sectors also played significant roles, contributing 13% and 10%, respectively, to overall emissions[75].

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[75] U.S. Environmental Protection Agency. 2023. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022.

The U.S. has committed to an emission reduction of 50% by 2030 compared to 2005 and net-zero emissions by 2050. It has also set targets to reduce methane emissions by about 30% by 2030 (compared to 2020) and to fully decarbonize the power system by 2035. Nevertheless, its long-term transition pathway is fraught with uncertainties in technology costs, economic growth, and other factors that will affect the rate of decarbonization.

The Biden administration has made significant breakthroughs in climate legislation through the BIL in 2021 and IRA in 2022. The BIL, with a planned $1.2 trillion investment over a decade, is the largest federal investment in infrastructure projects in recent years[76] and aims to stimulate large-scale investments and retrofits in infrastructure. The IRA, originally estimated to cost $370 billion but now expected to be larger due to stronger than expected response of its incentives, is dedicated to clean energy manufacturing and adoption, technology research and development, and promoting social equity and sustainable development. Additionally, the CHIPS and Science Act authorized $200 billion to promote scientific research and innovation in artificial intelligence, quantum computing, and other fields with applications in climate action over the next decade. Moreover, the U.S. Congress approved the Kigali Amendment in 2022, committing the United States to phase out the production and consumption of hydrofluorocarbons (HFCs). The Biden Administration has pledged to allocate 40% of the benefits stemming from federal clean energy and climate investments to vulnerable communities. Overall, according to Columbia University's Climate Reregulation Tracker, as of February 2023, the U.S. federal government has released 80 climate policies[77].

The unprecedented scale of investment positions the U.S. to take the lead in global decarbonization actions. Challenges persist, however, notably in policy consistency. Current policies rely heavily on tax credits, which are time-limited and have historically caused fluctuations in renewable energy deployment[78]. While recent bills provide a framework for the next decade, there is a notable absence of long-term policy planning and strategies. There is a pressing need to strengthen policy implementation and not rely disproportionately on

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[76] White House (2021). Fact Sheet: The Bipartisan Infrastructure Deal [EB/OL]. (2021-06-11) [2022-12-22] https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/

[77] Columbia Climate School Sabin Center for Climate Change Law (2023). Climate Reregulation Tracker [EB/OL]. New York: Columbia Law School, 2021. [2022-11-20]. https://climate.law.columbia.edu/content/climate-reregulation-tracker

[78] Mecking J., Lipscy P. Y., Finnegan J.J. et al., 2022. Why nations lead or lag in energy transitions. Science. Vol 378, Issue 6615, pp. 31-33.DOI: 10.1126/science.adc9973

subsidies[79].

4.2 Preliminary assessment on China’s ”1+N” climate policy package

In its 2021 Nationally Determined Contributions update, China committed to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060 (the "dual carbon goals"). In addition, China committed to reduce CO_2 emissions per unit of GDP by more than 65% (compared to the 2005 level) by 2030 while increasing the proportion of non-fossil energy in primary energy consumption to around 25%; to increase forest stock by 6 billion cubic meters (compared to the 2005 level); and to achieve a total installed wind and solar capacity of over 1.2 billion kilowatts. China's *Long-term Low-Greenhouse Gas Emission Development Strategy to the Middle of this Century*, also submitted in 2021, further proposed to achieve over 80% non-fossil energy consumption by 2060[80].

Furthermore, the central government has introduced the comprehensive "1+N" climate policy package, outlining systematic strategies, policies, and actions for the carbon peaking and carbon neutrality goals. In October 2021, the State Council issued two key documents: the *Opinions on Completely, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon Peaking and Carbon Neutrality* [81](hereinafter referred to as the "Opinions") and the *Action Plan for Carbon Peaking Before 2030*[82] (hereinafter referred to as the "Plan"). These documents reflect a top-level design that spans both the carbon peaking and carbon neutrality targets.

The Opinions serve as the foundational policy within the "1+N" framework, covering both carbon peaking and carbon neutrality. The document specifies phased goals across five key aspects: 1) building a green, low-carbon, and circular economic system; 2) improving energy efficiency; 3) increasing the share of non-fossil energy consumption; 4) reducing carbon dioxide emissions; and 5) improving ecosystem carbon sink capacity in 2025, 2030, and 2060. As the leading document for the carbon peaking period, the Plan focuses on goals and actions before 2030. It defines the main targets for the "14th Five-Year Plan" and the

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[79] National Academies of Sciences, Engineering, and Medicine. 2023. Accelerating Decarbonization in the United States: Technology, Policy, and Societal Dimensions. Washington, DC: The National Academies Press. https://doi.org/10.17226/25931.

[80] China’s Mid-Century Long-Term Low Greenhouse Gas Emission Development Strategy. https://unfccc.int/documents/307765

[81] Central Committee of the Communist Party of China (CPC), State Council. 2021. the Opinions on Completely, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon Peaking and Carbon Neutrality.

[82] State Council. 2021. Action Plan for Carbon Peaking Before 2030.

"15th Five-Year Plan" while proposing 10 overarching actions and 44 key tasks – including green and low-carbon transformations in energy and transport sectors, energy conservation and circular economy transition, carbon reduction and efficiency improvements, technology innovation, carbon sink consolidation and enhancement, building green and low-carbon society, and carbon peaking actions in the industrial sector, regions, and urban and rural areas.

China's "1+N" policy system stands out for its comprehensive and systematic design, breaking down top-level objectives into specific sectors, key industries, and regions. Fifteen fields and industries are involved at the sector level; different targets are assigned to key areas such as the circular economy, energy, industry, urban and rural areas, transportation, and carbon sinks. At the regional and provincial levels, local governments are actively issuing strategies and plans on carbon peaking and carbon neutrality. For state-owned enterprises (SOEs), the State-owned Assets Supervision and Administration Commission of the State Council issued the "Guiding Opinions on Promoting the High-quality Development of Central Enterprises in Achieving Carbon Peaking and Carbon Neutrality"; it also organized 98 large industrial SOEs to formulate plans for carbon peaking and carbon neutrality. Furthermore, various industry associations and key enterprises are actively promoting bottom-up policies and actions.

4.3 Comparing and contrasting U.S. and Chinese policies

Both China and the United States face challenges with climate policy implementation[83]. In China, challenges to the climate policy implementation include the impact of the COVID-19 pandemic, geopolitical risks, technology innovation and cooperation, rising energy costs, and pressure from the economic slowdown. At present, the "1+N" policy primarily relies on a "top-down" approach and lacks "bottom-up" engagement and participation from the broader society. There is also a noted deficiency in long-term climate measures within the existing framework[84].

U.S. policies rely heavily on incentives (such as large-scale investment, tax incentives, and subsidies), leading to issues of policy consistency. On the other hand, China's "1+N" policy package leans on “top-down”

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[83] Fransen, T., Meckling, J., Stünzi, A. et al. Taking stock of the implementation gap in climate policy. Nat. Clim. Chang. 13, 752–755 (2023). https://doi.org/10.1038/s41558-023-01755-9

[84] J. Burck et al., “Climate Change Performance Index Results” (2023); https://ccpi.org.

implementation, necessitating a more robust "bottom-up" involvement from society at large. In terms of time frames, climate policies in both countries are committed to making significant investments before 2030, with long-term climate measures requiring the acceleration of the development of new innovative clean technologies and enhanced policies to ensure their deployment. In the future, both countries must enhance their climate policy systems, bolster proactive measures, and improve implementation to achieve multiple, simultaneous goals – not only emissions reductions, but also justice and equality, health, employment, and public participation.

5 Conclusions and recommendations: China, the United States, and the wider picture

Currently, low-carbon technology innovation capacities and outputs are highly concentrated globally in only a few economies, and the current pace of deployment of low-carbon and deep decarbonization technologies falls short of the projected levels required to keep the rise in global average surface temperature under 1.5 degrees – the high-ambition objective of the Paris Agreement. Globally, significant progress has been made in technology R&D and commercialization, and a series of supportive policies have been introduced in some countries, including not only the U.S. and China but also the U.K., Japan, and the EU.

A key overall conclusion from the first two years of our Harvard-Tsinghua project is that the decarbonization pathways and technology demands in China and the U.S. are remarkably similar, which presents an critical opportunity for the two countries to expand their collaboration in ways that are mutually beneficial for meeting their respective climate goals. The resulting acceleration of progress in research and in the identification of best practices is certain to help other countries, as well, in meeting their own climate and energy goals.

Based on the research in the second year of our joint project, we recommend the following specific steps for the two governments:

(1) Clarify the strategy and goals of developing and deploying major decarbonization technologies such as heat pumps, green hydrogen, and CCUS. Align these technologies with global energy geopolitical shifts and

domestic long-term strategies for carbon neutrality and the energy transition.

(2) Strengthen climate policymaking by releasing clear and consistent policy signals. Actively cultivate domestic market demand for deep decarbonization technologies in order to encourage private sector investment and promote economies of scale.

(3) Enhance international cooperation in innovation to accelerate the commercialization of deep decarbonization technologies. Facilitate rapid reductions in technology costs and increased market penetration through global collaboration.

(4) Consider a comprehensive approach to unify the different technologies, infrastructures, and applications in the energy transition; examples include the co-production of thermal and electric energy for building sector decarbonization, integrating green hydrogen production with end-use sector applications, and fitting industrial clusters with CCUS infrastructure.

(5) Consider infrastructure investments in parallel with policies to enhance innovative clean technologies for both energy supply and demand. Recognize that infrastructure has become both a driver and constraint in the development of green hydrogen, CCUS, and other technologies.

(6) Promote the effective implementation of climate policies, improve long-term measures, and formulate climate policy packages to guard against the transition’s economic and social risks.

Finally, as noted in our first-year report, it will be critical to mobilize increased energy-climate finance for developing countries—not only for clean-energy technology and infrastructure but also for adaptation to climate change—and to strengthen institutions and mechanisms for technology transfer. Research indicates that developing countries will need to increase their climate investments by at least four to eight times by 2030. The international community will need to work collectively on both financing and technology transfer if such levels are to be achieved.

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ABOUT ICCSD

Institute of Climate Change and Sustainable Development (ICCSD) at Tsinghua University was founded in October 2017. ICCSD is committed to building a collaborative platform for strategy and policy research, talent cultivation, international dialogue, bridging the gap between academic research and policy, and providing support and solutions related to climate change and sustainable development. ICCSD conducts interdisciplinary research on global climate governance, China's energy transition and climate policies, and holds bilateral and multilateral dialogues including "Climate Change Global Lectures" and "Friends of the Paris Agreement", and provides full support for "Global Alliance of Universities on Climate".

For more, visit http://iccsd.tsinghua.edu.cn/

About Science, Technology, and Public Policy Program

The Science, Technology, and Public Policy Program (STPP) is a research, teaching, and outreach program of the Belfer Center for Science and International Affairs at the Harvard Kennedy School. Solutions to many of the world's most challenging problems involve complex scientific and technological issues. Good policy making in these areas requires access to the frontier of scientific knowledge – not simply translating scientific information, but building an appreciation for the potential and the limitations of scientific understanding, blending scientific insights with those from other relevant disciplines including economics and politics. STPP applies methods drawn from technology assessment, political science, economics, management, and law to study problems where science, technology, and policy intersect. Its goal is to develop and promote policies that expand the contribution of science and technology to human welfare.

About Harvard-China Project on Energy, Economy, and Environment

The China Project is a research program focused on China's atmospheric environment, collaborating across the schools of Harvard University and with Chinese universities. It conducts interdisciplinary, peer-reviewed studies on air pollution and greenhouse gases in China, from the root causes in the demand for and supply of energy powering its economy, to the chemistry and transport of pollutants in the atmosphere, to their impacts on human health and the economy.

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