Front. Environ. Sci. Eng. 2023, 17(2): 14
https://doi.org/10.1007/s11783-023-1614-3

PERSPECTIVES

China's carbon neutrality: an extensive and profound systemic reform

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HIGHLIGHTS

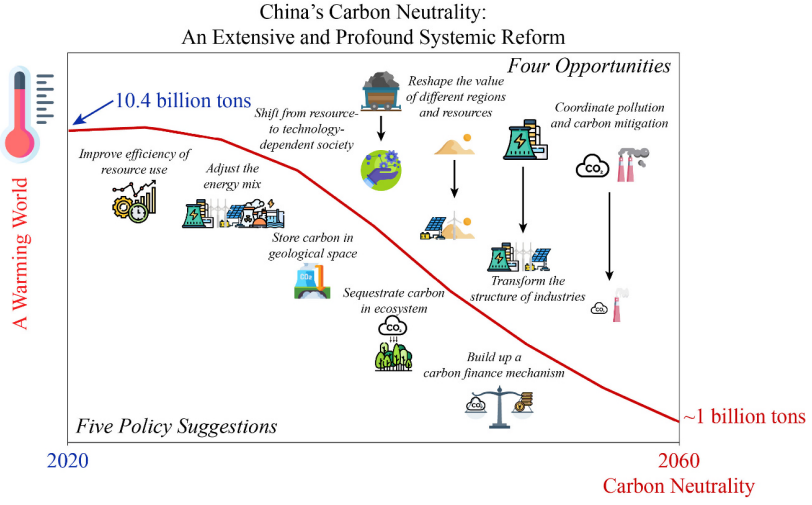
- China has pledged ambitious carbon peak and neutrality goals for mitigating global climate change.
- Major challenges to achieve carbon neutrality in China are summarized.
- The new opportunities along the pathway of China's carbon neutrality are discussed from four aspects.
- Five policy suggestions for China are provided.

ARTICLE INFO

Article history:
Received 3 May 2022
Revised 5 July 2022
Accepted 18 July 2022
Available online 22 August 2022

Keywords:
Carbon neutrality
Energy structure
Technology-dependent society
Coordinated mitigation for air pollutants and CO_2

GRAPHIC ABSTRACT



ABSTRACT

China is the largest developing economy and carbon dioxide emitter in the world, the carbon neutrality goal of which will have a profound influence on the mitigation pathway of global climate change. The transition towards a carbon-neutral society is integrated into the construction of ecological civilization in China, and brings profound implications for China's socioeconomic development. Here, we not only summarize the major challenges in achieving carbon neutrality in China, but also identify the four potential new opportunities: namely, the acceleration of technology innovations, narrowing regional disparity by reshaping the value of resources, transforming the industrial structure, and co-benefits of pollution and carbon mitigation. Finally, we provide five policy suggestions and highlight the importance of balancing economic growth and carbon mitigation, and the joint efforts among the government, the enterprises, and the residents.

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Special Issue—Visions

China's action in the warming world

Climate change has become a pressing matter for all mankind and so actions should be taken to mitigate global

temperature rise (IEA, 2021a). Due to greenhouse gas emissions, caused mostly by human activities, global temperatures are rising at an unprecedented rate (NOAA, 2022). The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) demonstrated how the global surface temperature increased by 1.09 °C from 2011–2020 compared to 1850–1900 (IPCC, 2022). The report indicates that the human-induced climate change has contributed to the observed increase in the frequency and intensity of climate and weather extremes, such as hot waves over land, which has led to widespread detrimental impacts on ecosystems, settlements, human lives, and infrastructure. Projection also shows that the frequency and intensity of such extremes will be larger with additional global warming. It is estimated that if the global average temperature rises by more than 1.5 °C, unavoidable and irreversible damage will happen (Schaeffer et al., 2012; Baker et al., 2018; Mitchell et al., 2018). To mitigate climate change, especially to achieve the goal of global temperature control of 1.5 °C, the world needs to decarbonize rapidly and achieve net-zero emissions around the middle of this century (Rogelj et al., 2016; Höhne et al., 2020). Currently, 136 countries have made carbon-neutral commitments (Fig. 1), accounting for over 88 % of global CO_2 emissions and over 90 % of the world economy (Zandt, 2021).

In 2020, Chinese government announced at the General Debate of the 75th Session of the United Nations General Assembly that China will increase its nationally determined contributions (NDCs), adopt stronger policies and measures, and strive to peak CO_2 emissions by 2030 and realize carbon neutrality by 2060 (Xinhua Net, 2020). In the past twenty years, China has made great efforts to lower its carbon intensity (i.e., CO_2 emissions per unit GDP) by around 70 %, laying solid foundation for carbon neutrality. The carbon neutrality target requires the share of non-fossil energy consumption to increase to more than 80 % by 2060 (Xinhua News Agency, 2021a). China's efforts will be a key contribution to global climate cooperation, potentially bringing forward the global achievement of carbon neutrality by 5–10 years (China Daily, 2021).

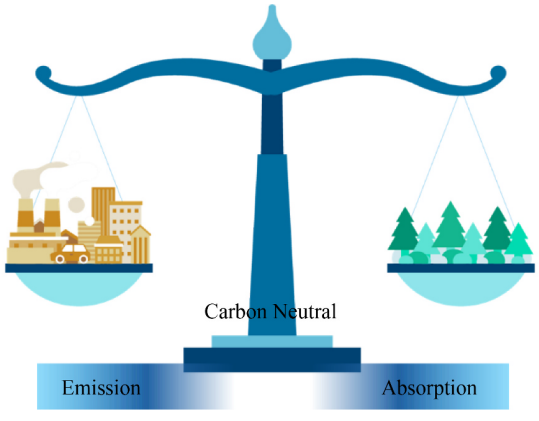

Fig. 1 Carbon neutrality is a balance of anthropogenic carbon emissions and absorption.

Towards carbon neutrality: an arduous journey

Achieving carbon neutrality is challenging for China. The major difficulties lie in four aspects (Fig. 2). First, China has a carbon-intensive energy structure. In the past, China's energy consumption was dominated by coal, with coal accounting for 56.8 % and natural gas, hydropower, nuclear power, and other clean energy resources together accounting for 24.3 % in 2020 (Ministry of Ecology and Environment of the People's Republic of China, 2021). The proportion of fossil energy in energy consumption far exceeds that of countries such as the United States and European countries (Höhne et al., 2020). Second, China's industrial structure is highly dependent on fossil fuels. Coal, iron and steel, petrochemicals, and cement account for a high percentage of China's industrial structure (Liu et al., 2015). These industries have a high dependence on fossil energy, but struggle to achieve raw material and fuel substitution as well as to reshape their carbon-intensive process within a short term, and thus many of them belong to hard-to-abate sectors (China Discipline Inspection and Supervision News, 2022; Fennell et al., 2022). Third, China is in the phase of economic upswing, which demands a continuous increase in energy consumption. China is the largest developing country in the world, and many regions are still in the process of industrialization and urbanization. This will drive up energy consumption in a short-term period, bringing a destined confliction to the long-term plan for carbon-neutrality (Zhang et al., 2022). The decoupling of economic development from the growth of fossil-fuel consumption and related carbon emissions remains a great challenge and needs considering in an integrated manner. Fourth, China needs to achieve carbon neutrality within a short time frame (Liu et al., 2021). Compared to the Europe Union and the United States spending 40 to 70 years to reach the "carbon neutral" goal, China has only 30 years between peaking and neutral emissions (Friedlingstein et al., 2020). China is currently the world's largest carbon emitter, with total carbon emissions of 10.4 billion tons or 32 % of the global total in 2020 (EDGAR, 2021) and expected to reach 11 billion tons by 2030 (Guan et al., 2018). Carbon neutrality will require China to reduce its carbon emissions by about 90 % (Duan et al., 2021).

Towards carbon neutrality: a flourishing era

Under the goal of carbon neutrality, China will greatly increase its proportion of renewable energy like wind and

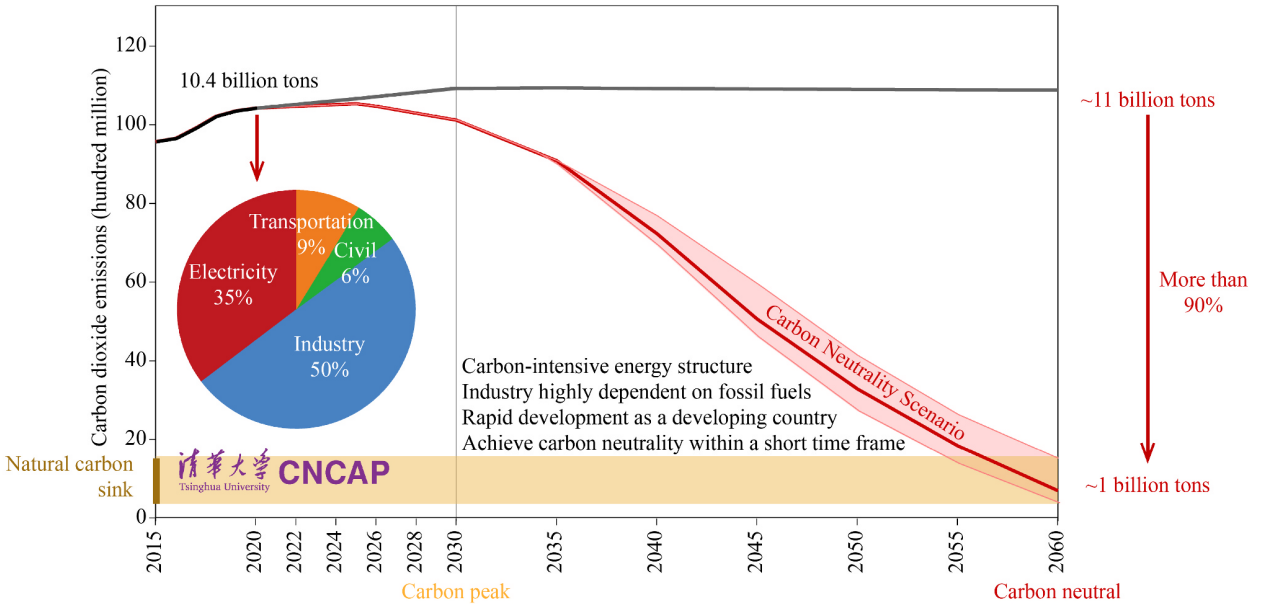

Fig. 2 China's carbon neutrality scenario (adjusted from Cheng et al., 2021).

solar energy (IEA, 2021a). In the past, China has relied heavily on fossil energy for its development, and since many of China's resources need to be imported to meet demand, there are constraints on energy security (Odgaard and Delman, 2014). China has abundant wind and solar resources, and has accumulated comparative advantages in technologies and costs (Liu et al., 2022). In terms of policies, the Central Committee of the Party has set up a leading group for carbon neutrality, and accelerated the establishment of the "1+N" policy system (Government of the People's Republic of China, 2021). China has established specialized research teams in various fields (Xinhua News Agency, 2021a), and with the promotion of carbon neutrality, the national incentive policy will be further improved.

There are four major opportunities through China realizing carbon neutral (Fig. 3). First, carbon neutrality requires a shift from resource-dependent in the past to a technology-dependent society in the future. Carbon neutrality by 2060 will force China's energy structure, industrial structure, and transportation structure to be adjust with advanced technology (Yang et al., 2021). Carbon-neutral technologies such as wind, solar, biomass and nuclear power generation, energy storage, as well as carbon capture, utilization and storage (CCUS) will provide strong support for the green and low carbon transformation of China's energy system (Koondhar et al., 2021; Tang et al., 2021; Liu et al., 2022). Second, carbon neutrality will lead to reshape the value of different regions and resources in China. China's wind and solar energy resources are mainly distributed in western and northern regions which are economically underdeveloped (Liu et al., 2020). It is estimated that if half of the 600000 km^2 arid area of the Ordos Plateau, Alxa Plateau, and Qaidam Basin were covered with solar panels, the country's power needs could be met (Ding, 2022). As of 2020, China's wind power and photovoltaic installed capacity are 280 gigawatts and 250 gigawatts, respectively (BP, 2021). In the past 10 years, the average costs per kilowatt of onshore wind power and solar power projects have dropped by about 30 % and 75 % respectively (IEA, 2021c; IRENA, 2021). In the process of promoting renewable energy, the competitiveness of China's renewable resource-intensive regions will be increased, and will help narrow regional disparity in terms of development in China (Xinhua News Agency, 2021c).

Third, carbon neutrality will also transform the structure of China's power system. The traditional power system relies on fossil energy (Tong et al., 2018), with the supply of electricity dependent on demand. When demand increases, the power generation can be ramped up to meet the demand and ensure the supply. In contrast, the new power system would mainly rely on "unstable" renewable energy sources such as wind and solar power, which have limited capacity to adjust their power outputs on the supply side (Rinaldi et al., 2021; Tong et al., 2021). Integration of wind and solar resources would require more consumer participation and response on the demand side. The electrification of industrial, transportation and residential sectors is expected to further enhance the potential capacity of demand side management. For example, during the 14th Five-Year Plan period, Sinopec has planned to build 1000 hydrogen refueling stations or combined oil-hydrogen stations, 5000 charging and exchange stations and 7000 distributed photovoltaic power stations (Xinhua Net, 2021). This new power system based on new energy is worth looking forward to (BP, 2021), as it will give rise to new

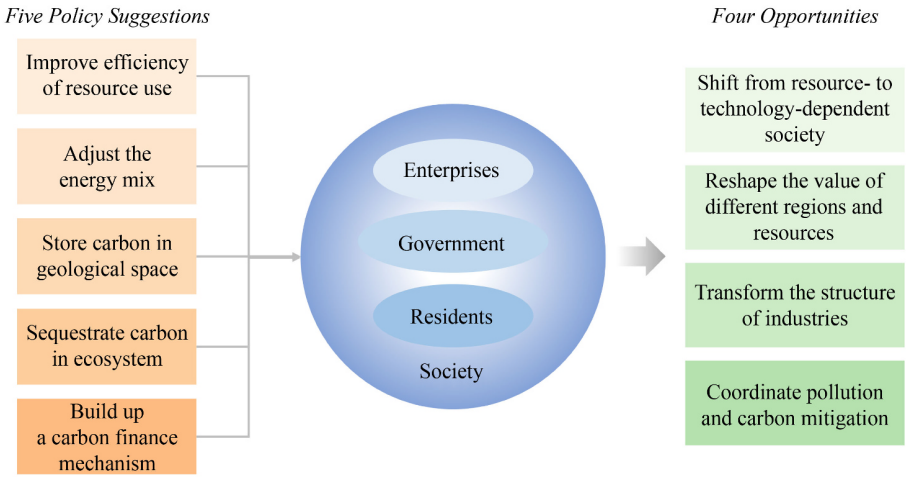

Fig. 3 Opportunities and policy suggestions of carbon neutrality.

industries such as virtual power plants (Tong et al., 2020).

Fourth, carbon neutrality offers a unique chance to maximize the synergetic effects in emission mitigation for pollution and carbon dioxide (CO_2), in order to address the dual challenges of climate change and pollution in China. For example, despite significant amelioration of air pollution in recent years, the $PM_{2.5}$ exposure is still far beyond the WHO air quality guideline, and CO_2 emissions have also shown a rebound after a several-year decline, highlighting the great potential for coordinated mitigation. China's carbon neutrality goal can not only cut down China's carbon emissions by 90 % through in-depth low-carbon energy transition, but also reduce $PM_{2.5}$ exposure to approach the WHO air quality guideline (5 μg/m^3). This synergetic effect would surpass the limit of exhausting end-of-pipe control potential, which will substantially contribute to the long-term air quality improvement (Cheng et al., 2021; Zhang et al., 2021). Carbon neutrality goal will also contribute to the mitigation of solid waste and water pollution through promoted low-carbon actions such as the development of circular economy and the construction of "waste-free-city" (Lee et al., 2021; Wei et al., 2021; Bleischwitz et al., 2022). Climate goals to promote the reduction of CO_2 emissions and coordinate the reduction of major pollutants are inevitable choices for China's long-term climate and environmental governance (Tong et al., 2020).

Finally, China's carbon neutrality will substantially benefit the world at large. As the largest developing economy and greenhouse gas emitter, China's steps towards carbon neutrality will not only alleviate the mitigation pressure of global climate governance, but hopefully set a positive example for other emerging emitters, and promote both political and technological climate collaboration worldwide. China is now leading in some low-carbon technologies, such as solar and wind power generation and ultra-high voltage alternating current (UHVAC) and ultra-high voltage direct current (UHVDC) transmission technology (Xinhua Net, 2016; Xinhua News Agency, 2021b). The technological cooperation and local investment of such technologies will help to lower carbon intensity in other economies, contributing to the global net-zero emission target. The past decade has witnessed the thriving investment and construction of low-carbon projects in developing countries by China through the Belt and Road Initiative, for instance, investment in new energy vehicles, solar power, and wind power (China Economic Daily, 2019; International Online, 2020; Xinhua News Agency, 2022). China's international low-carbon actions are expected to increase in the future, driven by the carbon neutrality goal.

Towards carbon neutrality: an extensive and profound systemic reform

Carbon neutrality is an extensive and profound economic and social, systemic reform. Five integrated measures are proposed here for China to achieve its carbon neutrality target (Fig. 3): 1) Improve the efficiency of resource use, and reduce energy demand as much as possible through energy conservation, efficiency improvement, product recycling and management systems (Xinhua News Agency, 2021c). 2) Adjust the energy mix, and substantially increase the proportion of non-fossil energy use by building a flexible renewable-energy-dominant power system and promoting the electrification of high-emitting end-use sectors (The State Council of China, 2021). Promote technological innovation in industrial processes to improve the capability of using low-carbon energy such as hydrogen, and strongly develop energy storage to increase the stability of the adjusted energy system. 3) Store carbon in geological space, and gradually promote the demonstration, and commercialization of carbon-negative technologies such as carbon

capture and storage (CCS) and bioenergy with CCS (BECCS). 4) Sequestrate carbon in the ecosystem, and maintain and enhance ecological carbon sink through strengthening forest cultivation and enhancing ecological protection and restoration. 5) Build up a carbon finance mechanism, and promote carbon emissions trading, introduce national regulations for legislative support, and probably hierarchically develop carbon-related financial product systems.

More broadly speaking, carbon neutrality can be extended beyond the mitigation of CO_2 emissions and includes methane (CH_4) and other greenhouse gases. Unlike the dominant role of fossil fuel combustion in CO_2 emissions, the other greenhouse gases have distinct sources such as livestock, rice cultivation, fossil fuel extraction, landfills, and wastewater treatment (Peng et al., 2016). Thus, the mitigation relies heavily on measures in the agricultural sectors, improvement of energy-producing activities, and progress in waste treatment systems (Yusuf et al., 2012). The mitigation of CO_2 and other greenhouse gases should be coordinated in terms of policymaking, financial investment, and technological development.

Carbon neutrality is a long-term undertaking that has been integrated into the structure of ecological civilization construction and the overall economic and social development of China. Given challenges and opportunities associated with carbon neutrality, actions either too rapid or too slow should be avoided. It requires a dynamic and smooth process that balances socioeconomic growth and carbon reduction, coordinates national policy and regional development, and merge both short-term and long-term targets. Great efforts are required to reshape the energy system, the industrial structure, and many aspects of the society in a steady and orderly manner by comprehensively considering energy security, the relationship between government and market, and the stability of supply chain etc. The public participation should be encouraged by incentive mechanisms, such as carbon Generalized System of Preferences (GSP) for personal carbon footprint mitigation (EU-China Emissions Trading System, 2020). In this way, a deep transition with wide coverage will be jointly promoted and implemented by the government, the enterprises, and the residents. Despite great challenges, the arduous journey to carbon neutrality will bring a great reform that leads the economy and society in China to a flourishing era.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Nos. 72140003 and 72025401) and by Tsinghua University Initiative Scientific Research Program. We particularly thanks Zilin Wang, Shi Chen, Rachael Fleming, Ruochong Xu and Lan Gao for their contributions.

References

Baker H S, Millar R J, Karoly D J, Beyerle U, Guillod B P, Mitchell D, Shiogama H, Sparrow S, Woollings T, Allen M R (2018). Higher CO_2 concentrations increase extreme event risk in a 1.5 °C world. Nature Climate Change, 8(7): 604–608

Bleischwitz R, Yang M, Huang B, Xu X, Zhou J, Mcdowall W, Andrews-Speed P, Liu Z, Yong G (2022). The circular economy in China: achievements, challenges and potential implications for decarbonisation. Resources, Conservation and Recycling, 183: 106350

BP (2021). Statistical Review of World Energy 2021. London: British Petroleum

Cheng J, Tong D, Zhang Q, Liu Y, Lei Y, Yan G, Yan L, Yu S, Cui R Y, Clarke L, et al. (2021). Pathways of China's $PM_{2.5}$ air quality 2015–2060 in the context of carbon neutrality. National Science Review, 8(12): nwab078

China Daily (2021). Promote "Carbon Peaking, Carbon Neutrality": adhere to the new development philosophy, planning for the "14th Five-Year Plan". Interview with Yanbing Kang, the Director of the Energy Sustainable Development Research Center of the NDRC Energy Research Center, 2021, Beijing

China Discipline Inspection and Supervision News (2022). Revolution: Interview with Academician of the Chinese Academy of Engineering, He Kebin, Dean of Tsinghua University Carbon Neutral Research Institute, 2022, Beijing

China Economic Daily (2019). Construction of Hungary's largest photovoltaic power station begins. 2019, Beijing

Ding Z L (2022). Research of China's Carbon Neutral Roadmap. Chinese Academy of Sciences Report. Beijing: CAS Publication

Duan H, Zhou S, Jiang K, Bertram C, Harmsen M, Kriegler E, van Vuuren D P, Wang S, Fujimori S, Tavoni M, Ming X, Keramidas K, Iyer G, Edmonds J (2021). Assessing China's efforts to pursue the 1.5 °C warming limit. Science, 372(6540): 378–385

Emissions Database for Global Atmospheric Research (2021). GHG emissions of all world countries—2021 Report. EDGAR Report. European Union: Publications Office of the European Union

EU-China Emissions Trading System (2020). Carbon Sink, Carbon Neutrality, GSP, and Carbon Footprint. 2020, Copenhagen

Fennell P, Driver J, Bataille C, Davis S J (2022). Cement and steel — nine steps to net zero. Nature, 603(7902): 574–577

Friedlingstein P, O'sullivan M, Jones M W, Andrew R M, Hauck J, Olsen A, Peters G P, Peters W, Pongratz J, Sitch S, et al. (2020). Global Carbon Budget 2020. Earth System Science Data, 12(4): 3269–3340

Government of the People's Republic of China (2021). The Central

Committee of the Communist Party of China and the State Council's opinions on the complete, accurate and comprehensive implementation of the new development concept and the carbon-peak carbon-neutralization work. 2021, Beijing

Guan D, Meng J, Reiner D M, Zhang N, Shan Y, Mi Z, Shao S, Liu Z, Zhang Q, Davis S J (2018). Structural decline in China's CO_2 emissions through transitions in industry and energy systems. Nature Geoscience, 11(8): 551–555

Höhne N, den Elzen M, Rogelj J, Metz B, Fransen T, Kuramochi T, Olhoff A, Alcamo J, Winkler H, Fu S, et al. (2020). Emissions: world has four times the work or one-third of the time. Nature, 579(7797): 25–28

Intergovernmental Panel on Climate Change (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. IPCC WGII Sixth Assessment Report (AR6). Geneva: IPCC Publication

International Renewable Energy Agency(2021). Renewable Power Generation Costs in 2020. Paris: IEA

International Energy Agency (2021a). An Energy Sector Roadmap to Carbon Neutrality in China. Paris: IEA

International Energy Agency (2021b). Net Zero by 2050: A Roadmap for the Global Energy Sector. Paris: IEA

International Energy Agency (2021c). Renewables 2021. Paris: IEA

International Online (2020). The Wind Power Project in Miramar, Argentina Officially Put into Commercial Operation. 2020

Koondhar M A, Tan Z, Alam G M, Khan Z A, Wang L, Kong R (2021). Bioenergy consumption, carbon emissions, and agricultural bioeconomic growth: a systematic approach to carbon neutrality in China. Journal of Environmental Management, 296: 113242

Lee R P, Seidl L G, Huang Q L, Meyer B (2021). An analysis of waste gasification and its contribution to China's transition towards carbon neutrality and zero waste cities. Journal of Fuel Chemistry & Technology, 49(8): 1057–1076

Liu L, Wang Y, Wang Z, Li S, Li J, He G, Li Y, Liu Y, Piao S, Gao Z, Chang R, Tang W, Jiang K, Wang S, Wang J, Zhao L, Chao Q (2022). Potential contributions of wind and solar power to China's carbon neutrality. Resources, Conservation and Recycling, 180: 180

Liu L, Wang Z, Wang Y, Wang J, Chang R, He G, Tang W, Gao Z, Li J, Liu C, Zhao L, Qin D, Li S (2020). Optimizing wind/solar combinations at finer scales to mitigate renewable energy variability in China. Renewable & Sustainable Energy Reviews, 132: 132

Liu N, Ma Z, Kang J (2015). Changes in carbon intensity in China's industrial sector: Decomposition and attribution analysis. Energy Policy, 87: 28–38

Liu Z, Deng Z, He G, Wang H, Zhang X, Lin J, Qi Y, Liang X (2021). Challenges and opportunities for carbon neutrality in China. Nature Reviews. Earth & Environment, 3(2): 141–155

Ministry of Ecology and Environment of the People's Republic of China (2021). 2020 China Ecological Environment Status Bulletin. 2021, Beijing

Mitchell D, Heaviside C, Schaller N, Allen M, Ebi K L, Fischer E M, Gasparrini A, Harrington L, Kharin V, Shiogama H, et al. (2018). Extreme heat-related mortality avoided under Paris Agreement goals. Nature Climate Change, 8(7): 551–553

National Oceanic and Atmospheric Administration (2022). State of the Climate: Global Climate Report for Annual 2021. NOAA Report. New York: NOAA Publication

Odgaard O, Delman J (2014). China's energy security and its challenges towards 2035. Energy Policy, 71: 107–117

Peng S, Piao S, Bousquet P, Ciais P, Li B, Lin X, Tao S, Wang Z, Zhang Y, Zhou F (2016). Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. Atmospheric Chemistry and Physics, 16(22): 14545–14562

Rinaldi K Z, Dowling J A, Ruggles T H, Caldeira K, Lewis N S (2021). Wind and Solar Resource Droughts in California Highlight the Benefits of Long-Term Storage and Integration with the Western Interconnect. Environmental Science & Technology, 55(9): 6214–6226

Rogelj J, den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K, Meinshausen M (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature, 534(7609): 631–639

Schaeffer M, Hare W, Rahmstorf S, Vermeer M (2012). Long-term sea-level rise implied by 1.5 °C and 2 °C warming levels. Nature Climate Change, 2(12): 867–870

Tang H, Zhang S, Chen W (2021). Assessing Representative CCUS Layouts for China's Power Sector toward Carbon Neutrality. Environmental Science & Technology, 55(16): 11225–11235

The State Council of China (2021). Action Plan on Achieving Carbon Peaking in 2030 for China. 2021, Beijing

Tong D, Cheng J, Liu Y, Yu S, Yan L, Hong C, Qin Y, Zhao H, Zheng Y, Geng G, Li M, Liu F, Zhang Y, Zheng B, Clarke L, Zhang Q (2020). Dynamic projection of anthropogenic emissions in China: methodology and 2015–2050 emission pathways under a range of socio-economic, climate policy, and pollution control scenarios. Atmospheric Chemistry and Physics, 20(9): 5729–5757

Tong D, Farnham D J, Duan L, Zhang Q, Lewis N S, Caldeira K, Davis S J (2021). Geophysical constraints on the reliability of solar and wind power worldwide. Nature Communications, 12(1): 6146

Tong D, Zhang Q, Davis S J, Liu F, Zheng B, Geng G, Xue T, Li M, Hong C, Lu Z, Streets D G, Guan D, He K (2018). Targeted emission reductions from global super-polluting power plant units. Nature Sustainability, 1(1): 59–68

Wei W, Chen Z, Geng Y, Cai W, Liu H (2021). Toward Carbon Neutrality: Circular Economy Approach and Policy Implications. Bulletin of Chinese Academy of Sciences, 36(9): 1030–1038

Xinhua Net (2016). From relying on foreign countries to leading the world–China's DC transmission technology has gradually achieved national production. 2016, Beijing

Xinhua Net (2020). Statement by Xi Jinping at the General Debate of the 75th Session of the United Nations General Assembly. 2020, Beijing

Xinhua Net (2021). The "14th Five-Year Plan" will build a thousand hydrogen refueling stations, and the prototype of "China's No. 1 Hydrogen Energy Company" has emerged. 2021, Beijing

Xinhua News Agency (2021a). Accelerating the Construction of Carbon Peaking and Neutrality and "1 + N" Policy System in China. 2021, Beijing

Xinhua News Agency (2021b). China's UHV transmission of wind and solar energy has reached a new level. 2021, Beijing

Xinhua News Agency (2021c). Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy. 2021, Beijing

Xinhua News Angency (2022). New energy vehicles contribute to low-carbon travel in Myanmar. 2022, Beijing

Yang Q, Zhou H, Bartocci P, Fantozzi F, Mašek O, Agblevor F A, Wei Z, Yang H, Chen H, Lu X, Chen G, Zheng C, Nielsen C P, McElroy M B (2021). Prospective contributions of biomass pyrolysis to China's 2050 carbon reduction and renewable energy goals. Nature Communications, 12(1): 1698

Yusuf R O, Noor Z Z, Abba A H, Hassan M A A, Din M F M (2012). Methane emission by sectors: A comprehensive review of emission sources and mitigation methods. Renewable and Sustainable Energy Reviews, 16(7): 5059–5070

Zandt F (2021). The Road to Net Zero. Beijing: Statista Publication

Zhang S, An K, Li J, Weng Y, Zhang S, Wang S, Cai W, Wang C, Gong P (2021). Incorporating health co-benefits into technology pathways to achieve China's 2060 carbon neutrality goal: a modelling study. The Lancet Planetary Health, 5(11): e808–e817

Zhang X, Brandt M, Tong X, Ciais P, Yue Y, Xiao X, Zhang W, Wang K, Fensholt R (2022). A large but transient carbon sink from urbanization and rural depopulation in China. Nature Sustainability, 5(4): 321–328