Technology Review for Carbon Neutrality

Review

Energy sector decarbonization in China: macro challenges, supporting technologies and systems, and policy recommendations

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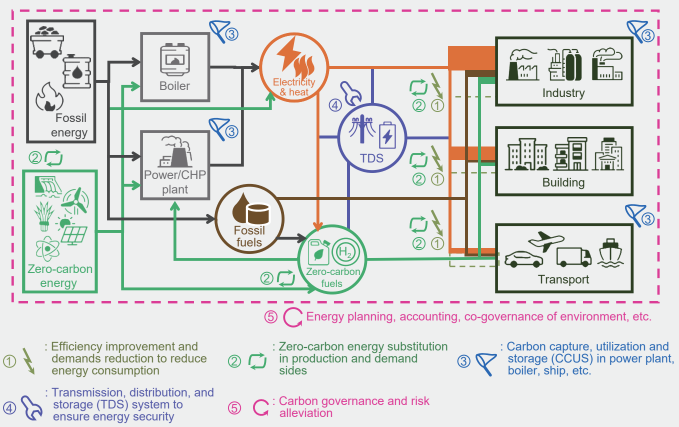
ABSTRACT

Energy sector decarbonization is a key battleground in China's march toward carbon neutrality, and understanding what it means and takes is crucial for its policy-making and sustainable implementation. Here we analyze the structural challenges and review the necessary supporting technologies and systems of energy sector decarbonization in China. It requires not only supporting technologies such as energy efficiency, zero-carbon energy, and carbon capture, utilization and storage, but also enabling systems such as the transmission, distribution and storage system, carbon governance mechanisms, and risk alleviation systems addressing risks of renewables waste and critical mineral supply. A technology roadmap highlighting techno-economics, environmental impact, technology innovation, and carbon market mechanisms is needed to facilitate energy sector decarbonization in China.



Supporting technologies and systems for energy sector decarbonization. CHP: combined heat and power; TDS: transmission, distribution, and storage.

KEYWORDS

Energy sector; decarbonization; technology development; innovation

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Received: 08 February 2024
Revised: 31 August 2024
Accepted: 23 December 2024
https://doi.org/10.26599/TRCN.2025.9550003

1. Introduction

Climate change mitigation has always been of great importance to China, especially after its pledge to achieve CO_2 emissions peak by 2030 and carbon neutrality by 2060[1]. Sectors and industries have proposed visions and pathways for decarbonization. The energy sector, a leading carbon emitter, has received considerable attention. The top-design Working Guidance for dual-carbon targets specifies "a special focus on the development of green and low-carbon energy" sources and accelerates "the development of a clean, low-carbon, safe and efficient energy sector"[2]. In almost all documents, action plans, and guidelines, decarbonization of the energy sector plays a vital role. At the most recent COP 28 conference, a roadmap for "transitioning away from fossil fuels" was approved, which will bring a new era of energy development[3].

Low-carbon technological innovation represents a substantial challenge to achieving the decarbonization targets. Since the first assessment report (AR) of the Intergovernmental Panel on Climate Change (IPCC), technological innovation and transfer have been listed as key strategies for climate change mitigation[4]. The latest AR6 report reiterated that innovation and technological diffusion have been substantially supported in the past and stated that technological availability will be the key challenge in constructing a zero-emission system[5]. According to the International Energy Agency (IEA), approximately 35% of the required technologies are currently not available in the market, despite rapid progress in the past few years[6]. In China's energy sector, technological innovation is considered as the primary driver of development and a key solution to climate change[7]. The dual-carbon Working Guidance also highlights low-carbon technology development in the energy sector[2], as along with the 14th Five-year Energy Technology Innovation Plan[8] and the Implementation Plan for Technological Support to 2030[9].

Numerous studies on the decarbonization of the energy sector have been published. A blueprint for a net-zero emission energy sector has been proposed, with a detailed description of its characteristics and technological constraints[10,11]. Moreover, many uncertainties present significant challenges, including the typical approaches of various countries or regions, path dependencies[12], and technology development[13,14]. Focusing on China, pathways and technologies for climate change mitigation have also been discussed. Compared with existing studies, our review highlights the challenges in a more comprehensive perspective considering both the supply and demand sides, the near and long terms, as well as governmental and market-based strategies. A more complete analysis of the challenges allows for a more complete analytical framework for technology needs, and therefore helps to achieve a better understanding of technology development and deployment, and to make more thoughtful policy recommendations. Meanwhile, besides the hard technologies[15], we also look into the soft technologies such as governance and planning, which have not been widely discussed.

Notably, this study only addresses CO_2 emissions given the distinct characteristics and solutions of non-CO_2 greenhouse gas emissions[16]. And only CO_2 emissions from fuel combustion is considered, without considering emissions from raw material.

2. Macro context and challenges of energy sector decarbonization in China

2.1 Structural changes of the energy sector toward carbon neutrality

China's energy consumption and carbon emissions have increased over the past few decades. In 2021, the total energy consumption was 5.3 billion tce and the share of fossil fuel was 83.3%[17], with carbon emissions from energy combustion of approximately 10.6 Gt CO_2[18]. Coal is the primary energy carrier for emissions. Electricity and heat generation is the largest contributor to emissions when energy supply is considered as a separate sector, and the industry sector is the highest emitter of three end-use sectors, as shown in Fig. 1.

To achieve the dual-carbon targets, as existing studies show, China's future energy sector will undergo the following transformation as shown in Table 1[18,19,23,26–29]. According to most studies, energy consumption will peak before 2040, and CO_2 emissions of the energy sector should peak before 2030. Electricity will serve as the primary energy carrier, and the electrification ratio may exceed 70% by 2060, almost doubling the current value. Hydrogen, biomass, and other zero-emission fuels or heat will be used for sectors inaccessible by electrification. Solar and wind

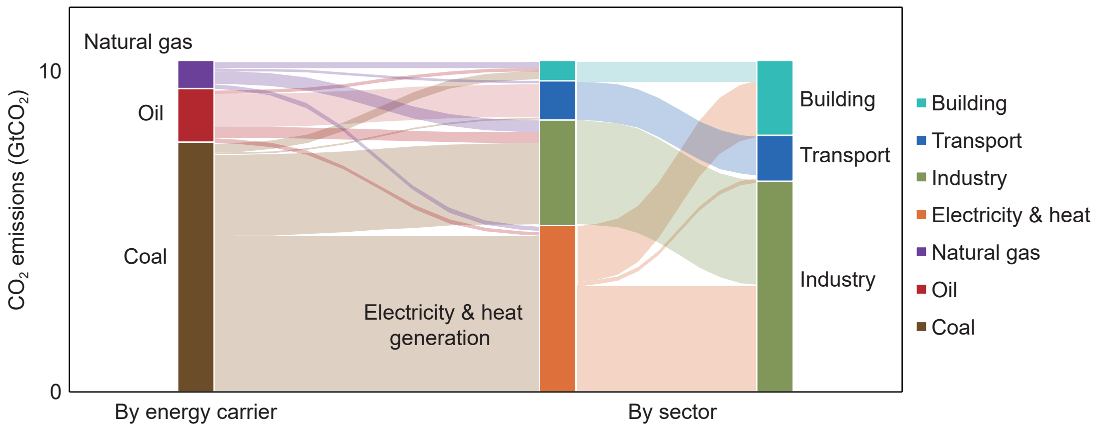

Fig. 1. China's CO_2 emissions from energy sector (2021)[17,19–25]. Industry includes agriculture, ore and mineral mining, manufacturing, construction, and waste management. The shadows between columns display the emission flows of different energy carriers and sectors.

Table 1. Key indicators of China's energy sector in 2021 and 2060.

	2021	2060
Energy consumption (billion tce)	5.3	5–6
Carbon emissions ($GtCO_2$)	10.6	below 1
Electricity consumption (PWh)	8.5	14–18
Share of renewable and nuclear energy	16.7%	More than 80%
CO_2 captured from CCUS ($GtCO_2$)	/	20–25

electricity are regarded as the primary energy sources accounting for more than 50% of the total renewable and nuclear energy. Carbon capture, utilisation, and storage (CCUS) technologies are still indispensable and negative-emission technologies such as bio-energy with CCUS (BECCS) and direct air capture (DAC) will be crucial to offset hard-to-abate emissions.

2.2 Macro challenges for energy system decarbonization in China

Future energy sectors are expected to be different from the status quo. Bridging this gap in both supply and demand sides in the next 40 years remains a major challenge. As a developing country with high diversity, China faces more challenges. Specifically, the primary obstacles and impacts on technological needs can be summarised as follows. These challenges result in different and increased technological needs and should be taken into account when developing each technology.

First, China must reduce carbon emissions against rising energy consumption. Compared with 2010, China's energy usage in 2020 was more than 30% higher, while the energy usage of most developed countries has remained relatively constant over the past decade[30]. This problem has become increasingly severe in China. China's carbon content of energy should drop further; specifically, a rapid reduction in the fossil fuels is required. Moreover, it highlights the importance of related technologies such as renewable energy and CCUS technologies.

Second, China is confronted with a serious geographical imbalance between energy production and consumption. China's carbon emissions, as well as energy consumption, are much higher during winter in the northeast of the Hu Huanyong line[31], which is used to show the uneven distribution of population, urbanization, and economic development[32,33]. However, renewable energy resources such as solar and wind electricity[34], which will be the main contributor in future's energy production, as well as carbon sinks for CCUS[35], are predominantly located on the opposite side of the line. Renewable electricity generation is lower during winter[36], which is opposite to the demand curve. Future technologies and policies should address this imbalance.

Third, China's fossil energy infrastructure is relatively new. The average age of existing coal power plants in China is approximately 15 years, whereas that in Europe and the USA exceeds 30 or 40 years, and the typical lifespan of a coal plant is approximately 40 years[37]. This situation is equally applicable to other sectors such as heavy industry[38]. The existing energy infrastructures may lead to lock-in effects[39] or stranded assets[40] to fossil fuel reduction. It is estimated that the stranded assets of China's coal plants may exceed USD 55 billion to achieve the Paris Agreement[41,42]. Therefore, technologies for retrofitting or reusing existing infrastructure are urgently required to achieve dual-carbon targets and minimise stranded assets.

Finally, China's decarbonization pathway should align with high-quality development[2]. Decarbonization should be pursued with minimal losses and yield maximum benefits. For energy sector, some relevant topics need to be considered at the same time, including energy security[43], industry development[44], air pollution[45], land use[46], just transition[47], and resilience[48].

3. Supporting technologies for energy sector decarbonization in China

To meet all those difficult challenges it requires using a package of technology solutions. The technologies can be categorized using different frameworks. Numerous studies have employed sector-specific analyses, such as the IEA's energy technology perspective (ETP), in which technologies are individually analysed for power generation, alternative clean fuels, industry, transport, and buildings[49]. Using this method will facilitate linking technology needs with the decarbonization pathways of various sectors, but often enough, a single technology can be applied across multiple sectors and may thus result in redundant analyses. Technologies and strategies can also be categorised based on the energy sector value chain, including energy generation, storage, transmission, distribution, and end use[50]. This framework focuses on the technical steps involved in each energy chain, providing a clear and practical tool for analysing of energy-efficient technologies[51]. However, in terms of decarbonization, many strategies beyond traditional efficiency are required. Recent studies have begun to analyse technologies according to their carbon emission reduction functions. Guo et al. classified carbon neutrality technologies into six typologies namely, zero-carbon electricity and non-emission fuel supply, substitution on the demand side, carbon offset, non-CO_2 emission reduction, and synergistic carbon governance[52]. Wang et al. classified carbon neutrality and sustainable technologies into five groups: observation, ecosystems, new energy, CCUS, and energy-saving[53]. These studies provide new perspectives on the dual-carbon targets and consistently consider GHG emissions in all fields, which are even more complex than the energy sector. This study adopts the third classification approach and analyses decarbonization technologies according to their emission reduction functions (Fig. 2).

CO_2 emissions from the energy sector originate from fossil energy combustion during the conversion process (boilers and plants) and end uses (industry, transport, and building)[a]. There are three direct pathways to reduce energy sector emissions and mitigate the conflict between increased energy consumption and the need to reduce emissions:

(a) efficiency improvement and demand reduction to reduce energy consumption;

(b) zero-carbon energy substitution on both production and consumption side, replacing fossil fuels with energy such as renewable, nuclear, or other non-emission energy carriers;

(c) CCUS to capture produced or existing CO_2 emissions.

However, the application of the above technologies may introduce new challenges. A high proportion of variable renewable energy may cause instability, thereby emphasising the importance of transmission, distribution, and storage (TDS) system[54]. Besides, more focus should be put on carbon governance of energy sector and addressing side effects, like waste management, availability of essential minerals, etc. These technologies will not reduce carbon emissions directly, but are the prerequisite for the diffusion of all the above technologies, and essential to ensure that China's low-carbon transformation in energy sector align with the needs of high-quality development. These technologies will be discussed in section 4.

3.1 Efficiency improvement and demand reduction technologies

These technologies aim to reduce energy consumption by reducing energy demands for production and service. Demands continues to increase due to sustained economic and social development; however, energy consumption can be managed within a reasonable range by applying technology and implementing policy strategies.

Technologies that improve efficiency receive the greatest focus. In recent decades, China has emerged as the global leader in energy intensity improvement[55]. It is believed that energy-efficient technologies will continue to have a substantial impact, and a series of policies have been deployed.

Improving efficiency is not the only method to decrease consumption. Traditionally, strategies to guide or control energy demands have been considered as policies rather than technological applications. However, the rapid development of digital technologies has shown great potential for effectively managing energy usage[56,57]. In addition, to improve material efficiency and reduce energy demands, related technologies like lightweighting and lifetime extension are also included and are of greater significance[58,59].

Another area of technological development relates to population behaviours. Behaviour patterns are one of the major reasons why China's energy use intensity is lower than that of most developed countries in the building and transport sectors, and the application of different technologies may bring about changes in behaviour patterns[60]. These technologies

[a]Emissions from upstream mining of fossil fuels are not included as energy sector emissions, but industry sector emissions.

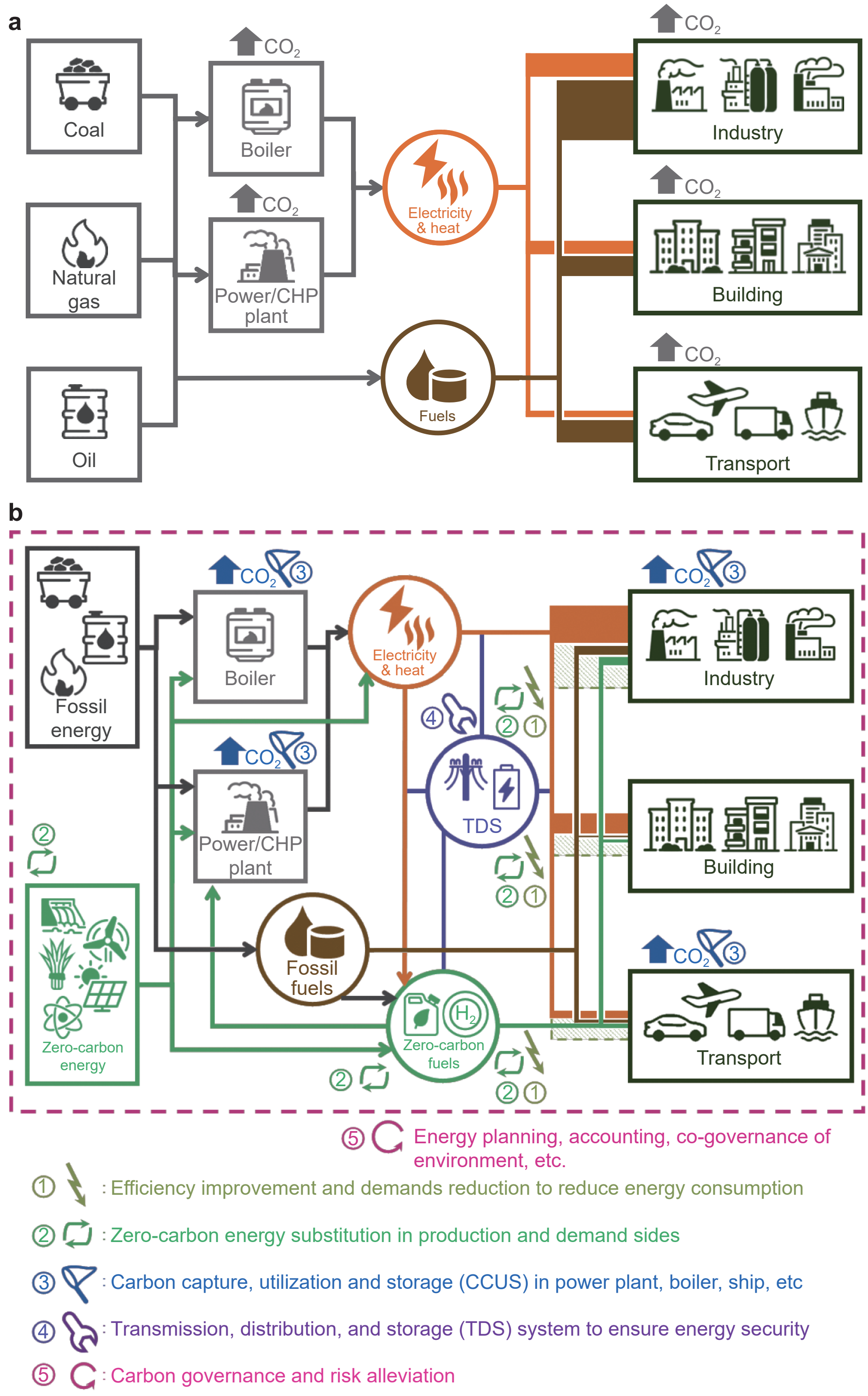

Fig. 2. CO_2 emissions of energy sector and the decarbonization technical requirements. (a) CO_2 emissions from the energy system; **(b)** supporting technological requirements of the energy system decarbonization. CHP: combined heat and power; TDS: transmission, distribution, and storage.

include improving the adjustability of equipment and systems to reduce redundant services, as well as design and management methods to encourage green lifestyle.

3.2 Zero-carbon energy substitution technologies

These technologies are widely recognised as major drivers in zero-emission energy sectors. Technologies to generate all kinds of non-carbon energy like electricity, heat, and fuels on the supply side, as well as those to match the altered energy carriers on the demand side are included.

Zero-carbon electricity has been extensively promoted, and its primary substitutes are renewable and nuclear electricity, especially solar and wind, which have been commercially used and are expected to account for high proportions in the future.

Non-carbon fuels, including hydrogen[61], biomass[62], ammonia[63], and e-fuels[64], have also been widely discussed. Generally, non-carbon fuel technologies are less mature than renewable electricity[52] and face problems such as high costs, safety concerns, and insufficient infrastructure[65,66].

Non-carbon heat sources, including industrial processes[67] and space heating[68], are becoming increasingly important. Industrial processes predominantly depend on heat pumps or non-carbon fuels. Space heating, which has a lower-grade requirement, can also use excess heat as a central heating source. This technology enables the use of the existing heating network in northern urban China to avoid early phase-out of the infrastructure; however, it also faces high uncertainty due to the decarbonization of the power and industry sectors[24].

In addition to the supply side, it is necessary to modify the demand side to realise the use of zero-emission energies, such as electrification technologies, hydrogen-based steel production, and fuel-cell vehicles. Certain technologies such as industrial electrification technologies for specific processes (e.g. direct electrification of high-temperature thermochemical processes) are still in the early stage[69,70]. Some technologies, such as electric cooking[71], are relatively mature but require a shift in habits. Moreover, infrastructure for technologies such as charging stations is still under development[72]. However, wider applications of these technologies still have a long way to go.

3.3 Carbon capture, utilisation, and storage (CCUS) technologies

CCUS technologies are the only option for coal power plants or other fossil-fuel-based infrastructure to achieve practically zero emissions, avoid stranded assets and enhance power system stability[73]. Comparing with a zero fossil fuel system, a power system with a certain percentage of fossil fuel generation will increase the energy supply safety and reduce investment obviously[74]. While carbon emissions are always difficult to entirely abate, negative emission technologies are needed. BECCS, DAC, and natural climate solutions (NCS), such as reforestation is the technology with the highest maturity[75], while BECCS and DAC are based on CCUS. Besides, to apply BECCS to the coal plants, coal–biomass co-firing power plants with retrofitted CCS, is also a promising option for the new coal plants to achieve zero-emission[76]. Recently, some novel scenarios are also being explored, such as on-board carbon capture in shipping, which may bring new opportunity[77].

Although not widely used worldwide, CCUS technologies have rapidly developed in the past decades, characterised by substantial increases in facility capacities and demonstrations[78]. In China, CCUS technologies have received considerable attention in recent years, with the number of demonstrations more than doubling over the last three years. However, China's CCUS still faces challenges, such as high cost, a lack of business models, insufficient evaluation measures, environmental risks, and difficulties in source–sink matching[79,80].

4. Enabling systems and technologies for energy sector decarbonization in China

As mentioned in section 3, several technologies and systems cannot directly reduce emissions but are indispensable to future energy sector.

4.1 Transmission, distribution, and storage (TDS) technologies

There are various types of energy storage technologies with different theories, maturities, and application scenarios. Pumped storage and Li-cased batteries have the highest maturity but run into certain obstacles such as efficiency, cost, longevity, and material dependency[81–83]. In addition, flexible generation and controllable loads can also be considered helpful storage forms[81]. These technologies introduce fresh perspectives on the technological needs of both the supply and demand sides. Potential future research directions may include exploring the flexibility of coal plants[84,85], buildings and electric vehicle (EV) loads[86].

New transition and distribution technologies are required to address the substantial variability in renewable energy. Related technologies, such as early-stage planning, system design, load prediction, operation and power electronic equipment, must be capable of facilitating major structural changes in electricity system[87,88]. China has made significant progress in related technologies and successfully constructed the Zhangbei Voltage Sourced Converter (VSC)-based Direct Current Grid Project in Hebei Province, which was the first project of this kind globally and provided a strong foundation for further technological development[89].

4.2 Carbon governance

In addition to the previously discussed technologies, emerging technologies and governance mechanisms may help to catalyse and defend a decarbonised energy sector. These technologies have not been widely discussed in the past due to their relatively recent advancements but are now receiving increasing attention.

As a new need for climate change mitigation, carbon governance, including accounting, monitoring, reporting, verification, and planning of carbon emissions, is of greater importance with stricter emission reduction targets. Multiple technologies are required to support these requirements. One group of technologies relate to the application of digital technologies, such as the use of block chains in emissions trading systems[90]. Another group of technologies add low-carbon emission principles into existing systems, for example, an increasing number of urban planning studies have focused on carbon governance and investigated solutions to achieve low-carbon emissions simultaneously[91,92]. Moreover, other technologies are also quickly evolving, such as modelling techniques for decarbonization pathway planning, and technologies for monitoring, reporting, and verification.

4.3 Risk alleviation systems

Risk alleviation systems are crucial for planning and implementation of the energy sector decarbonization. Some examples of technologies to address side-effects include waste renewable energy equipment (e.g. solar panels and batteries)[93], critical minerals[94] and land and space utilisation[95,96]. However, these technologies face various challenges, necessitating considerable efforts. For example, technologies to recover critical minerals from mine tailings have gained attention in recent years, but still face technical, economic, or environmental challenges for both traditional methods and the new bio-hydrometallurgical methods[97]. However, leading companies in the renewables and EV industry in China are moving quickly to advance their efficiency gains in recycling and recovery of metals. For example, CATL, the leading EV battery producer in China and around the world, claimed to have reached over 90% recovery rate of its lithium in their batteries by 2023[98].

5. Discussions and policy recommendations for a decarbonization technology roadmap

Given the wide array of technologies available and on the horizon, and both internal and external pressures and incentives, it is necessary to develop a decarbonization technology roadmap that integrates many technologies[99]. Countries and regions such as the USA[100] and Europe[101] have made technology plans in this regard. The decarbonization roadmap should consider many aspects of technologies, including technological maturity, economics, synergies of technologies, and the necessary equipment, management methods and systems supporting their deployment[54,102].

Regarding technological maturity, some existing technological developments have shown great progress but are yet to reach their utmost potential. Take solar photovoltaic (PV) as an example. In recent decades, both the efficiency and cost of solar PV have made unexpected progress and are still developing, whereas the installed capacity has rapidly increased and is expected to increase by two orders of magnitude by 2050[13,103]. While the current efficiency of solar PV is approximately 20%, the best research-cell efficiency reached 47.6% in 2022[104].

Techno-economics is a major concern when developing the roadmap. In recent decades, new energy industries such as PV and EV have developed rapidly in China mainly due to large cost reductions. These industries are witnessing rapid technological progress and rising new patents[105]. Notably, many technologies are still costly and not viable for commercial use because of insufficient infrastructure or regulatory systems. Taking CCS as an example, in China, the cost of CCS equipped in power plant is around 200 to 600 RMB per ton of CO_2, which is much higher than the current carbon price (around 90 RMB in 2024). In addition, lack of national CO_2 pipeline system also increases resistance to development[79].

To deal with the relationships of various kinds of technologies is another challenge for the roadmap. As shown in Fig. 2, the technologies should work together in both competition and cooperation. Energy-saving technologies used to take the lead in reducing carbon emissions, but their contribution gradually reduces due to increasing cost of implementation as decarbonization proceeds. According to existing pathway analysis, the contributions to emission reductions of energy efficiency improvement, renewable energy substitution, and CCS will change from 67%, 24%, and less than 1%, respectively, before 2030, to 11%, 48% and 69%, respectively, in the final decade before achieving carbon neutrality[19]. In many cases, energy efficiency improvements have been found to slow down[106]. Thus, the roadmap should balance the changing roles of these technologies in near and long terms.

Finally, technology innovation should always play a pivotal role. The current cost advantages of new energy industries in China primarily stem from its relatively cheaper labour costs, which may not continue in the coming decades. Technological innovation must take the lead in the new industries. Several countries have issued policies to support the deployment of new energy technologies to boost the economy. The European Green Deal, for example, mentioned that low-carbon technologies will have a significant potential in global markets[107]. The Inflation Reduction Act (IRA) of the USA, to address economic problems, designated more than 80% of funding for climate change and new energy to promote technological innovation[108]. It is also necessary for China to design a low-carbon technology roadmap led by technology innovation to ensure its competitiveness in the global market.

After the roadmap has been developed, policy design is also important to ensure the technology development goals. In a long-term, the governmental plan and support are the main tools to technology innovation in China and it will continue to play a vital role[109]. Meanwhile, the carbon emissions trading system (ETS), which is a new hotspot for climate policy analysis[110], is expected to be an essential contributor. In most studies, ETSs have consistently demonstrated both in theory and practice that they encourage low-carbon technological deployment[111–113]. By increasing the cost of carbon emissions, an effective ETS would encourage low carbon technology innovations[114].

Focusing on China's energy sector, in 2021, China initiated its national ETS for fossil fuel plants and is planning to expand its market coverage. A simulation analysis of the national ETS found that existing regulations can play a positive role in technological progress, especially in encouraging CCUS technology. However, because the existing ETS only covers fossil fuel plants, zero-carbon energy may not be encouraged. To promote the zero-carbon energy technologies, other ETS designs and support policies are required[115]. In 2024, the national voluntary carbon market, known as the China Certified Emission Reduction (CCER) scheme relaunched. Project methodology of two kinds of renewable energy, solar thermal power and offshore wind power were included in the release of the first batch[116], and more technologies about energy efficiency and clean energy generation are on the way. It is believed that the implementation of CCER can furtherly contribute to energy sector decarbonization.

6. Conclusion

Energy decarbonization is vital to China's low-carbon transition. It faces immense challenges in implementation as it counters the forces of rising energy consumption, geographical imbalances in energy production and consumption, relatively new infrastructure assets, and other development needs. Decarbonization technologies are needed to achieve China's carbon neutrality target, which comprise three main technology clusters including energy efficiency and demand reduction, zero-carbon energy technologies, and CCUS, as well as enabling supporting systems encompassing the grid transmission, distribution and storage system, carbon governance system, and risk alleviation system such as waste management. These decarbonization technologies and systems are coming into play under rapidly changing technological, economic, and regulatory landscapes in China. New noteworthy technological issues may arise, such as additional energy consumption brought by new decarbonization technologies. Technology economics continue to improve and empower deployment. And the regulatory landscape is shifting from regulatory policies only to combined regulatory and market mechanisms that may bring accelerated decarbonization.

While important progress is taking place, in addition to cost advantages, technology innovations are crucial for China to maintain competitiveness in decarbonization. A top-level design of a decarbonization technology roadmap would be necessary and beneficial, subject to periodic evaluations and dynamic adjustments to accommodate emerging technologies and solutions. Importantly, it should take note of existing technologies that are affordable and available but not widely applied. Actions should be taken to provide stable and effective policies supporting demonstrations of decarbonization technologies and evaluate their multisectoral and lifecycle effects.

Finally, because climate change is a global challenge, global cooperation plays an important role in technological deployment. Technology innovation cooperation has achieved important milestones in the past and is expected to progress further in the future. China has made remarkable progress in technology transfer to southern countries, particularly in the field of new energy sources such as solar panels. As countries must also achieve zero-carbon targets, energy decarbonization technologies are essential and may be prioritised in global cooperation.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (No. 72140005) and the Young Elite Scientists Sponsorship Program by CAST (No. 2022QNRC001).

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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