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China's industrial decarbonization in the context of carbon neutrality: A sub-sectoral analysis based on integrated modelling

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ABSTRACT

China's 2060 carbon neutrality requires the industrial sector to play a leading role in decarbonization. By refining China's industrial sector into 11 specific subsectors in the Global Change Analysis Model and representing industrial carbon capture and storage (CCS) and hydrogen, this study conducts a sub-sectoral analysis of China's industrial decarbonization under three carbon neutrality scenarios and explores the potential role of CCS and hydrogen. Regardless of the scenario, the results show that China's industrial CO_2 emissions peak during the 14th Five-Year Plan period, with a reduction of about 90% in 2050 compared to 2020; electricity becomes the primary energy for China's industrial sector by around 2035, with industrial electrification reaching about 64% in 2050, while coal and oil change from fuel to feedstock. Tapping the mitigation potential of cement, steel, and chemical is a fundamental requirement for China's industrial decarbonization, while further deeper mitigation requires more additional efforts in other subsectors. Cement, steel, and chemical need to reach peak CO_2 by the 14th Five-Year Plan period, and together they are responsible for 83–85% of total industrial emissions reductions from 2015 to 2050. An important way to reduce emissions from these three subsectors is to reduce energy consumption. The other industrial subsectors are expected to reach peak CO_2 by the 15th Five-Year Plan period. Increasing the electrification rate is a key way to reduce emissions in other subsectors. CCS and hydrogen can play an important role in decarbonizing China's industrial sector. In the scenarios of this study, the annual deployment of CCS in China's industrial energy use exceeds 0.3 $GtCO_2$ in 2035–2040, while hydrogen provides 5.2–10.4% of total industrial energy use in 2050.

1. Introduction

Under the Paris Agreement, the international community has agreed to limit the global average temperature rise to well below 2 °C and even below 1.5 °C [1]. To support the achievement of the Paris Agreement, China announced in September 2020 that it would achieve carbon neutrality by 2060. In 2019, the industrial sector accounted for about 28% of China's total CO_2 emissions, well above the global average of 18.6% [2]. Therefore, decarbonization of the industrial sector will play an important role in achieving carbon neutrality in China.

Existing studies have explored decarbonization scenarios for the global industrial sector. The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) suggested that the global industrial sector would need to reduce its emissions by about 50–100% in 2050 compared to 2019 in order to limit warming to below 1.5 °C [3]. Electrification has been identified as a core mitigation strategy for industry [3–6]. According to the International Energy Agency (IEA), the share of electricity in global industrial final energy consumption could increase from 21% in 2020 to 45% in 2050 under a net-zero emissions scenario [7]. Under the 1.5 °C scenarios of the IPCC AR6, global industrial electrification could reach about 25–75% in 2050 [3]. For China's industrial sector, coal remains the primary energy for a long time. In 2020, the share of coal in China's industrial final energy consumption was 44% [8]. Zhou et al. [9,10] proposed that there was an urgent need for China to continue phasing out coal and shifting from energy-intensive industries to high value-added industries. Existing studies on China's industrial sector have focused mainly on examining mitigation measures in a single energy-intensive sector such as cement [11,12], steel [13–16], chemical [17], and non-ferrous metals [18,19]. Among their findings, improvement in production technologies, deployment of carbon capture and storage (CCS), and clean fuel

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Nomenclature

Abbreviations

AR6	The Sixth Assessment Report
CCS	Carbon capture and storage
China-TIMES	China-The Integrated MARKAL-EFOM System Model
CO_2	Carbon dioxide
GCAM	Global Change Analysis/Assessment Model
GDP	Gross Domestic Product
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contribution

Symbols

s_i	Share weight
γ	Logit exponent
p_i	Levelized cost
Y	Per-capita GDP
P	Service price
N	Population
α	Income elasticity
β	Price elasticity

Units

EJ	Exajoules
Gt	Gigatonnes
Mt	Million tonnes

substitution were considered as key measures. To explore the long-term decarbonization pathways in China's industrial sector, the integrated assessment model (IAM) is a frequently used approach. For example, Zhang and Chen [20], by coupling Monte Carlo analysis with China-The Integrated MARKAL-EFOM System Model (China-TIMES), showed that under a carbon-neutral vision, China's industrial energy-related emissions would decline to 0.3–1.7 $GtCO_2$ in 2050. By applying the Global Change Analysis/Assessment Model (GCAM)-Tsinghua version, Pan et al. [21] found that China's industrial (&other conversions) emissions would decrease sharply to −0.4–1.5 $GtCO_2$ in 2050 under 2 °C scenarios. Through a multi-IAM model comparison, Duan et al. [22] showed that the decline in China's industrial emissions could reach 37% from 2030 to 2050 under 1.5 °C scenarios. These existing IAM-based studies derived energy transformation and carbon mitigation pathways for the whole industrial sector in China. However, detailed sub-sectoral analyses of China's industrial decarbonization remains insufficient, especially in the new context of carbon neutrality. Since a sub-sectoral analysis could shed light on the role, contribution, and progress of each subsector in the industrial decarbonization process, it would provide useful information for policymakers to develop a more comprehensive industrial decarbonization strategy.

Furthermore, although CCS and hydrogen are often considered as important promising options for deep decarbonization of energy systems [3], there is still debate and confusion regarding their explicit role and scale in future industrial energy use. In particular, CCS, especially hydrogen, in industrial decarbonization in China has not been sufficiently assessed in previous IAM studies, and even many studies on China's industrial decarbonization [9,10,23–25] have not yet considered the application of hydrogen in industry. To fill the research gap, this study will apply a modified GCAM to explore China's industrial decarbonization at a sub-sectoral level in the context of its carbon neutrality. By combining China's current industrial status and assumptions about macroeconomics, industrial demand, and CCS and hydrogen deployment, we will explicitly understand China's industrial energy consumption and CO_2 emissions by subsector in support of national carbon neutrality, and the potential role and scale of CCS and hydrogen in industrial decarbonization. The study could also provide a reference for other countries to consider their industrial decarbonization in alignment with carbon neutrality. The remainder of this work is organized as follows: Section 2 describes the methods; Section 3 presents the assumptions and scenarios; Section 4 shows the results; and Section 5 provides the conclusions.

2. Methods

In this section, we first introduce GCAM and then present the modifications to China's industrial sector in the GCAM framework. Finally, based on existing studies, we present the assumptions for CCS and hydrogen in this analysis.

2.1. GCAM

GCAM, developed by the Pacific Northwest National Laboratory of the United States (U.S.), is a global IAM that incorporates the dynamics and interactions of five human and earth systems: the energy system, the agriculture and land use system, the economy system, the water system, and the climate system. Of these, the energy system is the core. GCAM has been widely used across the international community for research on energy, climate, and environmental issues for over 30 years, including IPCC scenarios [26], the Representative Concentration Pathways [27], and the Shared Socio-economic Pathways [28]. This study will be conducted based on GCAM version 5.4, which runs in a five-year time step starting in 2015 (the base year). GCAM integrates the representation of the whole energy system (including energy supply, conversion, and demand) and various related technology options into a consistent framework. The industrial sector is modelled as one of three end-use sectors (industry, building, and transportation) on the demand side. Therefore, the model can simulate the dynamic interactions and mitigation trade-offs between industry and other sectors to derive industrial decarbonization pathways from the perspective of cost-effective decarbonization across the whole energy system. More information on GCAM can be found at the GCAM Documentation (http://jgcri.github.io/gcam-doc/). However, when applying this version of GCAM to China's industrial decarbonization analysis, a critical challenge is that the industrial sector is treated in a highly aggregated form, where only cement is described separately, while steel, chemical, non-ferrous metals, and all other industrial subsectors are combined together, as shown in Fig. 1.

2.2. Modifications of China's industrial sector

For the purpose of subsector analysis, we modify the structure of China's industrial sector within the framework of GCAM, also shown in Fig. 1. We subdivide China's industrial sector from a highly aggregated form into 11 specific subsectors, including cement, steel, chemical, non-ferrous metal, machinery, textile, food, paper, construction, agriculture, and mining. We calibrate the energy consumption of these subsectors mainly according to the 2015 IEA Energy Balance Table (https://www.iea.org/data-and-statistics), as shown in Table 1.

Referring to Zhou et al. [9], we further relate the output of manufacturing subsectors to seven intermediate industrial services, including process heat, boilers, machine drive, electrochemical, process cooling, other end use, and feedstock. For example, in order to produce per unit of steel output, X units of process heat, Y units of boilers, and Z units of machine drive (and so on) are required as inputs. In the modelling, we keep the relative proportions of X, Y and Z (and so on)

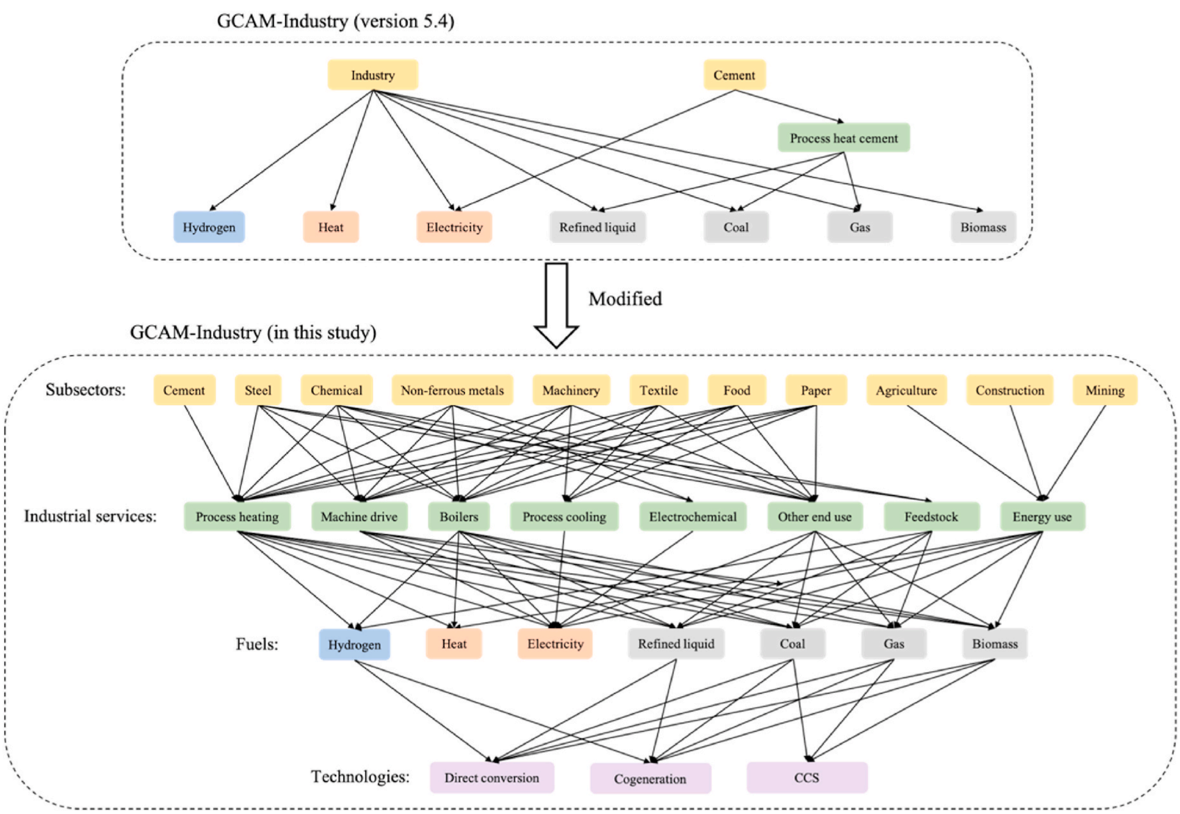

Fig. 1. Comparison of China's industrial sector in the standard GCAM 5.4 and the modifications of this study. Note that the chemical subsector in this study does not include nitrogenous fertilizer, which is modelled separately in GCAM and used in the agriculture and land use module.

Table 1
Industrial subsectors and processes in the modifications of this study. Note that in this study, the machinery subsector treats IEA's machinery manufacturing and transport equipment manufacturing as a whole, as there is a strong linear relationship between them.

Subsector in this study	IEA corresponding flow	Process
Cement	Non-metallic minerals (only cement)	(1) Process heat cement; (2) Electricity
Steel	Iron and steel	(1) Process heat; (2) Boilers; (3) Machine drive; (4) Other end use; (5) Feedstock
Chemical	Chemical and petrochemical (excluding nitrogenous Fertilizer)	(1) Process heat; (2) Boilers; (3) Machine drive; (4) Electrochemical; (5) Other end use; (6) Feedstock
Non-ferrous metals	Non-ferrous metals	(1) Process heat; (2) Boilers; (3) Machine drive; (4) Electrochemical; (5) Other end use
Machinery	(1) Machinery; (2) Transport equipment	(1) Process heat; (2) Boilers; (3) Machine drive; (4) Process cooling; (5) Other end use
Textile	Textile and leather	(1) Process heat; (2) Boilers; (3) Machine drive; (4) Process cooling; (5) Other end use
Food	Food and tobacco	(1) Process heat; (2) Boilers; (3) Machine drive; (4) Process cooling; (5) Other end use
Paper	(1) Paper, pulp and printing; (2) Wood and wood products	(1) Process heat; (2) Boilers; (3) Machine drive; (4) Process cooling; (5) Other end use
Agriculture	Agriculture/forestry	(1) Energy use
Construction	Construction	(1) Energy use
Mining	Mining and quarrying	(1) Energy use

constant to reflect the non-substitutability of each energy service. For example, machine drive cannot be replaced by process heat. The relative proportions of energy services within each subsector in the base year are set from the U.S. Manufacturing Energy Consumption Survey (http://www.eia.gov/emeu/mecs/mecs2018/2018tables.html), based on the assumption that production technologies within each industrial subsector are typically use energy for similar purposes, regardless of facility location. As industrial production technologies develop, the absolute values of X, Y and Z (and so on) are assumed to decrease over time to reflect the reduced demand for industrial services and energy inputs per unit of output. The assumptions on the development of industrial production technologies in this study are based on Zhou et al. [10] and updated based on some recent studies [11,13,20,21,24]. Due to the lack of specific energy service data, energy consumption in agriculture, construction, and mining is still modelled as total energy use in these subsectors. The modifications of this study also include a physical representation of cement fabrication, which includes process heat cement and electricity for cement mixing, and their allocation ratios are based on Worrell et al. [29].

Industrial services are provided by different fuels such as coal, refined liquids, wholesale gas, electricity, and hydrogen. Each service has a different fuel preference. For example, coal is currently the dominant fuel for process heat and boilers, while electricity is the dominant fuel for electrochemistry, process cooling, and machine drive. In the simulation, the fuel share under each industrial service and the technology share under each fuel will be determined according to a logit choice function [30], given by Eq. (1),

$$share_i = \frac{s_i p_i^{\gamma}}{\sum_i s_i p_i^{\gamma}} \tag{1}$$

where s_i is the share weight of alternative i, γ is the logit exponent, and p_i is the levelized cost of alternative i. This logit choice could not only incorporate the impact of energy and carbon prices, but could also avoid 'winner-take-all'.

2.3. Settings of CCS and hydrogen

The mitigation potential of promising low-carbon technologies such as CCS and hydrogen is eagerly anticipated for the future industrial decarbonization [3]. However, so far, these technologies have not been applied to industry on a large scale in China. Based on the utilization characteristics and industrial application areas of CCS and hydrogen [3, 31], they are represented in this study as shown in Table 2.

For many large industrial combustion facilities, CCS is considered a technically viable option to maintain their existing production processes [32,33]. Globally, several industrial CCS development concepts and pilot projects have been proposed to explore the benefits from the removal of concentrated CO_2, for example, hisarna (Isarna process combined with Hismelt reactor) direct oxy-combustion smelting for steel [34]. Dahowski et al. [35] estimated that cement, steel, and chemical would contribute more than 90% of the industrial CO_2 capture in China. Therefore, in this study, it is assumed that CCS is mainly applied in cement, steel, and chemical, while we still consider a few CCS deployments in non-ferrous metals [24] and paper [33]. More specifically, process heat in cement, steel and chemical is expected to be a main energy service for CCS applications, considering that CCS captures CO_2 mainly from fossil fuel-rich combustion. In addition, we also consider the deployment of CCS for energy feedstock in steel and chemical, as their feedstock is mainly used in blast furnaces or coal chemicals (large point sources within industrial facilities). In the model setup in this study, CCS with a 90% CO_2 remove-fraction will be deployed starting in 2025, assuming a cost of \$30 tCO_2^{-1} for steel, \$40 tCO_2^{-1} for cement, and \$9 tCO_2^{-1} for chemical in 2025 [9].

GCAM 5.4 includes 12 hydrogen production technologies with production and distribution costs referenced from the Hydrogen Analysis of the U.S. Department of Energy (https://www.nrel.gov/hydrogen/h2a-production-models.html). It models hydrogen as a future industrial fuel with zero consumption in the base year. We note that, in addition to being a high-quality heat source, hydrogen can contribute to decarbonization of the industrial sector as a clean alternative feedstock for steel and chemical [5,36,37]. Therefore, in this analysis, hydrogen will not only be used in all subsectors whose energy services include process heat and boilers, but will also compete with fossil feedstock in steel and chemical. In this study, we use the assessment of the Hydrogen Council [38] as a basis for cost assumptions for hydrogen applications in different industrial subsectors. We generally assume that hydrogen is fully accepted by 2035, with a readiness period of 2025–2035. That is, the hydrogen share weights in Eq. (1) are set to low values in 2025 and gradually increasing to neutral values in 2035.

3. Key assumptions and scenarios

After the core structure of China's industrial sector is constructed, the next step in driving the model is to set key input parameters and scenarios. The projection of industrial output or demand in GCAM requires setting the parameters of Eq. (2),

$$D_t = D_{t-1}(Y_t/Y_{t-1})^{\alpha}(P_t/P_{t-1})^{\beta}(N_t/N_{t-1}) \tag{2}$$

where Y is per-capita GDP, P is service price, N is population, α is income elasticity, and β is price elasticity (in this study, we assume a price elasticity of -0.7 for each industrial subsector [10,21,39]). Since service prices are endogenous in the modelling, we only need to make assumptions to determine population and GDP and calibrate income elasticities to ensure that the calculated outputs (without the impact of prices) match the expected levels of industrial demand. In this section, we first provide assumptions for China's population and GDP, and then provide demand assumptions of each industrial subsector based on existing research and related policies. Finally, we present the three carbon neutrality scenarios assessed in this study.

3.1. Socioeconomic assumptions

Socioeconomic development is the main exogenous driver of demand for energy services. In this analysis, we follow a recent study by Pan et al. [21] for socioeconomic assumptions, as shown in Table 3.

3.2. Development trends by subsector

Considering that the overall production of some subsectors is difficult to standardize statistics, we use the production of major products to represent the overall capacity demand of each subsector. The production trends of energy-intensive subsectors such as cement, steel, chemical, and non-ferrous metals are represented by the output of cement, crude steel, ammonia, and aluminum, respectively. The assumptions for China's industrial product outputs are shown in Table 4. The outputs of cement, crude steel, and ammonia in 2050 are referenced from the "Reinventing fire: China – A roadmap for China's revolution in energy consumption and production to 2050" [40], while their outputs in 2025 are estimated by combining *Chinese Statistical Yearbooks* and related policies. Both cement and steel consumption are projected to peak during the 14th Five-Year Plan period (2021–2025) due to saturation of infrastructure and reduction of overcapacity [11,13,15,41]. Synthetic ammonia, one of the important inorganic chemical products, is projected to follow the declining trend in developed countries such as the U. S. and Japan after 2020 [40]. However, the rapid growth of new energy vehicles and photovoltaic and wind power generation is projected to strongly stimulate aluminum consumption in China during the 14th and 15th Five-Year Plan periods [42]. After 2030, with the decline of traditional infrastructure, China's aluminum consumption is projected to show a stable trend of around 52 Mt [42]. Note that different output assumptions would change the nuances of the modelling results; however, absent significant changes in international trade that greatly affect product imports and exports, we believe that the key features and lessons derived from this study that align China's industrial decarbonization with carbon neutrality would remain largely unchanged. It is

Table 3
Socioeconomic assumptions for China from 2015 to 2050.

Year	2015	2020	2025	2030	2040	2050
Population (billion)	1.375	1.411	1.426	1.428	1.395	1.331
GDP (billion $\$_{2015}$)	11,060	14,630	19,228	23,826	34,260	46,719

Table 2
Applications of CCS and hydrogen in this analysis.

	Cement	Steel	Chemical	Non-ferrous metals	Machinery	Textile	Food	Paper
CCS	process heat	(1) process heat; (2) feedstock	(1) process heat; (2) feedstock	process heat				process heat
Hydrogen	process heat	(1) process heat; (2) feedstock; (3) boilers	(1) process heat; (2) feedstock; (3) boilers	(1) process heat; (2) boilers	(1) process heat; (2) boilers	(1) process heat; (2) boilers	(1) process heat; (2) boilers	(1) process heat; (2) boilers

Table 4
Assumptions of China's industrial product outputs.

Subsector	Product	2020	2025	2030	2050
Cement	Cement (Mt)	2395	2300	2065	1123
Steel	Crude steel (Mt)	1064	1000	898	491
Chemical	Ammonia (Mt)	51	49	47	39
Non-ferrous metal	Aluminum (Mt)	37	44	52	50

also worth clarifying that Table 4 is only used as a benchmark for calibrating the income elasticities in Eq. (2). During the modelling, output will be changed by model-endogenous service prices. In addition, we also predict output trends for other subsectors such as mining, agriculture, food, textiles, machinery, construction, and paper. Unlike the subsectors in Table 4, the development of these subsectors is more determined by the degree of national development. Their outputs are assumed to be consistent with Zhou et al. [9,10].

3.3. Scenario settings

To assess China's industrial decarbonization in the context of carbon neutrality, in this study we consider three representative dates for China to achieve carbon neutrality. After completing the Nationally Determined Contribution (NDC), we assume that China will reach carbon neutrality in its energy system in 2060, 2055 and 2050, respectively. Fig. 2 illustrates the assumed CO_2 trajectories. The trajectory of the 'S55' scenario follows the NDC-to-1.5 °C transition scenario in "Comprehensive report on China's Long-Term Low-Carbon Development Strategies and Pathways" by Tsinghua University [43]. The trajectory of the 'S50' scenario implements more rapid mitigation between 2031 and 2050 to reach net-zero CO_2 in 2050. The trajectory of the 'S60' scenario reaches net-zero CO_2 in 2060. In the modelling, these trajectories will be set to the carbon cap constraints that China would achieve domestically without international emissions allowance trading. GCAM will solve dynamic-recursively to find the carbon prices that drive China's energy system to strictly meet these carbon constraints.

4. Results

4.1. Total energy consumption and CO_2 emissions

Fig. 3(a) provides the total industrial energy consumption and CO_2 emissions (energy-related) in China under the three scenarios. During the 14th Five-Year Plan period, China's energy-intensive industrial subsectors, such as cement, steel and chemical, will undergo a planned de-capacitation (*The* 14th *Five-Year Plan for Green Industrial Development*). In all scenarios, China's total industrial energy consumption plateaus over this decade, consistent with China's current industrial

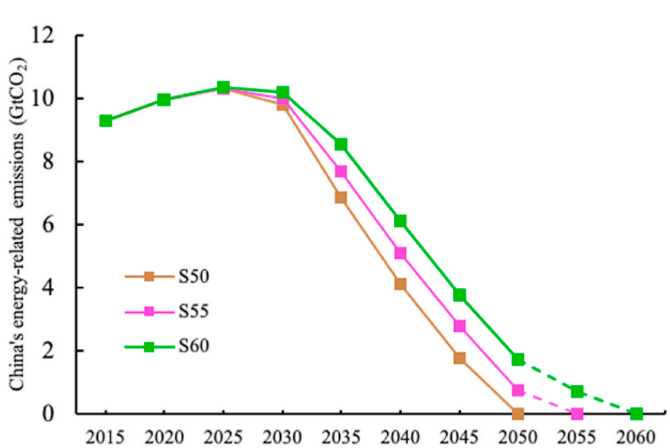

Fig. 2. CO_2 trajectories assumed for China toward achieving carbon neutrality.

energy consumption trend. Thereafter, as overall demand for industrial products gradually becomes saturated and production efficiency increases, China's industrial energy consumption declines to about 33 EJ in 2050 under all three scenarios, a decline of almost 40% from the 2020 level. Compared to energy consumption, industrial CO_2 emissions decline more rapidly. Currently, industry is the second largest CO_2 emitting sector in China [7]. With the implementation of the NDC, China's industrial emissions could start to decline during the 14th Five-Year Plan period. Before 2040, industrial emissions decline faster than total national emissions, reflecting the large economic mitigation opportunities in China's industrial sector during this time stage [44]. However, because high-temperature, high-quality process heat is expensive to be deeply decarbonized and CCS cannot completely eliminate CO_2 [35,45], China's industrial sector is not projected to achieve net-zero emissions in the first half of the century in the scenarios assessed here. In 2050, China's industrial emissions fall to 0.27–0.41 $GtCO_2$, a reduction of 88–92% from 2020 levels, which is within the range (82–94%) estimated by Zhang et al. [20]. Fig. 3(a) also shows that industrial emissions and energy consumption are overall lower in the 'S50' scenario than in the 'S55' and 'S60' scenarios, implying that the earlier the carbon neutrality date, the faster the required pace of decarbonization in the industrial sector. In addition, the carbon prices in the three scenarios are shown in Fig. 3(b).

4.2. Energy structure by fuel and subsector

In the existing studies [9,10,20,46,47], electricity and coal show opposite development trends in the future energy system. This study further shows that an earlier carbon neutrality date would accelerate this tendency, as shown in Fig. 4(a). In all three scenarios, electricity replaces coal as the primary energy carrier for China's industrial sector around 2035; and in 2050, the share of electricity in China's industrial energy consumption reaches about 63%. This electrification rate lies between the global industrial electrification rate of 45% projected in the IEA net-zero emissions scenario [48] and China's industrial electrification rate of 69.5% projected in the Tsinghua University 1.5 °C scenario [43], reflecting that the decarbonization efforts required in China's industrial sector tend to be higher than the global average in the context of carbon neutrality. Hydrogen is generally more costly than electricity. The development of hydrogen in China's industrial sector is more determined by the date of achieving carbon neutrality than electricity. In the 'S50' scenario the share of hydrogen in China's industrial energy consumption reaches 10.4% in 2050, twice as much as in the 'S60' scenario, suggesting that hydrogen can be an important option for further deep decarbonization in China's industry. The hydrogen share here is within the range reported in the IPCC AR6 (3–16% globally in 2050 under 1.5 °C). The penetration of electricity and hydrogen squeezes the shares of coal and refined liquids, especially as fuels. In 2050, coal's share in China's industrial energy consumption is 7.2–10.6%, of which 52–67% is used as feedstock, and refined liquids' share is 8.9–10.5%, of which 79–87% is feedstock.

As shown in Fig. 4(b), the share of energy consumption in energy-intensive subsectors including cement, steel, chemical, and non-ferrous metals is projected to decrease from 78% in 2015 to about 58% in 2050, which is broadly consistent with the findings of Zhou et al. [9]. In contrast, the share of machinery energy consumption increases from 6% to 14%. This implies a shift in the composition of China's industrial sector from energy-intensive production of raw materials to high value-added production of finished goods, aligning with the orientation of *The* 14th *Five-Year Plan for Green Industrial Development*. Similar to its impact on the fuel mix, an earlier carbon neutrality date accelerates the shift in the structure of energy use by subsector.

4.3. Energy consumption and emissions by subsector

As shown in Fig. 5, energy consumption in cement, steel, and

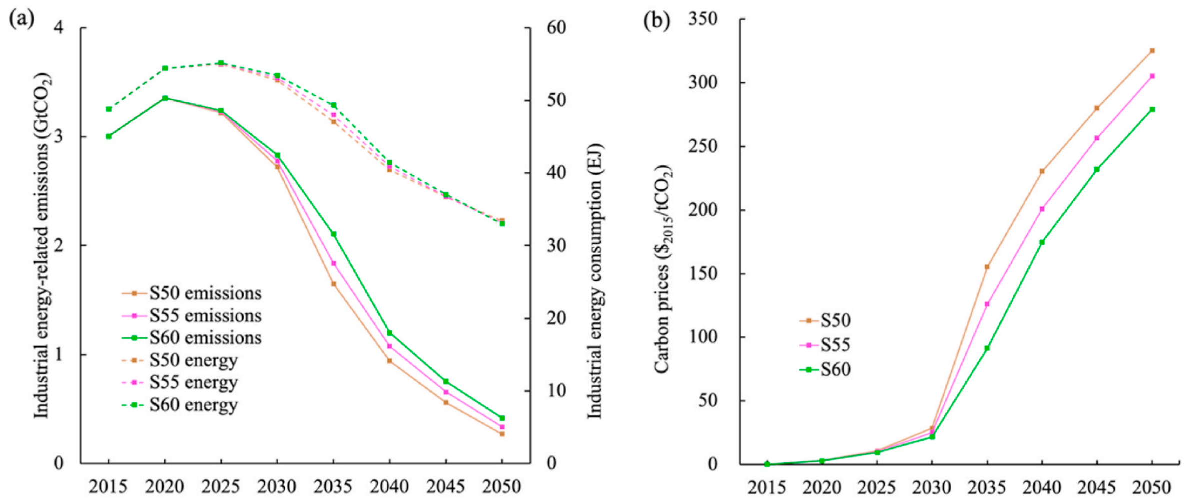

Fig. 3. Total energy consumption and direct CO_2 emissions of China's industrial sector (a) and carbon prices (b).

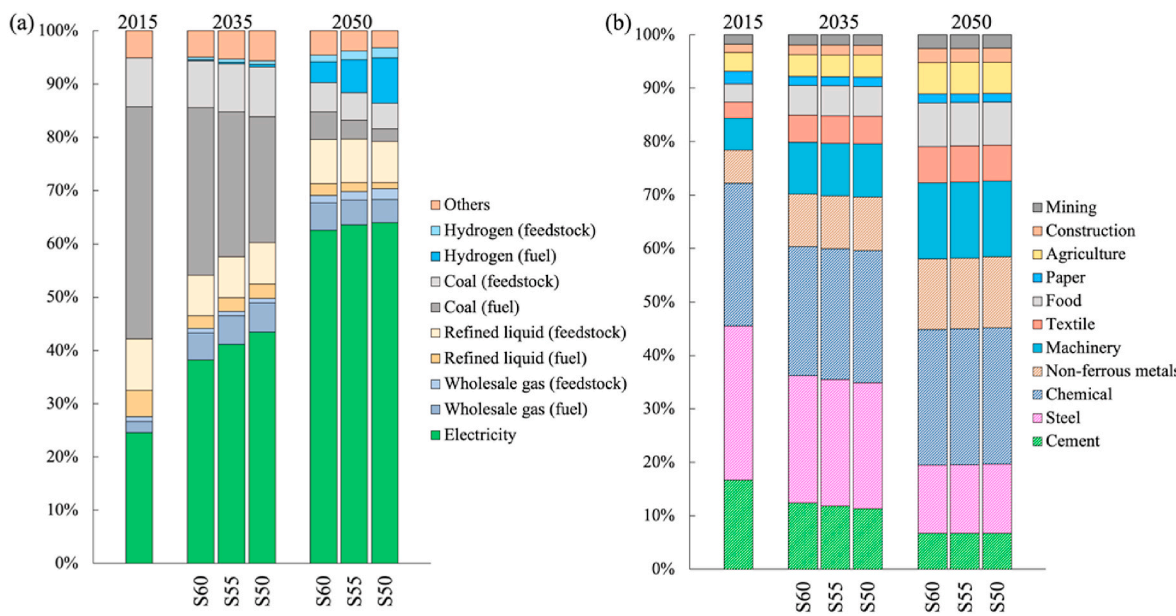

Fig. 4. Energy structure of China's industrial sector by fuel (a) and by subsector (b).

chemical begins to decline from the 14th Five-Year Plan period as China phases out obsolete energy-intensive production capacity, consistent with changes in their product outputs. Energy consumption in non-ferrous metals is projected to increase until around 2030 with the development of new energy infrastructure. The paper industry, which once had a high energy intensity in China [49], continues to upgrade its production structure and reduce energy consumption. Other subsectors that primarily serve the living needs of people, such as food, agriculture, textile, and construction, maintain relatively stable energy consumption after 2030. Consistent with the results for the whole industrial sector in Section 4.1, achieving an earlier carbon neutrality date requires faster CO_2 reductions in all subsectors. In particular, this study features that emissions in cement, steel, chemical, and paper change almost in parallel with their energy consumption, suggesting that reducing energy consumption is a key lever for mitigation in these subsectors, which is generally consistent with the findings of several existing studies [9,10,22,24]. However, as energy consumption remains stable while emissions decline rapidly after the peak emissions year, emissions in all other subsectors are gradually decoupled from energy consumption, suggesting that their main mitigation driver is energy structure optimization. Finally, to support the achievement of China's carbon neutrality, we emphasize the need for cement, steel, and chemical to reach peak CO_2 by the 14th Five-Year Plan period, while all other subsectors are expected to reach peak CO_2 by the 15th Five-Year Plan period.

4.4. Decarbonization and electrification by subsector

As the largest industrial emitting subsectors in China, cement, steel, and chemical together accounted for 81% of total industrial emissions in 2015. Fig. 6(a) verifies that cement, steel, and chemical are the major contributors to industrial emissions reductions in China, with their total mitigation contributions of 85%, 84%, and 83% between 2015 and 2050 under the 'S60', 'S55', and 'S50' scenarios, respectively. Fig. 6(a) further shows that achieving an earlier carbon neutrality date has a more pronounced impact on mitigation in other subsectors than in these three sectors. For example, when moving from the 'S60' scenario to the 'S50' scenario, the emissions reductions in steel increase by only 2.2%, while those in non-ferrous metals increase by 20%. In summary, mitigation in cement, steel, and chemical is the fundamental requirement for decarbonization of China's industrial sector, while further deeper mitigation

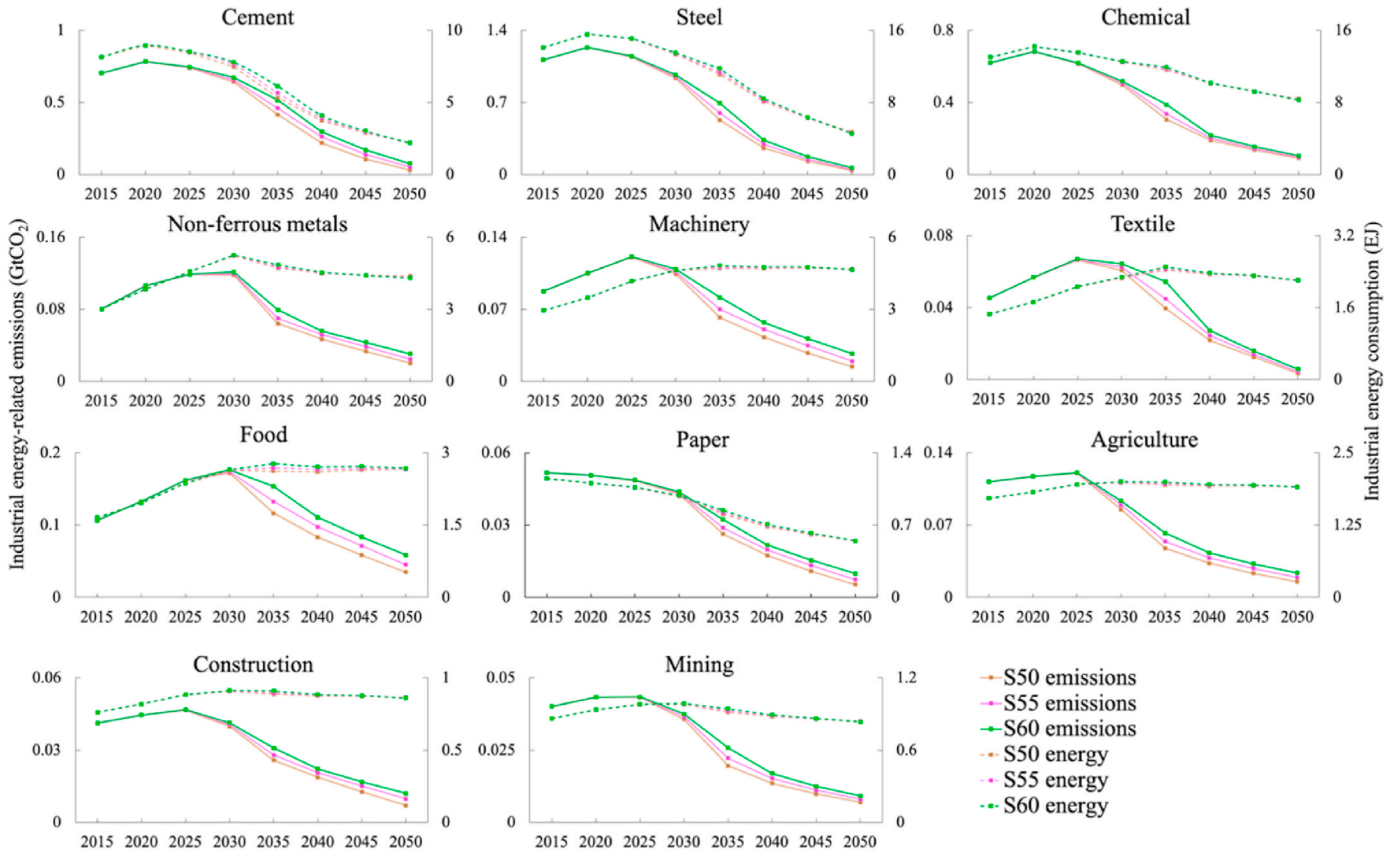

Fig. 5. CO_2 emissions and energy consumption of industrial subsectors in China.

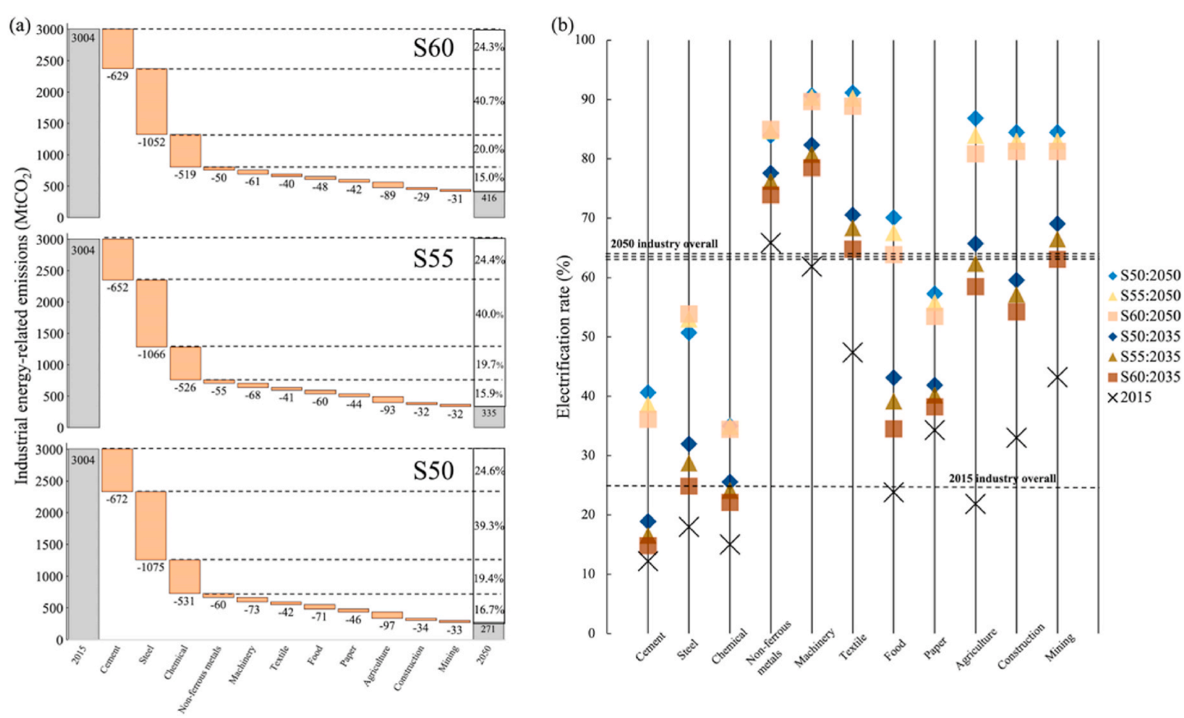

Fig. 6. Mitigation contribution (a) and electrification rate (b) of industrial subsectors in China.

requires more additional efforts in other subsectors.

As mentioned earlier, electrification is a highly recognized strategy for industrial decarbonization [3–6]. Fig. 6(b) shows the electrification rate for each subsector in different scenarios. We find the electrification progress of cement, steel, chemical, and paper slower than the whole industrial sector, which validates the finding in Section 4.3 that these subsectors are more dependent on reducing energy consumption to reduce emissions than the other subsectors. In fact, the electrification rate of each subsector is closely related to the composition of its energy services. For example, most of the energy used in cement is for clinker calcination [50]. Since the cost of converting electricity into high-quality process heat is still likely to be too high to compete with other energy in the first half of this century, the electrification rate of cement reaches only 36–41% in 2050 in the scenarios of this study. Electricity also cannot replace energy feedstock. Therefore, electrification of steel and chemical may also be limited. In the scenarios assessed here, electrification rates for steel and chemical are 51–54% and 34–35% in 2050, respectively. In contrast, the non-ferrous metals subsector has the potential to exceed 84% electrification in 2050, as electrochemical and machine drive are its main energy services. In all scenarios, machinery, textile, agriculture, construction, and mining also reach electrification rates above 80% in 2050. In general, the earlier the carbon neutrality, the higher the subsector electrification rate in 2050, which is consistent with the results in Section 4.2. The only exception is steel, whose 2050 electrification rate in the 'S50' scenario is modelled to be lower than in the 'S60' scenario due to the intervention of hydrogen. When hydrogen and electricity are considered together, their total share in steel energy consumption is 64% in the 'S60' scenario, increasing to 72% in the 'S50' scenario.

4.5. CCS and hydrogen by subsector

As shown in Fig. 7(a), the model suggests that CCS can play an important role in the decarbonization of cement, steel, and chemical in China. However, as demand for cement, steel, and chemical decreases and hydrogen becomes increasingly competitive, this study features that the amount of CCS may not need to keep rising over time. This differs from the continued growth in CCS deployment reported in previous modelling studies of China's industry that did not include hydrogen applications [9,10,24], but is consistent with the trend in global industrial CCS deployment in some of the 1.5 °C scenarios in the IPCC AR6 [3]. The amount of CCS in industrial energy use in China (including bioenergy with CCS) is projected to peak at 0.30 $GtCO_2$ in 2040 in the 'S60' scenario and at 0.33 $MtCO_2$ in 2035 in the 'S50' scenario. This implies that the earlier the date of carbon neutrality, the faster the deployment of CCS is expected in China's industrial sector. The scale of CCS deployment in subsectors is related to their fossil fuel consumption and energy service properties. Across the three scenarios in this study, in 2050, about 9% of the CO_2 captured by CCS from China's industrial energy use is in cement, about 34% in steel, and about 50% in chemical.

In the context of achieving carbon neutrality in China, hydrogen can also play an important role in industrial decarbonization (Fig. 7(b)). In the 'S60' scenario, hydrogen consumption in 2050 is 0.51 EJ, 0.47 EJ, and 0.45 EJ in cement, steel, and chemical, respectively, accounting for 23.2%, 10.3%, and 5.4% of their energy consumption. With the carbon neutrality date of 2050, hydrogen consumption in these three subsectors grows to 0.88 EJ, 1.03 EJ, and 0.84 EJ in 2050, respectively. Its share in energy consumption reaches 40%, 21.9%, and 10%, respectively, almost twice as much as in the 'S60' scenario. Moreover, consistent with Fig. 4 (a), we find that the carbon neutrality date has a greater impact on the use of hydrogen as fuel than as feedstock. For example, hydrogen consumption as fuel increases from 0.32 EJ in the 'S60' scenario to 0.8 EJ in the 'S50' scenario in steel and from 0.16 EJ to 0.42 EJ in chemical, both showing a greater increase than as feedstock. Despite its increasing economic competitiveness, the cost of hydrogen as feedstock is still likely to be higher than the cost of fossil feedstock equipped with CCS in the first half of the century. In all three scenarios, in 2050, about 50% of China's industrial feedstock still comes from fossil energy (without CCS) and about 40% from fossil-CCS. CCS is difficult to be deployed on a large scale in other subsectors (except cement, steel, and chemical). With fewer application limitations than CCS, total hydrogen consumption in all other subsectors increases significantly from 0.32 EJ in the 'S60' scenario to 0.83 EJ in the 'S50' scenario, validating that hydrogen can be a critical option for long-term deep decarbonization of the industrial sector in China.

5. Conclusions

By refining China's industrial sector and including industrial CCS and hydrogen in GCAM framework, this study analyzed China's industrial decarbonization at the subsector level under three representative carbon neutrality scenarios. This sub-sectoral analysis can help

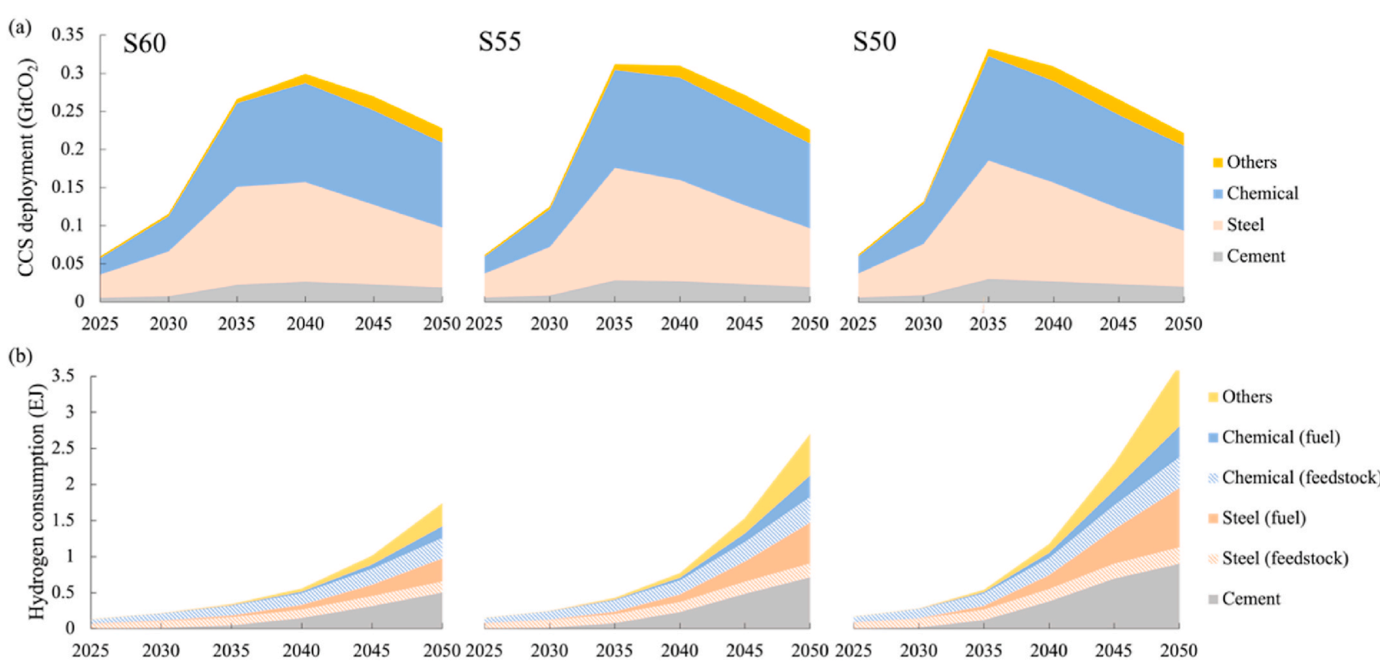

Fig. 7. CCS (a) and hydrogen (b) development in China's industrial sector. Note that CCS reported here refers to CCS deployed in energy use and does not include CCS in industrial processes such as capturing CO_2 released from limestone.

policymakers better identify the role and key mitigation targets of each subsector in transforming China's industrial sector to align with the 2060 carbon neutrality.

To support the achievement of national carbon neutrality, all three scenarios show that China's industrial CO_2 emissions peak during the 14th Five-Year Plan period and achieve a reduction of about 90% from 2020 levels in 2050. Considering that energy consumption and structure are key determinants of industrial emissions, policymakers should develop a more detailed transition strategy from energy-intensive to high value-added industries and from fossil energy to low-carbon alternatives. This study suggests that electricity becomes the primary energy carrier for China's industrial sector by around 2035, with industrial electrification rate reaching about 64% in 2050, while the role of coal and oil gradually changes from fuel to feedstock.

Cement, steel, and chemical are the fundamental subsectors for industrial decarbonization in China. They are all expected to reach peak carbon emissions by the 14th Five-Year Plan period and are collectively responsible for 83–85% of total industrial CO_2 reductions from 2015 to 2050. For these three subsectors, an important way to mitigate emissions is to accelerate the reduction of overcapacity and the development of efficient, energy-saving and CO_2-reducing technologies. Further deep decarbonization in China's industrial sector will require more additional efforts in other subsectors, which are expected to reach peak carbon emissions by the 15th Five-Year Plan period. Increasing the electrification rate is the most important way to reduce emissions in other subsectors. By 2050, electrification rates in non-ferrous metals, machinery, textile, agriculture, construction, and mining are expected to exceed 80%. CCS and hydrogen are expected to play an important role in China's industrial decarbonization in the context of carbon neutrality. The annual deployment of CCS in China's industrial energy use may exceed 0.3 $GtCO_2$ in 2035–2040, and hydrogen consumption is expected to grow through 2050. In 2050, hydrogen accounts for 5.2–10.4% of China's total industrial energy consumption. To achieve commercial utilization of CCS and hydrogen, China could focus more on addressing technological and other bottlenecks to facilitate the construction of their supply chain and reduce utilization costs.

The study has its limitations and weaknesses. Due to the availability of data, this study modelled China's industrial sector through intermediate energy services. Future work could consider modelling actual production processes and incorporating them into IAMs, which could derive more nuanced results. In this study, the cost assumptions for hydrogen production and application were based on global assessments. More localized cost projections could be further explored and applied to future modelling. In addition, this study was limited to decarbonization within China's industrial sector. Future studies could also analyze the interaction of industrial decarbonization with broad dimensions such as employment and social justice to better support China's achievement of the 2060 carbon neutrality.

Credit author statement

Tianming Shao: Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - original draft, Visualization. Xunzhang Pan: Conceptualization, Methodology, Formal analysis, Writing - original draft, Supervision, Project administration, Funding acquisition. Xiang Li: Validation, Formal analysis, Investigation, Writing - review & editing, Visualization. Sheng Zhou: Methodology, Investigation, Writing - review & editing. Shu Zhang: Validation, Investigation, Writing - review & editing. Wenying Chen: Conceptualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112992.

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