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Special Section:
Climate Change, Global Air Quality, and Society

Key Points:

- Carbon capture, utilization, and storage, hydrogen- and scrap-based technologies need accelerated deployment
- Technological solutions to net-zero emissions with less investment are identified
- Provincial disparities for typical current and innovative technologies are projected

Supporting Information:

Supporting Information may be found in the online version of this article.

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Technological Solutions to China's Carbon Neutrality in the Steel and Cement Sectors

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Abstract China has set Nationally Determined Contributions (NDCs) and carbon neutrality targets without providing expected industry-specific technological details. By focusing on the steel and cement industries in China, this study analyzes the energy consumption of different technology routes, decarbonization pathways of innovative technologies, and the synergistic impact of air pollutants. The study finds that the incumbent technology routes for steel and cement production have limited carbon reductions, and the deployment of innovative technologies (carbon capture, utilization, and storage [CCUS], electrolytic- and hydrogen-based, and scrap-based technologies) need to be accelerated to achieve carbon neutrality targets. We find that the net-zero emissions pathway relying upon innovative technologies needs less investment than the NDCs scenario. Furthermore, electric arc furnace deployment will be mainly concentrated in Jiangsu, Guangdong, and Sichuan, while CCUS should be mainly in Hebei, Shandong, Liaoning, and Jiangsu provinces. The increased electrification of innovative technologies in steel and cement requires a shift in energy inputs from fossil energy to electricity. A combination of strict climate change mitigation and air pollution control will have higher synergistic effects.

Plain Language Summary Carbon neutrality means achieving a balance between emitting and absorbing carbon from the atmosphere in carbon sinks, and therefore imposes stringent requirements on human economic production activities. China has announced ambitious plans to achieve carbon neutrality by 2060, which will require deep decarbonization across carbon-intensive sectors. The steel and cement sectors account for 70% of China's overall industrial emissions and are prioritized for emissions reduction. We believe that traditional technologies and process improvements are insufficient to reduce emissions from steel and cement production and that innovative technologies must be considered. The new technologies may be low-carbon processes or fuel supplies. The MESSAGEix-China model was developed in this study to explore the decarbonization pathways for steel and cement in China based on the least-cost approach, providing technological solutions under different scenarios. This study identifies technological solutions that can achieve net-zero emissions targets with lower economic costs. The synergistic effects of air pollutants are also discussed for effective climate policy.

1. Introduction

To achieve the goal of limiting global temperature rise to 2°C by 2100, China has not only pledged Nationally Determined Contributions (NDCs), but also committed to peak CO_2 emissions by 2030 and to work toward achieving carbon neutrality by 2060 (Duan et al., 2021; Lewis & Edwards, 2021; Mallapaty, 2020; Nature, 2021; United Nations, 2020). Carbon neutrality is a strategy that can bring significant changes in the structure of the economy, particularly by driving the development and deployment of innovative technologies (He et al., 2020; IEA, 2021a) and energy efficiency improvement. These changes include a shift toward renewable energy sources, the electrification of transport and heating, and the implementation of energy efficiency measures in industry, buildings, and other sectors. In addition, carbon neutrality requires the development of new policies, business models, and financing mechanisms that can support the transition to a low-carbon economy.

The industrial sector is a critical component of China's carbon emissions inventory, responsible for approximately 35% of the country's total emissions. Within this sector, the steel and cement industries are particularly significant, as China is the world's largest producer of both materials, accounting for around 50% and 55% of

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global production, respectively (IEA, 2021a, 2021b, 2021c; Mysteel Global, 2021). The related carbon emissions account for almost 70% of China's total industrial emissions, making them key to achieving the country's net-zero emissions (NZEs) target and improving air quality (N. Li et al., 2019; Shan et al., 2018b; Wang et al., 2017). Therefore, there is a pressing need to decarbonize the steel and cement sectors and implement synergistic control of both carbon emissions and air pollutants, which represents a critical area of research.

The decarbonization pathways for technologies are particularly critical in the context of China's carbon neutrality targets. Currently, China's steel feedstock comes mainly from virgin iron ore and reductants are dominated by coke and coal, with blast furnace-basic oxygen furnace (BF-BOF) being the main production process. The direct reduction of iron-electric arc furnace (DRI-EAF) and scrap-based EAF processes with lower carbon emissions per ton of steel are still poorly utilized in China (IEA, 2020a; Zhang et al., 2019, 2022). In addition, in China, steel production facilities are typically replaced after a single operating cycle (rather than being extensively refurbished), which helps to alleviate the expected burden of replacing existing assets to avoid locked-in emissions. However, the age of China's existing steel production capacity is generally younger than the international average, and its scale is enormous, making it challenging to match the deployment of innovative technologies with the operating cycles of existing facilities, thereby hindering progress toward carbon neutrality (IEA, 2021a). Cement production technologies are relatively mature and vary little from country to country, but emissions from the production process are difficult to reduce through efficiency improvements. Therefore, in the future, the development of innovative technologies coupled with clean energy will be necessary for decarbonization pathways in China's steel and cement sectors.

Currently, research on decarbonization pathways to achieve carbon neutrality targets in China is mostly limited to cost-benefit analyses of individual technologies and driving factors (Kermeli et al., 2019; Z. Li et al., 2019; Liu et al., 2021; Ma et al., 2016; Sun et al., 2022; Van Ruijven et al., 2016; Wu et al., 2016). These studies provide detailed analyses of some technologies but are unable to explore the inter-relationship and material flow between technologies in different industries and lack a broader scope of research. In addition, some studies have used Integrated Assessment Models (IAMs) to explore China's decarbonization pathway, like China-TIMES model (Tang et al., 2021; Zhang & Chen, 2022), GCAM (Zhou et al., 2021), MESSAGEix-CAEP (Dong et al., 2023), CHEER (Zhang et al., 2021). However, as these models are generally constructed based on regions, the model parameters for studying China are very limited, and therefore, insights into decarbonization pathways are also limited (Shan et al., 2018a). A number of studies predict that future emission reductions in the steel and cement sectors will rely on the transformation of the energy mix (electricity and hydrogen), the use of steel scrap and the deployment of innovative technologies like carbon capture, utilization, and storage (CCUS) (IEA, 2020a, 2020b, 2021a, 2021f; Kim et al., 2022), however few foresee future technology deployment and energy activities at the provincial level. Such lack of understanding may hinder the design of more effective strategies for future deep decarbonization in the steel and cement sectors.

Therefore, the main objective of this research is to examine the latest technological developments in China and explore the decarbonization pathways for innovative technologies. The study aims to gather information on the distinctive features of these technologies and their impact on various crucial processes. In addition, the research incorporates specific point source data obtained from steel and cement plants in China. Then decarbonization pathways and technology deployment costs are provided, as well as disparities in carbon emissions and synergies of pollutants for 2020–2050 are explored based on MESSAGEix-China and Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) IAMs (Zhang et al., 2022, 2019). We find that current technology routes for steel and cement production have limited potential for carbon reductions and it is urgently needed to accelerate the deployment of innovative technologies (e.g., CCUS, electrolytic- and hydrogen-based, and scrap-based technologies). This suggests that existing energy saving, and energy efficiency improvement measures are no longer sufficient to achieve China's carbon neutrality and that more innovative technologies need to be deployed in the steel and cement sectors.

2. Materials and Methods

2.1. Model Framework

Figure 1 illustrates the model framework for this study. The scenarios analyzed combine two main categories of climate policy objectives and air pollution policy objectives, acting on the MESSAGEix-China and GAINS

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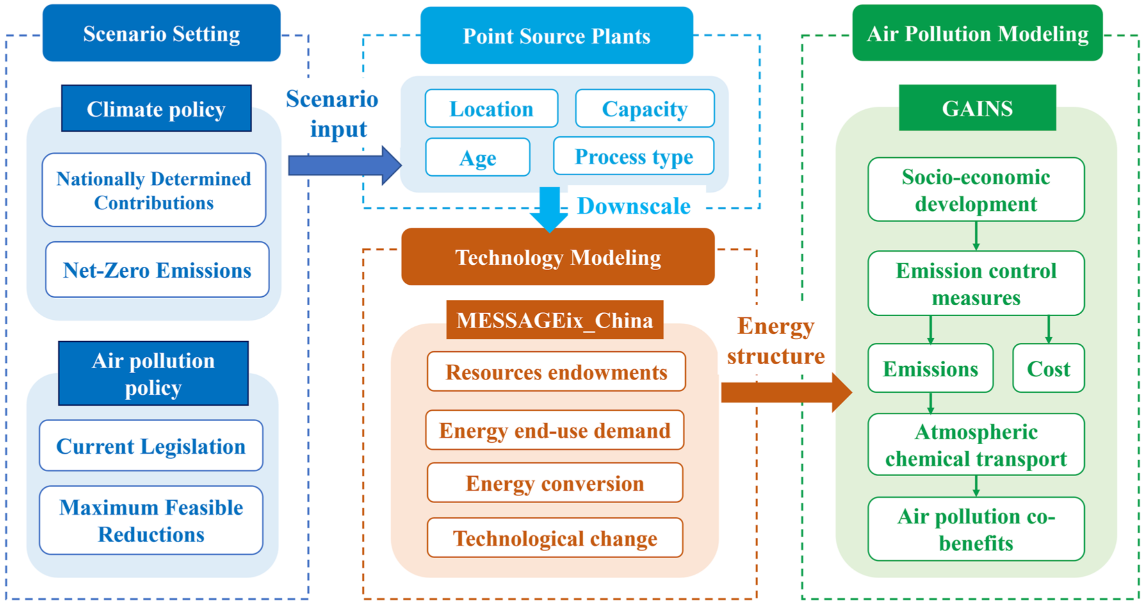

Figure 1. Modeling framework. This study integrates two designed scenarios, point source plants database and two models to project decarbonization pathways for China's steel and cement sectors.

models, respectively. In the different scenarios, the point source database for steel and cement is combined with the process-based MESSAGEix-China model, which considers national resource endowments, energy and material conversion, energy and material demand, manufacturing for product etc. The energy mix, intermediate products, and the corresponding carbon emission reduction costs are calculated by MESSAGEix-China model. The scope of the original MESSAGEix-China model was at the national level and this study downscales the national scope to the provincial and plant level based on the process capabilities and plant locations. Finally, the resulting energy consumption by fuel types and intermediate products (e.g., sinter, pellets, pig iron, crude steel, cast steel, and cement etc.) are integrated into the GAINS model as an activity pathway to quantify the potential for air pollution abatement and to assess the potential co-benefits with and without the use of air pollutant control measures (N. Li et al., 2019).

2.1.1. MESSAGEix-China Model

Developed by the International Institute for Applied Systems Analysis (IIASA), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is a dynamic systems optimization model widely used to investigate future developments in medium to long-term energy planning and policy analysis, and has become a central tool for energy-environment-economic systems analysis in science and policy worldwide (Huppmann et al., 2019; Keppo & Strubegger, 2010; Sullivan et al., 2013). By integrating different process technologies and commodities, MESSAGEix creates models of energy and material flows. These models aim to provide a comprehensive view of the energy and resource footprints of various processes such as extraction, beneficiation, conversion, distribution, and consumption. The objective of the model is to establish energy supply and demand systems with targeted greenhouse gas emissions or concentrations. This is accomplished through a bottom-up approach that combines various energy technologies to create a portfolio that can meet energy demands while being cost-effective (Grubler et al., 2018; Johnson et al., 2017; Keppo & Strubegger, 2010; Kikstra et al., 2021). Furthermore, the model facilitates the visualization of energy and resource flows, which allows for a comprehensive assessment of the environmental impacts associated with diverse processes.

MESSAGEix-China, an energy-resource system IAM based on IIASA's open-source MESSAGEix modeling framework (Zhang et al., 2022). In the MESSAGEix_China, specific characteristics and related policies of China's energy and resource systems are incorporated and extended to the energy and material demand modules of building, transportation, and industrial sectors such as iron and steel. In this study, a more detailed process technology (see Figure 2) for steel and cement sectors is developed in MESSAGEix-China, representing a significant resolution for energy, materials and water and related technologies through the interactions of energy,

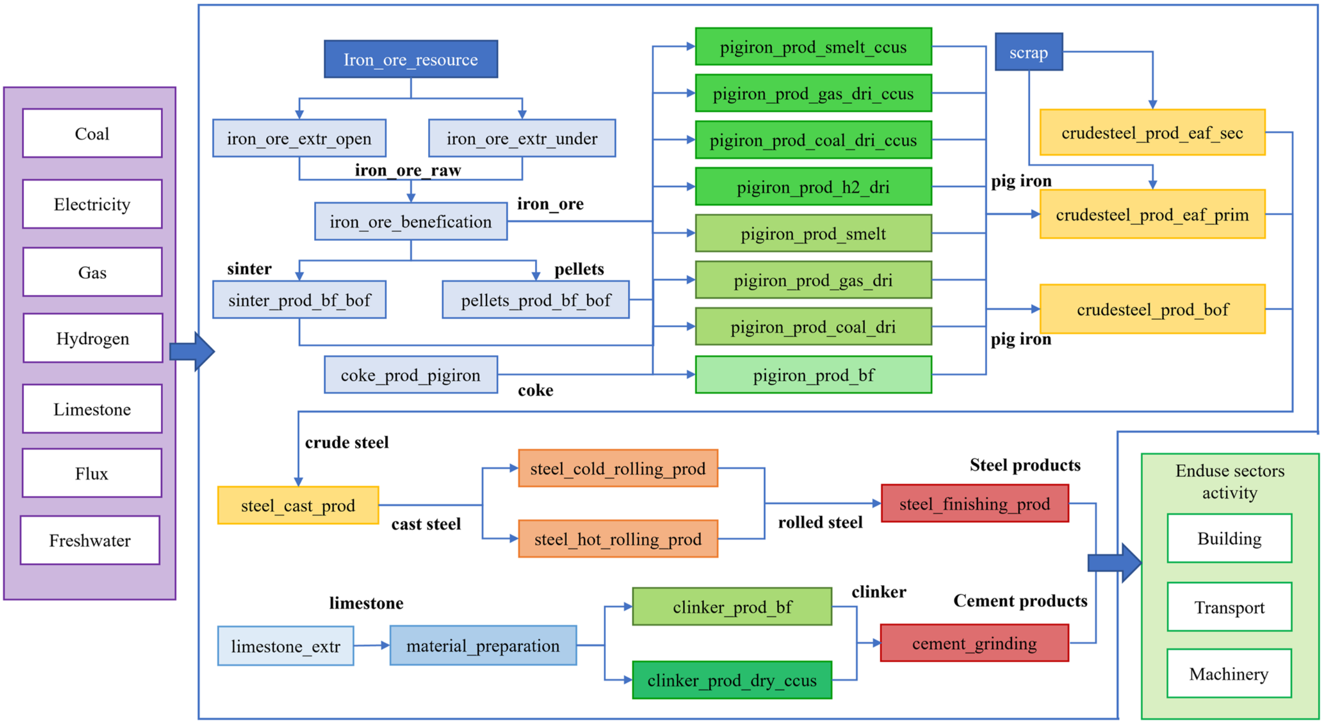

Figure 2. Technologies interactions in steel and cement sectors in MESSAGEix_China model. These technologies connect 6 different energy commodities (i.e., coal, coke, electricity, fuel oil, natural gas, hydrogen) and 18 materials and water carriers (e.g., iron ore, limestone, sinter, sinter flux, pellets, pellet flux, lime, pig iron, crude steel, cast steel, rolled steel, scrap, slag, clinker, sandstone, steel products, cement products, fresh water, and water withdrawal), and the technology process flows are shown in Figure S1 in Supporting Information S1. Innovative technologies here involve carbon capture, utilization, and storage, electrolytic- and hydrogen-based direct reduction of iron and scrap-based electric arc furnace.

material, water per process technology between sectors that covers, from the extraction, conversion, and distribution of mineral resources to the provision of energy end-use services (Zhang et al., 2019). An important feature of MESSAGEix-China is the technology-rich representation of the energy and resource system, including a complete description of the long-term energy, transport, and building structure (Sullivan et al., 2013). A major contribution of this study is to extend the process technologies for Chinese steel and cement sector of the MESSAGEix and combine the point information of steel and cement plants in China that allow to model long-term pathways to achieve China's proposed autonomous contribution targets and carbon neutrality targets, at the national, provincial and plant levels based on process capabilities and plant locations. The findings of this study can provide better policy guidance on decarbonization pathways for China's steel and cement sectors (Zhang et al., 2022).

This study collectively analyzes 26 technology routes in the steel and cement sectors, with workflows as shown in Figure 2. Among them, there are various steel production processes, which consist of different processes, such as iron ore mining under different technologies, coking, sintering, pellet, iron making, and steel making. Here, iron ore is agglomerated in a sintering plant to produce sintered ore, and pellets are formed by a pellet plant at high process temperatures. These products are converted into pig iron in the BF. The pig iron is then fed into BOF or EAF to produce crude steel (Zhang et al., 2019). The other technology routes are the iron ore or scrap, which can be directly used to produce pig iron by DRI and EAF technologies. The crude steel is then cold rolled or hot rolled into finished steel. The production process for cement is much simpler, from limestone through raw material preparation and new dry production to cement grinding. See Table S2 in Supporting Information S1 for the technologies list.

2.1.2. GAINS Model

The GAINS model, developed by IIASA, is an assessment model focused primarily on analyzing the costs and potential of air pollution control and greenhouse gas mitigation, and evaluating the interactions between various policies, developed by IIASA and the Air Quality and Greenhouse Gas (AIR) project (Amann et al., 2011; Rafaj et al., 2021, 2013). This model analyzes the cost and environmental impact of pollution control strategies

Table 1
Description of Decarbonization Scenarios

Scenario	Climate policies
BAU (WEO-2021 STEPS)	China's 14th Five-Year Plan: (1) Reduce CO_2 intensity of economy by 18% from 2021 to 2025. (2) Reduce energy intensity of economy by 13.5% from 2021 to 2025. (3) 20% non-fossil share of energy mix by 2025. (4) 25% non-fossil share of energy mix by 2030.
NDC	The current policy in steel and cement sectors is considered in the implementation of Nationally Determined Contributions until 2025/2030, equivalent effort thereafter.
NZE	In 2050, the CO_2 emissions of steel and cement sectors will be decline by 90% than 2015 which consistent with the net-zero emissions target.

by combining social-economic activities, including energy consumption, industrial production, transport, agriculture, etc., into different air pollutants and simulating the dispersion patterns of pollutants through atmospheric chemical transport models. In its optimization mode, GAINS identifies the least-cost balance of emission control measures for different pollutants and economic sectors to meet air quality and climate objectives (Amann et al., 2020).

GAINS uses a simplified form of source-receptor relationships to define the spatial response of air quality to changes in precursor emissions within a region in a computationally valid form (N. Li et al., 2019). Pollutants in the model include primary emissions of fine (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), non-methane volatile organic particles ,and ammonia (NH_3), among others, and the pollutants analyzed in this study are mainly SO_2, NO_x, and $PM_{2.5}$. In the discussion section of this study, the health impacts are further investigated, including attributable deaths estimated by applying the attributable fraction of specific diseases and ages to the total deaths of specific diseases/ages. The calculation of population attributable fraction uses the integrated exposure-response functions of the WHO (2016) Burden of Ambient Air Pollution assessment. The baseline mortality rate for specific diseases is estimated based on the share of specific diseases and ages in the total number of deaths reported in the Global Burden of Disease Study 2013 (Forouzanfar et al., 2015) and applied to the total number of deaths in the scenario year reported/forecasted in the UN World Population Prospects (2017 Revision). In this study, the GAINS model is used to explore potential for regional air pollution abatement due to implementation of CO_2 mitigation measures and air pollution control technologies, under different scenarios.

2.2. Scenario and Technology Narratives

The scenarios used in this study combine a baseline scenario with two designed policy scenarios (Table 1). The baseline scenario is developed based on the IEA's World Energy Outlook 2021 (WEO-2021), the Stated Policies Scenario (STEPS), which provides a more conservative benchmark for the future (IEA, 2021e). The NDCs target assumes the implementation of country specific NDC by 2030 and the continuation of equivalent global climate action beyond 2030. The NZEs target is defined as the CO_2 emissions of steel and cement sectors will decline by 90% in 2050 compared to 2015, which is consistent with the impact of the climate target on the steel and cement sectors, mainly simulated through the MESSAGEix-China model.

2.3. Data Source

Our point source database records steel and cement plants under each ownership. Considering the complex structures of joint ventures and the varied ways in which production is organized in Sino-foreign joint ventures, where some production materials in the supply chain may come from foreign companies, planning based on the total capacity may overestimate the material flow of the enterprise in China. Therefore, we distinguish capacity allocation based on the proportion of joint ventures. For example, Lianyuan Iron and Steel Plant, which is located in Changsha, Hunan, owned by Hualin Iron and Steel Group (China) and ArcelorMittal Group (Luxembourg), whose ownership is 0.63:0.37, and we have divided the ownership of the total capacity according to this ratio.

Historical activity for energy commodities (e.g., coal, coke, and electricity) and materials commodities (e.g., iron ore, sintered ore, pellet ore, pig iron, crude steel, limestone) in the model is taken from the China Iron and Steel

Industry Yearbook (CSDRI, 2019, 2020), the China Cement Yearbook (CSDRI, 2016), China Cement Association (China Cement Association, 2023) and the China Statistical Yearbook (National Bureau of Statistics of China, 2019). Historical steel consumption and cement consumption for end uses (e.g., construction, machinery, automobiles, household appliances, and infrastructure) from China Industry Information Network (China Industry Information Network, 2015), and previous studies (Ma et al., 2016; Zhang et al., 2022, 2019).

Parameters such as investment and operating costs, fuel, material and water consumption, total historical capacity, and annual growth capacity of the currently adopted process technology are taken from the China Energy Statistics Yearbook, China Iron and Steel Yearbook, China Cement Yearbook, surveys of relevant literature and exchanges with Chinese experts (CSDRI, 2019, 2020; IEA, 2010; Zhang et al., 2019). Variable costs of production processes from IEA-Clean Coal Center and Metals Consulting International (MCI) (Carpenter, 2012; Metals Consulting International, 2018). Among the parameters of the new steelmaking technologies-scrap EAF, coal-based direct iron reduction (with and without CCUS), gas-based direct iron reduction (with and without CCUS), hydrogen-based direct iron reduction and oxygen-rich smelting reduction (with and without CCUS)-obtained through recent studies and exchanges with Chinese experts (Battle et al., 2014; IEA, 2020b; IRENA, 2020; Material Economics, 2019).

Emission factors for fossil fuels were obtained from the GAINS model and some calibration was done in conjunction with previous studies (Hasanbeigi et al., 2013; Zhang et al., 2014). The CO_2 average emission factors for electrolytic hydrogen technologies up to 2050 from the STEPS by the reports (IEA, 2020a, 2020b), the sustainable development scenario of the GAINS model, and the work by previous research (Rapier, 2020).

3. Results

3.1. Steel and Cement Plants in China

This study covers a total of 731 iron and steel plants in 2018 and 2,894 cement plants in 2019 operating in China (no data in Taiwan). The geographical distribution and capacity of steel plants are shown in Figure 3a, with a dense distribution in northern China and the southeast region, and most of the plants have a capacity of less than 10 million tones. There are about 2,894 cement plants in China (Figure 3b, excluding Taiwan), of which 56 clinker-only plants, 1,631 grinding plants, and 1,207 integrated plants. The national cement production capacity is about 3,243 Mt/year. Figure 3e illustrates how capacity is distributed across different age ranges for cement plants, with the majority falling between 6 and 20 years old and an average age of approximately 12 years old. However, it is important to note that emission-intensive assets like cement kilns typically have a lifespan of around 40 years (IEA, 2021d). Given that China's cement capacity has a long operating cycle, it is crucial to discuss and implement innovative technologies to improve environmental sustainability in the industry.

Figures 3c and 3d show statistical groups based on steel production processes, age and capacity. China's steel production is dominated by BF-BOF, and 76% of these are large-scale capacity (>6 Mt/year) steel plants; the EAF production process is mainly DRI-EAF, with a more balanced range of steel plants across the capacity. DRI and Scrap-EAF steel plants are few in China, and the utilization rate of scrap is much lower than in other countries. Most of the scrap currently used for steelmaking is mixed into primary steel production as a blend, which is almost always made via the BF-BOF route. Steel processing accounts for a large part, involving casting, rolling, and finishing processes that follow the crude steel. In addition, the age of existing steel plants is relatively low, concentrated in the range of 11–15 years. After one operating cycle, iron and steel plants in China typically choose to upgrade their steelmaking facilities rather than be extensively refurbished. While this mitigates the carbon lock-in effect by reducing the need to update the asset stock, the different operating cycles of individual iron and steel plants inevitably lead to the deployment of innovative technologies at different times, which may also incur additional costs and delay the carbon neutrality process significantly (IEA, 2021a).

3.2. Innovative Technological Solutions

The future pathway of technologies in the steel and cement sectors varies in different scenarios, it would bring about a significant shift in China's energy structure. Figures 4a and 4b indicate the percentage of pig iron and crude steel output attributed to each respective technology. In 2050, pig iron production will be cut by 50% in NDC scenario and 65% in NZE scenario compared to 2020, while crude steel production will be reduced by 31% and 35%, respectively. Future steel production will continue to rely on the current technology routes, but their

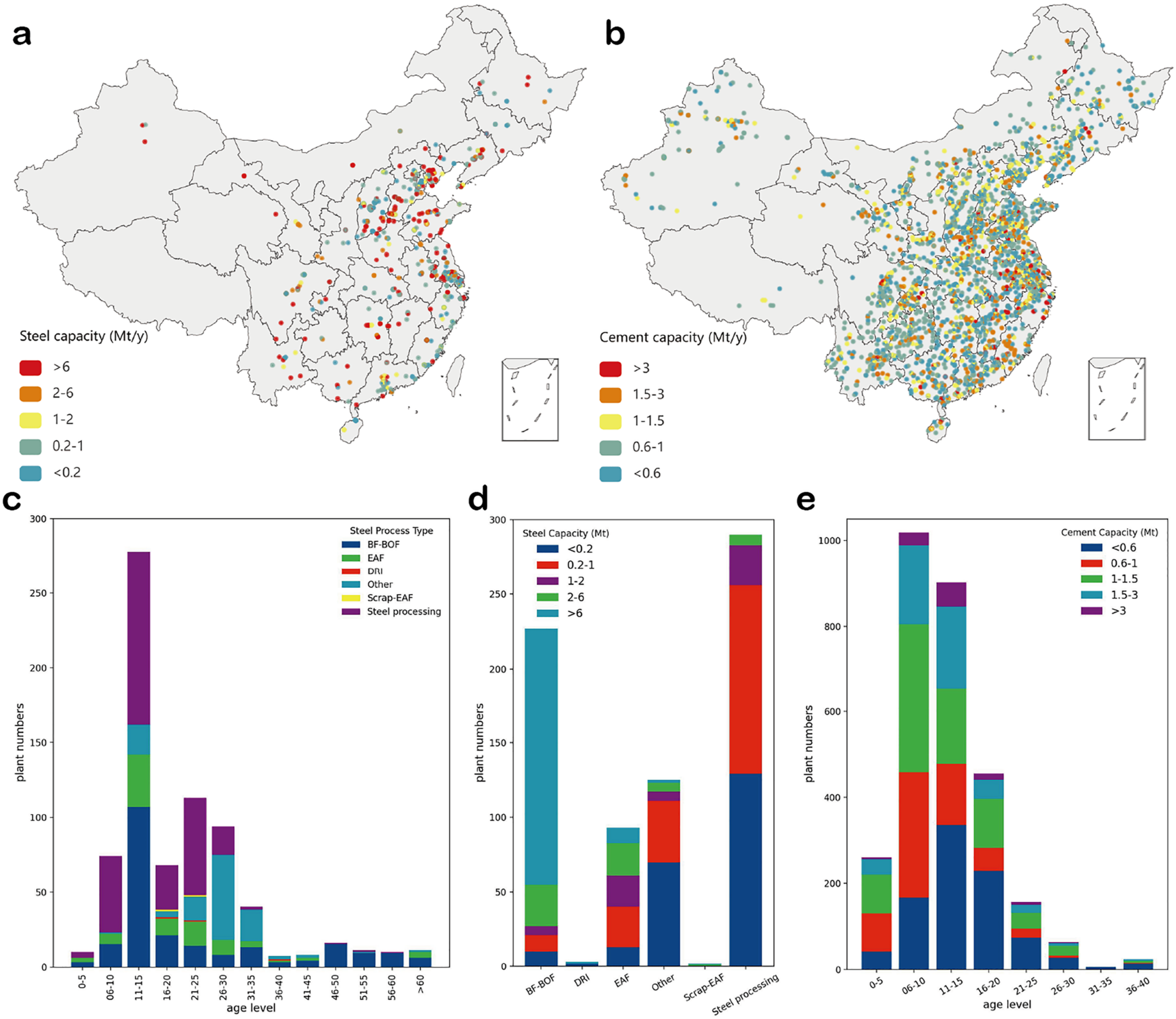

Figure 3. Existing iron and steel plants (2018) and cement plants (2019) in China. (a) Location and capacity of iron and steel plants in China. (b) Location and capacity of cement plants in China. (c) Iron and steel plants classified by age and process. (d) Iron and steel plants classified by process and capacity. (e) Cement plants classified by age and capacity. Here, the "Other" in steel process type means coke, sinter and oxygen, etc. "Steel processing" means casting, rolling, and finishing processes that follow the crude steel. See Table S1 in Supporting Information S1 for details.

share is decreasing, while EAF- and DRI-routes are expanding. Under the NZE scenario, the existing BF-BOF will be replaced by the more efficient EAF, with a large rise in scrap consumption (Figure 4c), which will, to some extent, drive a shift in energy input to electricity in the steel industry. This coincides with the ratio of coal to electricity in Figures 4d and 4e and is largely consistent with the findings of the IEA study (IEA, 2021a).

For future steel production, the burden of CO_2 abatement will fall on the deployment of innovative technologies, such as CCUS, 100% scrap-based EAF and hydrogen-based DRI. For example, pig iron production by fossil fuel-based DRI with CCUS that will avoid the use of coke ovens and sintering and spherical processes, produce a purer and more capture-friendly CO_2 stream and are equipped with terminal decarbonization technology. The other latest measures of pig iron production are hydrogen-based DRI and 100% scrap-based EAF, both routes are more energy efficient and commercially available, but require renewable-based electricity for achieving NZEs.

Cement production in the future scenario is significantly lower (Figure 4d), with NDC and NZE scenarios in 2050 being 52% and 65% lower than in 2020, respectively. However, there are not many improvements in the

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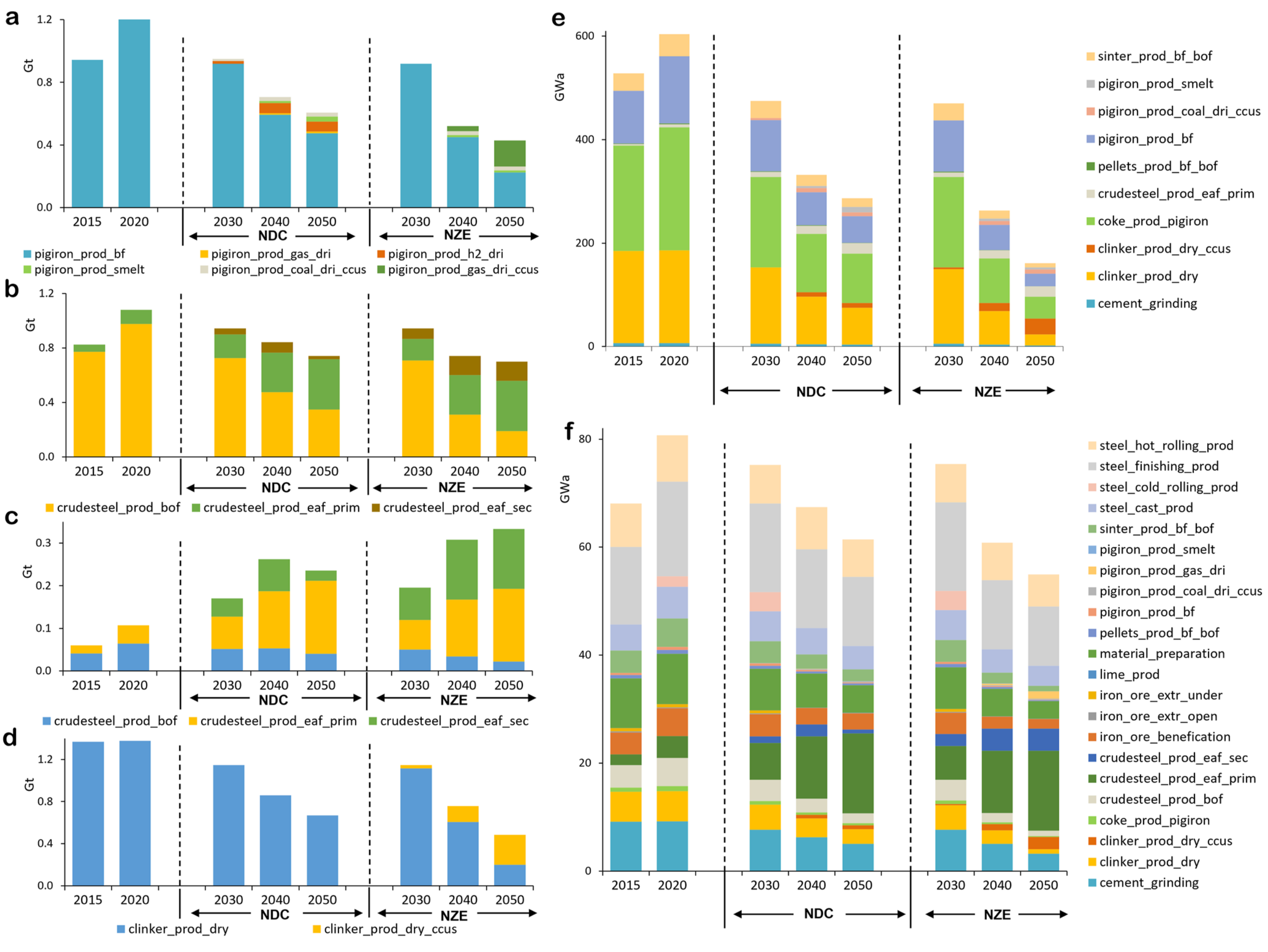

Figure 4. A roadmap of technological solutions for different scenarios. The production, material, and energy consumption composition of the different technologies for each product/commodity, comprising (a) pig iron production, (b) crude steel production, (c) scrap consumption, (d) clinker production, (e) coal consumption, (f) electricity consumption.

production process for decarbonization, which is mainly based on the addition of CCUS technology to the clinker production with dry process. The main reason is that the current Chinese cement production technologies are the most energy efficient across the globe (around 34% of capacity per clinker production line and grinding production line are 5,000 t/day and 2 Mt/year) and the clinker to cement ratio is the lowest (66% in China in 2020, 8% lower than the global average) (IEA, 2021a). The proportion of kilns equipped with CCUS in cement clinker production will increase to around 59% in 2050.

Figure 4e depicts coal's phasedown, with decarbonization pathways relying less on coal in the future, but not to the point of phrase-out. Most of the coal consumption in the period 2015–2050 is for coke making and clinker production with dry process, both accounting for over 60%, followed by iron making and foundry, rolling, and finishing, much higher than the 46% for NDC.

Figure 4f shows a modest reduction in demand for electricity from future innovative technologies. As coal use decreases, EAF steelmaking from scrap will expand, and the steel and cement sectors become progressively more electrified. Thus, even with a significant reduction in steel and cement demand, electricity demand will decline much more slowly by comparison.

3.3. Decarbonization Pathways

Decarbonization pathways require profound shifts in energy structure and technological portfolio in the Chinese steel and cement sectors. In 2050, carbon emissions in the NDC scenario will fall by 17% compared to the BAU

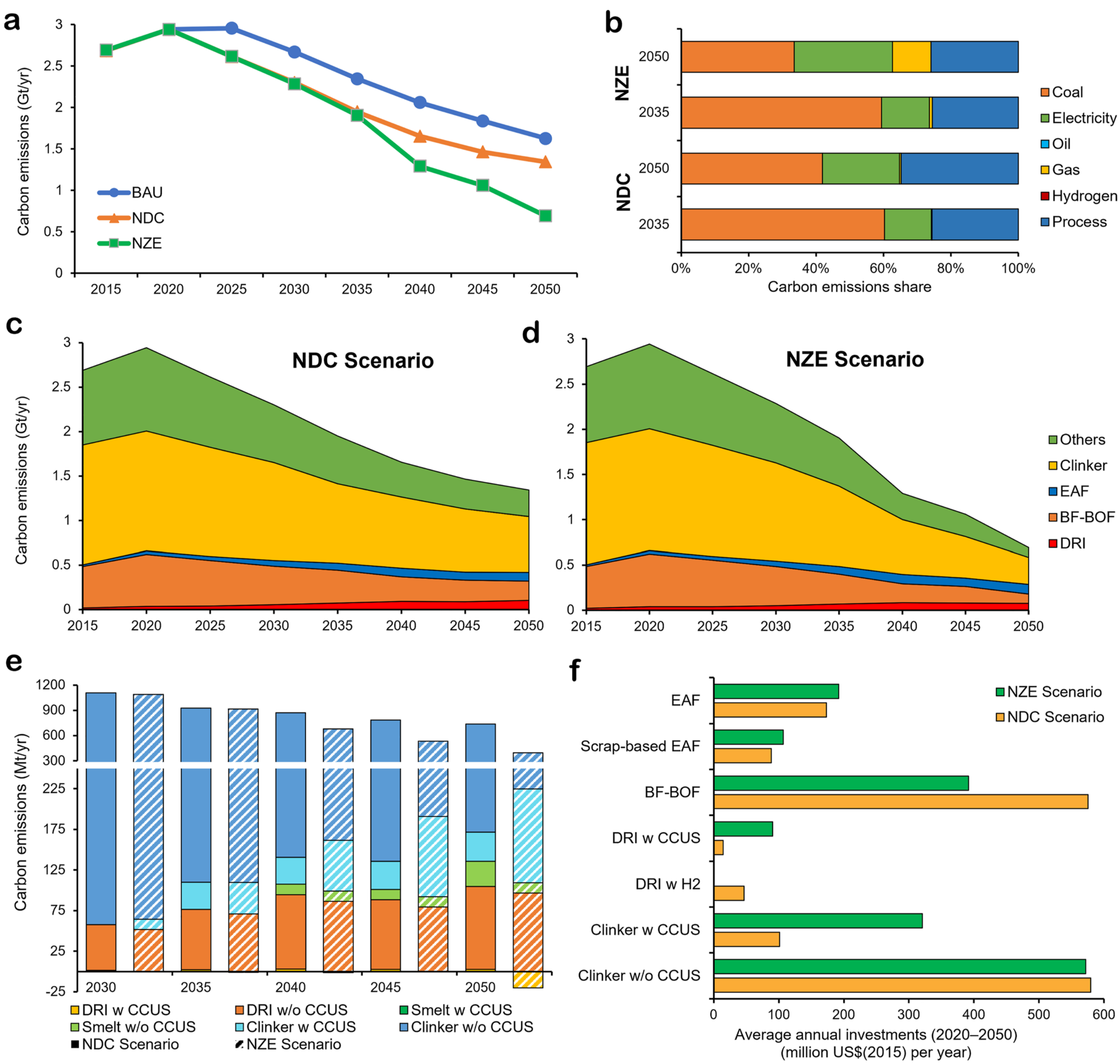

Figure 5. Carbon emission pathways and investment for different scenarios. (a) Carbon emissions by scenarios, 2015–2050. (b) Carbon emissions by energy types. (c, d) Carbon emission trajectories under Nationally Determined Contribution (NDC) and net-zero emission (NZE) scenarios (here "Others" means iron ore, pellet, pig iron production, and material preparation. Table S3 in Supporting Information S1 contains technology category). (e) Carbon capture, utilization, and storage (CCUS)-related technologies carbon emissions in 2035 and 2050 under NDC and NZE scenarios. Here, "Smelt" means pig iron production in oxygen-rich smelting reduction process. (f) Average annual investments for key technologies from 2020 to 2050, with a discount rate at 5%.

scenario, while in the NZE scenario, emissions will fall by 57% (Figure 5a). Moreover, carbon emissions in 2035 mainly come from coal and clinker production processes, with coal emissions accounting for nearly 60% of the total. By 2050, the share of coal emissions will decrease significantly, and the share of electricity will increase (Figure 5b). In general, the decline in carbon emissions is primarily due to process improvements (Figures 5c and 5d) and CCUS technology (Figure 5e). In both NDC and NZE scenarios, carbon emissions from clinker production are the main component and are very limited to decline over time. This results in high emissions from cement production, accounting for 44% of total emissions in 2035, but with the implementation of innovative technologies such as CCUS and hydrogen-based technology, clinker emissions in the 2050 NZE scenario fall by

78% compared to 2020. Further, CCUS is one of the few viable technology options for reaching NZEs in industries where it is difficult to reduce emissions such as cement sector.

China will incur significant technology costs for steel and cement supply to achieve carbon neutrality. Perhaps more important to investors is how energy investments evolve with technology portfolios under different scenarios (McCollum et al., 2018). This study compares average system costs, which include capital and operating costs, of 56.3 and 50.9 billion US$ (2015) per year for the NDC and NZE scenarios from 2020 to 2050 and finds that the NZE scenario has lower system costs and lower total emissions. This is because that the projected demand for steel and cement is lower under the NZE scenario. The deployment of current technologies (e.g., clinker production with dry process, BOF) is gradually reduced and innovative technologies are accelerated, and the overall system costs (include investments, fixed costs, and variable costs) are lower than those of current technologies, making the system cost of NZE lower than that of NDC.

In addition, this study reveals the average annual investment costs for several critical technologies from 2020 to 2050 (Figure 5f). Traditional BO-BOF and clinker without CCUS will still account for a considerable share, but the investment in 100% scrap-based EAF is a more significant part of the total EAF investment. Looking at other innovative technologies, the NZE scenario deploys more CCUS technologies and the NDC scenario accelerates the development of hydrogen-based DRI, all of which speed the decarbonization pathways.

3.4. Provincial Disparities

Reducing the scale of carbon emission reduction potential to provincial level and exploring technology distribution and diffusion in China's steel and cement sectors is urgently required (Figure 6). First, activity levels for both clinker production with dry process without CCUS and BOF decline over time, and the activity under NZE scenario is lower than the NDC. Second, clinker production with dry process without CCUS has a high line elimination rate, especially under NZE scenario, where the phase-out rate can reach 11% per year. Whereas the activity levels for EAF and CCUS technologies increase over time, again with the NZE scenario outperforming the NDC scenario. Steel production in the future is expected to gradually shift from BOF to EAF, while the deployment of CCUS technologies is rapidly increasing, especially in clinker production with dry process with CCUS, with an average annual growth rate of 9% under the NZE scenario. From a provincial perspective, in 2050, Hebei, Liaoning, and Shandong will be among the top three provinces in China in terms of BOF route; also, the EAF route in Jiangsu, Guangdong, and Sichuan and the CCUS in Hebei, Shandong, Liaoning, and Jiangsu are among the leading in China. Therefore, the key deployment areas for innovative technologies in steel and cement are still in the Hebei, Liaoning, as well as in Shandong, Jiangsu, and Guangdong in southern China.

Under each scenario, Hebei, Shandong, Jiangsu, Liaoning, and Henan will be the top five contributing provinces for carbon emissions from steel and cement sectors, which is directly related to the industrial structure of the provinces (Figure S2 in Supporting Information S1). For example, Hebei has largest steel production capacity in China. The importance of carbon emissions reduction in areas with substantial steel and cement output cannot be overstated, as well as pollution controls. Under the scenario combining the climate objectives of the NDC with the current legislation (CLE) pollutant controls, carbon emissions from steel and cement in Hebei province in 2035 are reduced by 13% compared to the BAU scenario. Under the NDC and maximum technically feasible reductions (MFR) scenario, the decrease will change to 16% compared to the BAU scenario. In the long term (in 2050), the emissions will be reduced by a further 31% and 34% respectively. Under the NZE scenario, Hebei's steel and cement emissions will fall by 17% and 42% in 2035 and 2050 respectively compared to the BAU scenario. Of the five most emitting provinces in the steel and cement sectors, Jiangsu and Henan provinces will benefit most from the deployment of innovative technologies (mainly scrap-based EAF and CCUS), which could reduce carbon emissions by 56% and 53% in 2050 NZE-MFR scenario, respectively.

Even though overall national carbon emissions are declining, as well as in the steel and cement sectors, for the major industrial provinces, the share of steel and cement carbon emissions in the provincial total emissions will rise (Figures S2c and S2d in Supporting Information S1). In 2035, carbon emissions of steel and cement sectors in Hebei under BAU scenario account for 48% of the total provincial emissions, but the figure reaches 68% under NZE-MFR scenario in 2035 and 87% under NZE-MFR scenario in 2050. This suggests that the decarbonization progress in the steel and cement sectors is notably slower compared to other sectors within the economy. Given the carbon-intensive nature of these industries, there is an imperative to expedite the advancement of decarbonization

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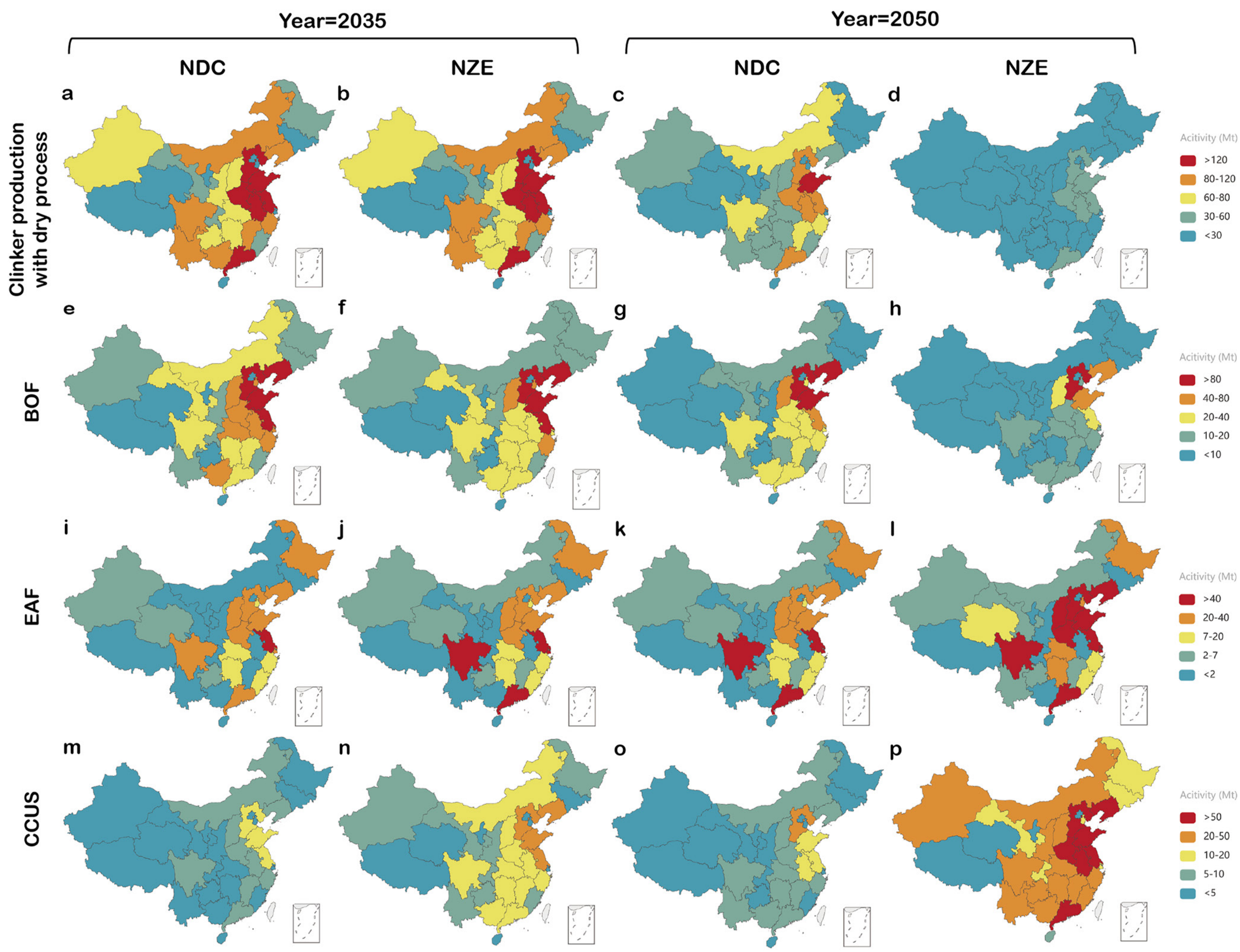

Figure 6. Provincial disparities of typical current and innovative technologies. Scenarios show energy activity of clinker production with dry process in 2035 under Nationally Determined Contribution (NDC) (a) and net-zero emission (NZE) scenario (b), in 2050 under NDC (c) and NZE scenario (d); basic oxygen furnace (BOF) route in 2035 under NDC (e) and NZE scenario (f), in 2050 under NDC (g) and NZE scenario (h); electric arc furnace (EAF) route in 2035 under NDC (i) and NZE scenario (j), in 2050 under NDC (k) and NZE scenario (l); carbon capture, utilization, and storage (CCUS) technology in 2035 under NDC (m) and NZE scenario (n), in 2050 under NDC (o) and NZE scenario (p). Here, BOF involves crude steel production with BOF, pellets production with BF-BOF and sinter production with BF-BOF. CCUS involves clinker production with dry process with CCUS, pig iron production coal DRI with CCUS and pig iron production gas DRI with CCUS.

technologies specifically tailored to iron, steel, and cement production. It is crucial to accelerate the implementation of innovative technologies to effectively contribute to the achievement of the NDC and NZE targets.

3.5. Air Pollutant and Health Co-Benefits

While seeking technological solutions to decarbonize industrial production, China is also under pressure to reduce air pollutant emissions. Greenhouse gases (mainly carbon emissions) and air pollutants are inextricably linked, both deriving mainly from the combustion and use of fossil fuels, and are highly synergistic in treatment (N. Li et al., 2019). Up to now, the strategy of "synergistic governance of greenhouse gases and air pollutant emissions" has been widely accepted and incorporated into national policy. The ability of steel and cement, as representative sectors of industry, to achieve synergies between carbon and air pollutant reductions is key to achieving deep decarbonization (Ma et al., 2016; Wu et al., 2016; Zhang et al., 2015).

This study discusses the projected future trajectories for the three main pollutants resulting from steel and cement sectors (Figure 7), including primary particulate matter ($PM_{2.5}$) and secondary PM precursors (SO_2 and NO_x). As a result of current policy legislation, all pollutants decline under the CLE scenario. $PM_{2.5}$, which has been

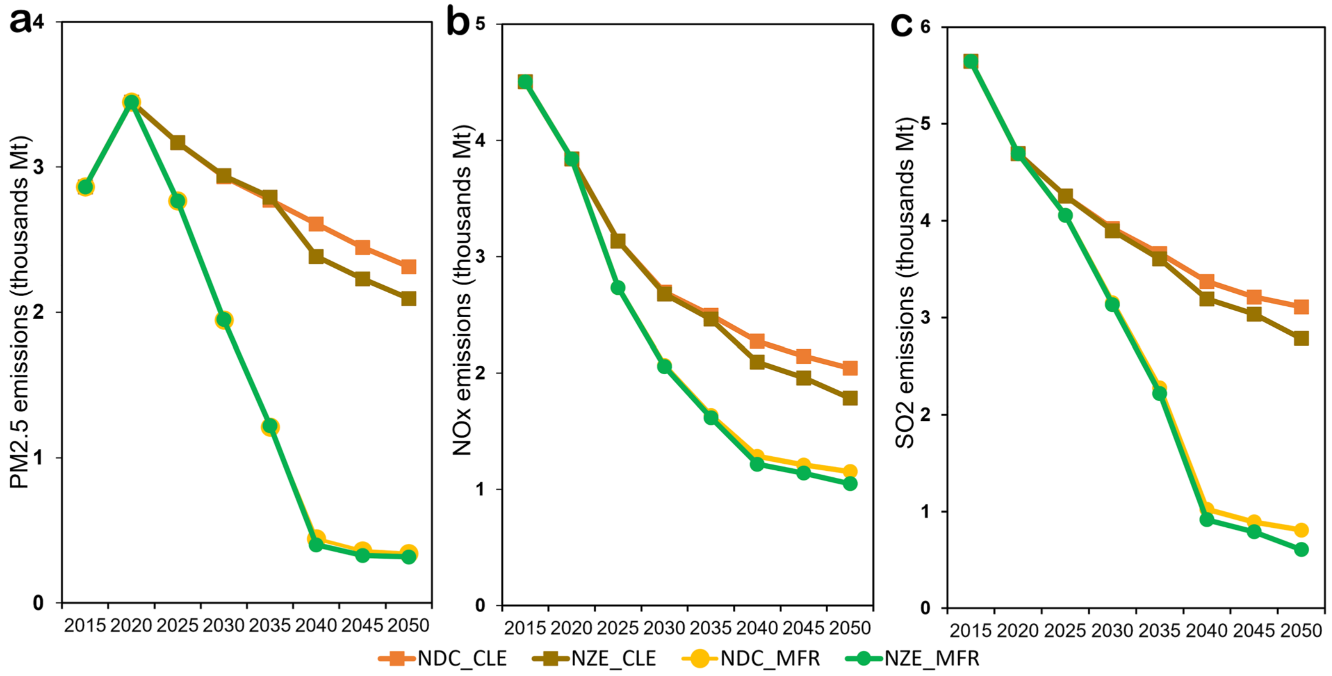

Figure 7. Future air pollutant emissions in China's steel and cement sectors. (a) $PM_{2.5}$ emissions, (b) NO_x emissions, and (c) SO_2 emissions. Here, current legislation (CLE) means current legislation, and maximum technically feasible reductions (MFR) means maximum technically feasible reductions.

maintaining an upward trend from 2015 to 2020, declines more substantially from 2020 onwards, particularly under the more stringent end-of-pipe air pollution control scenarios (MFR), where $PM_{2.5}$ in 2050 is only 10% of that in 2020. Pollutant concentrations are both much lower in the MFR scenario than in the CLE scenario, and there are significant differences in pollutant concentrations between the NDC and NZE in the CLE scenario (the air pollution emissions from other sectors in NDC and NZE scenarios developed in this study are remain same with IEA's WEO-2021 NZE and NDC scenarios). There is a 10% difference in $PM_{2.5}$ concentrations between the NDC-CLE and NZE-CLE in 2050, indicating significant differences in the restructuring of the energy system between the different model scenarios. The control measure of the MFR scenario is highly effective in the prevention and control of pollutants, with rapid decreases of more than 70% for each pollutant by 2050. This effect is reinforced by the NZE scenario, suggesting that the combination of strict climate policies and air pollution control measures will have higher synergistic effects, in line with the previous study (Rafaj et al., 2021).

In response to the current air pollution issue, China has attached great importance to environmental protection and established stricter air quality standards of 15 μg/m^3 (Class I) and 35 μg/m^3 (Class II); they are still significantly below the U.S. 15 μg/m^3, EU 25 μg/m^3 and 2021 WHO guideline standards of 5 μg/m^3 (N. Li et al., 2019; World Health Organization, 2021). According to the projections in this study, in Figure 8, 14 provinces (out of a total of 31) will be in Class 1 in 2050 under the NDC, whereas 24 provinces will be in Class 1 under the NZE. This is in line with China's overall medium to long-term clean air goals (Tong et al., 2020). From the perspective of interprovincial heterogeneity, Hebei, Jiangsu, Shandong, and Henan are the provinces most affected by premature deaths caused by $PM_{2.5}$ pollution. However, if stronger climate policies are adopted, provinces such as Jiangsu, Shandong, and Henan will see a significant improvement in their air quality, with the attainment of Level 1 air quality standard from the current Level 2 standard, and there will be a substantial increase in the corresponding health benefits.

Figure shows mean $PM_{2.5}$ concentration (*y*-axis), CO_2 emissions (*x*-axis), and premature deaths (point size) under NDC (a) and NZE (b) scenario in 2050.

4. Discussion

At present, China's steel production mainly relies on iron ore rather than scrap steel, and the limited amount of scrap steel that is used is often blended with a significant amount of primary steel, which inevitably requires the

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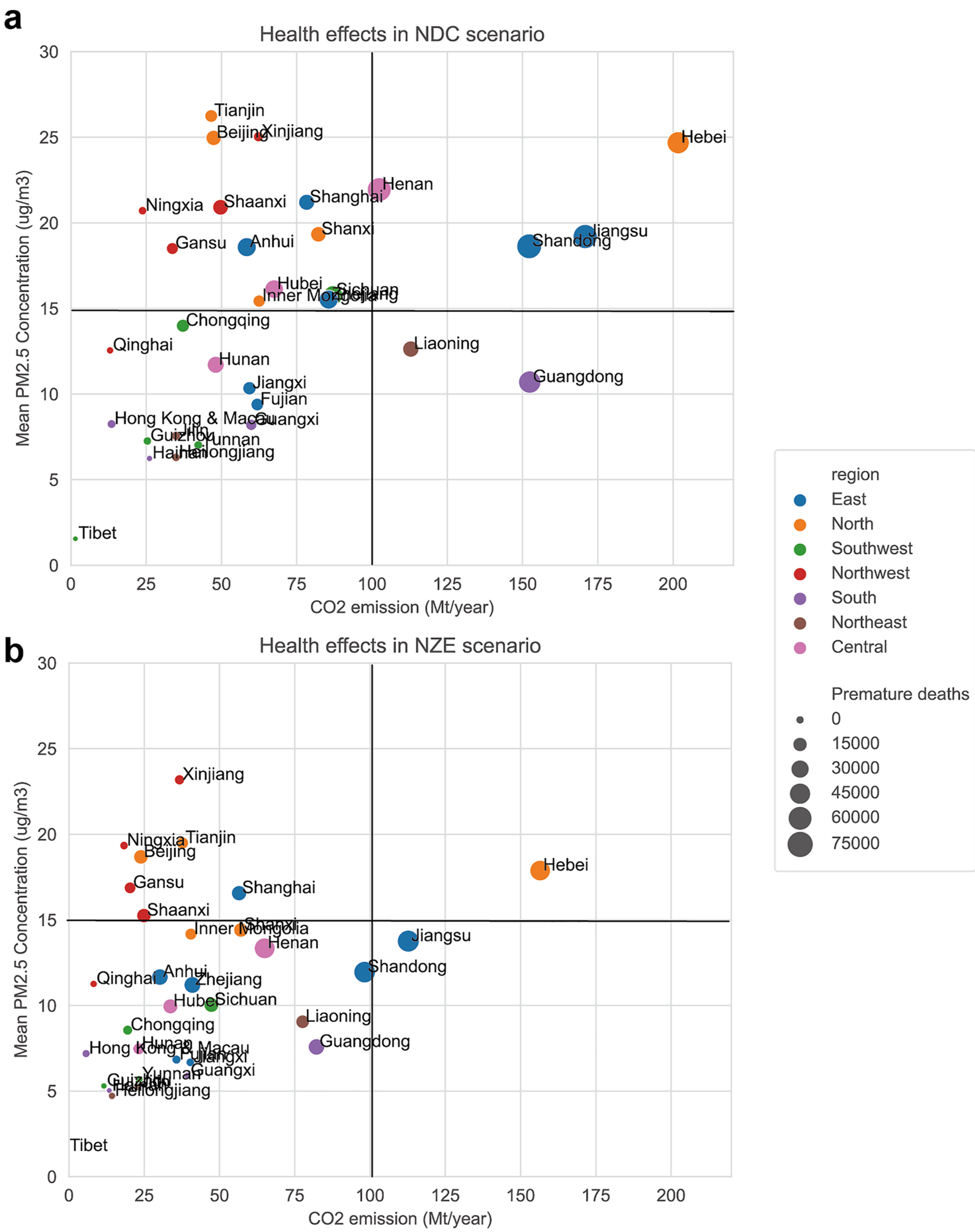

Figure 8. Health effects of $PM_{2.5}$ and CO_2 emissions in 2050.

use of BOF in the production process. As China's construction and infrastructure industries mature, there will be an increasing amount of scrap steel reserves, which could potentially facilitate future utilization of scrap steel. In this study, we assume that China will have sufficient quantities of scrap steel to meet future demand. Reports indicate that China's scrap steel production is expected to increase by 10% annually up to 2050 (Energy Transitions Commission & Rocky Mountain Institute, 2021). As a result, EAF is expected to be widely adopted in China's steel production, becoming the primary pathway for steelmaking. This transition is likely to shift energy input toward electricity to a certain extent in the steel industry.

Developing decarbonization strategies for specific industries should consider the inter-industry interactions (Dong et al., 2023). For example, innovative technologies in the steel and cement industries have led to an increase in electricity demand, which could add decarbonization pressure to the power sector depending on whether electricity is generated from fossil fuels or renewable energy. Therefore, when constructing a macro policy framework in China, it is necessary to consider the interactive effects of various industries. Moreover, more ambitious decarbonization targets may not necessarily increase system costs (Dong et al., 2023). First, energy demand would decrease under higher decarbonization targets. Second, system costs can be reduced through more optimal technology combinations.

Stricter climate policies and end-of-pipe pollution control policies can lead to better atmospheric synergistic effects. Most decarbonization technologies in the steel and cement industries have the effect of coordinating and reducing air pollutants; thus it is necessary to consider increasing the proportion of short-process steelmaking and improving the ratio of BF burden. Currently, ultralow emission standards of air pollutants ($PM_{2.5}$, SO_2, and NO_x), have been released and implemented in the steel industry, while ultralow emission standards for the cement industry have been released and are about to be implemented. However, at the provincial level, local standards have been introduced and gradually promoted in local enterprises in provinces such as Hebei, Sichuan, and Henan. Whether for industry decarbonization or pollution prevention and control, exploring provincial-level measures is essential.

Currently, the carbon trading market in China has included the steel and cement industries, but it has not been officially launched yet. Environmental economic policies, such as carbon taxes and carbon markets, can help internalize the costs of carbon emissions and atmospheric pollutant emissions through market mechanisms, promoting steel and cement enterprises to implement energy-saving, carbon reduction, atmospheric pollution control technologies and advance China's decarbonization pathway.

This study has limitations. Model uncertainty, for example, parameter uncertainty, model structural uncertainty, and uncertainty associated with assumptions such as boundary conditions, are important in the decision support process (Zhang et al., 2022). There are many approaches, such as robust and chance constrained optimization, to better understand the uncertainty and associated effects of multiple parameters, but they cannot determine which techniques are most important for any given solution (Giannakidis et al., 2015). This study analyzes the uncertainties inherent in socio-economic and technological responses to energy and climate challenges by designing different model scenarios that internalize the objectives of climate and air pollution policies in a model. Moreover, the GAINS model utilizes the baseline mortality rate derived from the Global Burden of Disease Study 2013. However, while there is currently no substantial variance with the latest study, we will revise this value in future updates.

Some aspects of this study's model, such as natural resource availability in the steel and cement sectors, material/energy substitution and its trade-offs across regions, domestic and international market developments, and robust technology strategies and associated portfolios, are subject to some uncertainty. In practice, policy makers are more interested in robust strategies and that multiple scenario carve-outs can better provide a roadmap with more far-reaching implications than uncertainty analysis that changes the model parameters (Amann et al., 2011).

5. Conclusion

China has announced ambitious plans to achieve carbon neutrality by 2060, which requires deep decarbonization across carbon-intensive sectors. Steel and cement sectors account for 70% of China's overall industrial emissions and are prioritized for emissions reduction. Therefore, MESSAGEix-China model is developed in this study to explore the decarbonization pathways for steel and cement in China based on the least-cost approach, providing 26 technological solutions under different scenarios. This study also identifies technological solutions that can achieve NZEs targets with less economic costs and discusses synergistic effects of air pollutants for effective climate policy.

With the adoption of innovative technologies, these two sectors require more economical and efficient technological solutions. In this study, we project the decarbonization pathways under different scenarios based on the least-cost approach. We find that the current technology routes have limited carbon reductions, and the deployment of innovative technologies (CCUS, electrolytic- and hydrogen-based, and scrap-based technologies) needs to be accelerated. We also show that innovative technological solutions (CCUS, hydrogen- and scrap-based technologies) can achieve NZEs with less economic costs. The average system costs of NZE scenario are 50.9 billion US$ (2015) per year, lower than NDC scenario. Furthermore, EAF deployment will be mainly concentrated in Jiangsu, Guangdong, and Sichuan, while CCUS should be mainly in Hebei, Shandong, Liaoning, and Jiangsu provinces. We provided that the increased electrification of innovative technologies in steel and cement requires a shift in energy inputs from fossil energy to electricity. A combination of strict climate change mitigation and air pollution control will have higher synergistic effects.

Overall, we project and discuss the future technological solutions to China's carbon neutrality in the steel and cement sectors. We find that many innovative technologies will be applied in the future, for example, CCUS, electrolytic- and hydrogen-based technologies. However, the upstream and downstream chains of the steel and cement sectors, and producers of innovative technologies have not been analyzed. Any technology consumes resources (water, raw materials, energy, etc.). How the achievement of carbon neutrality targets affects the steel and cement supply chain will change future technological solutions and investments, and this is an area that should be further explored in the future.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

MESSAGEix model is available in Huppmann et al. (2019), Keppo and Strubegger, (2010), and Sullivan et al. (2013). GAINs model is available in Amann et al. (2011) and Rafaj et al. (2013, 2021). Activities and parameters of energy commodities and materials commodities are taken from the China Iron and Steel Industry Yearbook (CSDRI, 2019, 2020), the China Cement Yearbook (CSDRI, 2016), China Cement Association (China Cement Association, 2023), and the China Statistical Yearbook (National Bureau of Statistics of China, 2019). Historical steel consumption and cement consumption from China Industry Information Network (China Industry Information Network, 2015), and previous studies (Ma et al., 2016; Zhang et al., 2019, 2022). Variable costs of production processes from IEA-Clean Coal Centre and Metals Consulting International (MCI) (Carpenter, 2012; Metals Consulting International, 2018). The new steelmaking technologies are available in Battle et al. (2014), IEA (2020b), IRENA (2020), and Material Economics (2019).

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