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Global iron and steel plant CO_2 emissions and carbon-neutrality pathways

Tianyang Lei[1], Daoping Wang[2,3], Xiang Yu[4], Shijun Ma[5], Weichen Zhao[5], Can Cui[1], Jing Meng[5], Shu Tao[6], Dabo Guan[1, 5, *]

[1] Department of Earth System Sciences, Tsinghua University, Beijing, China

[2] Department of Geography, King's College London, London, UK.

[3] Department of Computer Science and Technology, University of Cambridge, Cambridge, UK.

[4] University of Chinese Academy of Social Sciences, Beijing, China

[5] The Bartlett School of Sustainable Construction, University College London, London, UK

[6] College of Urban and Environmental Sciences, Peking University, Beijing, China

Summary paragraph

The highly energy-intensive iron and steel industry contributes about 25%[1] of global industrial CO_2 emissions in 2019 and is therefore critical for climate change mitigation. Despite discussions of decarbonization potentials at national and global level[2-4 5,6], plant-specific mitigation potentials and technological driven pathways remains unclear, which cumulatively determinates the progress of net-zero transition of global iron and steel sector. Here we develop a CO_2 emissions inventory of 4,883 individual iron and steel plants with their technical characteristics, including processing routes, operating details (status, age, operation-years, etc.). We identify and match appropriate emission removal or zero emission technologies to specific possessing routes or what we define thereafter as a techno-specific decarbonization roadmap for every plant. We find that 57% global plants have 8~24 operational years, which is the retrofitting window for low carbon technologies. Low-carbon retrofitting following plants' operational characteristics is key for limiting warming to 2 C, while advanced retrofitting may help limit warming to 1.5 C. If each plant were retrofitted 5 years earlier than the planned retrofitting schedule, this could lead to cumulative global emissions reductions of 69.6 Gt CO_2 from 2020 to 2050, almost double of global CO_2 emissions in 2021. Our results provide a detailed picture of CO_2 emission patterns associated with production processing of iron and steel plants, illustrating the decarbonization pathway to the net-zero emissions target with the efforts from each plant.

Main text

Many countries have set climate neutrality targets in order to limit global temperature increase to below 2°C and to pursue efforts to avoid a 1.5°C increase, as required by the Paris Climate Agreement[7-9]. These targets entail a transition to net-zero CO_2 emissions across all sectors globally during the second half of the 21st century[8,10].The ever-expanding energy-intensive industrial infrastructure, in particular in sectors such as iron and steel production[10,11] where emissions are hard to mitigate (with tremendous energy and products demand[1,12], long-lived assets, and lack of commercially available decarbonization technologies[13]), will 'lock-in' a substantial amount of carbon allowance.

The production of iron and steel is a complex activity that is varied among world regions due to differences in the availability of iron ore, energy supply[14], processing routes[5], technological characteristics[15] and socioeconomic demands[16,17]. As a result, there cannot be a "one-size-fits-all" decarbonization solution across the global iron and steel sector. It is worth noting that all mitigation effort~~s~~, including technology retrofitting~~,~~ will have to take place at facility level, with each processing unit should set individually according to its techs specification. Therefore, the decarbonization of the entire iron and steel industry depends on the efforts undertaken by every single plant. Research on mitigation strategies for the iron and steel industry has focused mostly on estimating the potential of energy saving and the associated CO_2 emissions reductions[18-20], alongside cost[5,21] of energy efficiency improvement[10], fuel shifting[1], and the adoption of the emerging technologies[6]. Yet, most previous studies are limited to the national level[2-4,22], or using a few hypothetical plants with specific processes as examples[5,6], which are not comprehensive enough to inform globally adoptable emissions reduction strategies featuring substantial regional diversity and they cannot be used to design mitigation actions at plant level across the whole sector worldwide. See detailed literature review on carbon mitigation in *Supplementary Information section 1.1.*

A publicly available, harmonized, and comprehensive dataset for measuring CO_2 emissions is crucial to support decarbonization efforts of the iron and steel industry at all scales, such as at plant level, country level and global level. Previous studies compiled databases of CO_2 emissions from China's iron and steel plants [23] but lacked detailed operating and processing information that is critical to predict how iron and steel plants will decarbonize over time. Here, we have first developed a comprehensive, publicly available global CO_2 emissions inventory for Global Iron and Steel Plants (CEADs – GSEI), based on 19,678 individual processing units (specific processing facilities, including coking, sintering, ironmaking, steelmaking, etc.) located in 4,883 individual iron and steel plants (for details about the integration of various processing units, see *Supplementary Table S1*). Details of the methods and data used to construct the CEADs-GSEI are shown in *Extended Data Figure 1*.

Furthermore, we have quantified the "committed CO_2 emissions"[8] of the existing iron and steel plants, based on the type of processing routes, country, age, and the operational lifetime including retrofitting. Finally, we have identified possible plant-level mitigation measures that would help to meet 2030 and 2050 regional targets.

Emission patterns of global plants

Figure 1 presents the geographical location, processing routes (the steps and technologies of iron and steel production), and CO_2 emissions of 4,883 iron and steel plants producing major products (coke, sinter, iron, and steel) in 2019. The total crude steel capacity is 2,592 Million tons (Mt), of which 63% were from Blast Oxygen Furnaces (BOF), 36% from Electric Arc Furnaces (EAF), and the remaining 1% from Open Hearth Furnaces (OHF) (Detailed information is shown in *Extended Data Figure 2*). The aggregated CO_2 emissions in 2019 were about 2,815 Mt. Across regions, the producing capacity for crude steel, and associated carbon intensity (CO_2 emissions per ton of crude steel produced), is different across plants as they use different processing routes depending on access to raw materials and available technology. Such diversity explains the spatial distribution of CO_2 emissions from iron and steel industries globally.

We find that, in 2019, up to 74.5% (1389.1 Mt) of the total crude steel produced come from coal-based iron and steel plants. Specifically, coal-based blast furnace-blast oxygen furnace (BF-BOF) plants (red dots in Figure 1) are concentrated in China, Japan, and India, accounting for 49.4%, 3.9%, 2.8% of global crude steel output, respectively. The coal-based direct reduction iron (DRI) plants are mainly concentrated in India, where they produce 67.0% of the global crude steel output from coal-based DRI plants. Detailed information on crude steel producing capacity is shown in *Extended Data Figure 2*. As a result, crude steel is primarily produced through energy-intensive coal-based processes worldwide (accounting for 85.0% of the total emissions), with carbon-intensive plants (*Supplementary Table S1*) running with coal-fired blast furnaces (Coal BF, all red points in Figure 1) being the main source of CO_2 emissions from iron and steel plants in most of the world regions. The Middle East and North America regions are an exception as crude steel there is produced mainly via gas-based direct reduction ironmaking (DRI) plants and coal and natural gas mixed injection blast furnace (Gas BF) due to sufficient local natural gas resources[1,13]. (see *Supplementary Information section 1.2* for further details). The spatial distribution of CO_2 emissions from iron and steel production reflects a concentration of iron and steel plants in eight countries (namely top eight countries) that contributed 85.7% of the total CO_2 emissions from the global iron and steel industry. The iron and steel operations in each country, with different smelting processes and product output, face different challenges when it comes to reduce emissions (see *Supplementary Information section 1.2* for detailed information on the top eight countries), suggesting the need to adopt mitigation strategies specific to the smelting process characteristics of the iron and steel plants.

Age and operation-years of global plants

Figure 2 presents CO_2 emissions and crude steel output of all iron and steel plants operating in 2019 by regions (see *Extended Data Figure 3* for detailed region definition in this study) and based on operation-years (defined in this study as the total number of years from the commissioning year up to 2019 for the original plants, or the total number of years from the last refurbishment year up to 2019 for the retrofitted plants) and processing units (coal/charcoal-fired iron and steel plants Figure 2a, Figure 2b, the other types of iron and steel plants Figure 2c, Figure 2d). The number of operation-years is critical to determine any plant's production efficiency. The old production units (operating for a long time) with outdated technologies usually have poor energy efficiency and low secondary energy recovery rate, resulting in higher carbon emissions than the new ones[18].

We find that 43.2% of global iron and steel plants were retrofitted with enhanced process integration and new technologies to extend the plants operating lifetime (meaning that plants could continue producing beyond the normal operating life, for example 25 years for plants equipped with blast furnaces). In 2019, the average age (defined in this study as the total number of years from the commissioning year up to 2019) of global iron and steel plants was 29.7 years, much longer than the average operation-years, 19.9 (*Supplementary Table S2*). Over two-thirds of crude steel produced by EAF came from retrofitted plants (Figure 2a, 2d) in 2019; 80.5% of crude steel from the stainless-steel plants was produced by retrofitted plants. Further, it's expected that all low-carbon upgrade of existing plants will be fit during the retrofitting window, with such window being determined by plants' age and operation-years. We find that the average operation-years (from the latest retrofitting years up to 2019) varies across regions (*Supplementary Table S2*). For example, the average number of years were 15.2 and 18.2 in China and India respectively, whereas they were 26.5, 27.4 and 22.6 years in the EU+UK, Japan and South Korea, and North America, respectively. See *Supplementary Information section 1.3* for a detailed description of the importance of retrofitting iron and steel plants to reduce CO_2 emissions.

Depending on the type of processing routes and given the limited lifetime of the processing units, global plants can be categorized into six operation-years groups: 0~4 years, 5~9 years, 10~14 years, 15~19 years, 20~24 years, and ⩾25 years, respectively. The young plants whose operation-years ranged 0~4 and 5~9 accounted for 52.2% of global crude steel output and 51.2% of associated emissions. Specifically, one-quarter of those plants are coal/charcoal-fired plants. The mid-age plants, primarily equipped with coal-based processing routes and whose operation- years ranged 10~14, 14~19 and 20~24, accounted for 44.5% of global crude steel output and 44.5% of associated emissions. It's worth noting that 73 Chinese mid-age coal/charcoal-fired plants whose operation-years ranged 10~24 (accounting for 16.5% of total crude steel production in China), did not go through a retrofitting process since they were built. The elderly plants operating for longer than 25 years, the majority (95.1%) being other types (non-coal/charcoal-fired plants, Figure 2b) of iron and steel plants, accounted for 3.3% of global crude steel output and 4.3% of associated emissions. The high concentration of global crude steel output, and the associated emissions, from young (0~9 operation-years) and mid-age (10~24 operation-years) coal/charcoal-fired plants indicate that globally the likely operating lifetime of such plants is less than 25 years. Besides, the share of output and CO_2 emissions from the retrofitted iron and steel plants in 2019 were strikingly high and varied across regions. *See Supplementary Information section 1.4 for a detailed description of CO_2 emissions from retrofitted iron and steel plants by processing routes in each region worldwide.*

Decarbonation options for global plants

Iron and steel plants vary substantially by age, operation-years and retrofitting cycle (defined in this study as the number of years that go from one retrofitting to the next of plants in this study) across regions, therefore in each region the timing of future route-specific retrofitting of plants will also vary substantially. Because many existing plants have decades of remaining lifetime, a huge amount of CO_2 (53.4 Gt) will be emitted as a result – what is known as carbon 'lock-in'[8] (*Extended Data Figure 4*). Early retirement or retrofitting of plants, depending on the typical operating lifetime of different processing types, would help to mitigate CO_2 emissions from the iron and steel industry.

We analyze possible CO_2 emissions mitigation pathways at the plant level, over the short term and long term, by optimizing when to retrofit each plant and how – this analysis is based on three key parameters: the type of processing routes, latest retrofitting year, operating lifetime. Specifically, each plant will be retrofitted according to the time of its last retrofitting and the average retrofitting cycle of the specific processing route in place. For example, the Baotou Iron and steel plant in China, a 'Coal BF-BOF plant', was last retrofitted in 2015. As this type of plant has an average retrofitting cycle of 14 years (see *Supplementary Table S3*), Baotou will be retrofitted in 2029 under the *S2* (Default, details in Methods section) scenario. When a plant has been in operation for longer than the average retrofitting cycle of the specific processing route in place, we assume that retrofitting will take place after the plant reaches 25 years of operating lifetime. Furthermore, we assume adoption of the retrofitting option as proposed by the IEA[1] and the Institute for European Studies[24]; the technical retrofitting solution is determined not only by the processing route, but also the production and emissions mitigation targets at the regional level. Going back to the Baotou Iron and steel plant example, using fuel switch transformation technology, the plant will move from being a carbon-intensive 'Coal BF-BOF plant' to being a 'natural gas-based DRI plant', instead of a 'scrap-based EAF plant', given the insufficient scrap accumulation and late carbon neutrality climate goals. Differently, the ArcelorMittal Ghent plant in the European Union (owned by the company in Luxemburg and located in Belgium), also a 'Coal BF-BOF plant', will change from a long processing route, carbon-intensive 'Coal BF-BOF plant' to a short processing route 'scrap-based EAF' one, due to sufficient scrap accumulation in European Union countries. *Detailed description and* *examples of processing route-/operating lifetime-/region specific CO_2 emissions mitigation pathways at plant-level are included in the Supplementary information section 1.5.*

We project the annual CO_2 emissions over 2020-2050 under three different scenarios, namely a default retrofitting low-carbon scenario (the iron and steel plants will upgrade with the adoption of low-carbon technology at their planned retrofitting year), 5-year ahead retrofitting low-carbon scenario (all iron and steel plants will complete the low-carbon refurbishment five years earlier than the scheduled year), 5-year-late retrofitting low-carbon scenario (all iron and steel plants will complete the low-carbon refurbishment five years later than the scheduled year). Detailed information about the setting of parameters for the low-carbon scenarios is provided in the *Methods* section.

Overall, retrofitting and upgrading plants as early as possible can promote large-scale emissions reduction from the iron and steel industry. Under the default retrofitting low-carbon scenarios（Figure 3 e, h, k）, from 2020 to 2050, global cumulative CO_2 emissions would decrease by 58.7 Gt. However, emissions mitigation could be 16% higher (69.6 Gt) by retrofitting plants five years ahead of the planned retrofitting year. By stark contrast, cumulative global emissions reduction would be 16% lower, at only 49.1 Gt, by retrofitting plants five years later than the planned retrofitting year, putting at risk the goal of achieving carbon neutrality.

The spatial distribution of the hot spots of emission reduction (countries with large emission reductions, the dark areas in Figure 3) gradually shifts from advanced regions to emerging ones over time. From 2020 to 2030, with sufficient supply of scrap resources and the promotion of low-carbon technologies[5], advanced regions will achieve more than half of global cumulative emissions reductions, or 784.3-4,118.8 Mt. In particular, Japan and South Korea, the EU+UK, and North America would contribute about 25% (379.3 Mt-1,956.0 Mt), 17% (242.1 Mt-1,342.7 Mt), and 5% (70.3 Mt-378.3 Mt) of global cumulative emissions reductions, respectively, under the three mitigation scenarios displayed in Figure 3. The remaining half of the global cumulative emissions reductions over the period 2020-2030 will come from the iron and steel plants in emerging region, mainly China and India. With the growth of scrap availability and progress with deep carbon reduction technologies (including scrap-based EAF transformation, carbon capture, use and storage retrofit, and combinations of these decarbonization approaches), emerging regions will improve substantially their CO_2 emissions reduction potential along with a growing steel production over the long term. From 2031 to 2050, up to 84% of global cumulative emissions reductions, or 39,589.1 Mt – 52,700.9 Mt, will likely come from emerging economies. In contrast, and along with stagnating production, cumulative emissions reductions in advanced regions over 2031-2050 only account for 16% (8059.4 Mt-8915.1 Mt) of the global emissions reductions; over the same period, the average annual growth of emissions reductions will likely be 1% (‘5-year-ahead retrofitting’ scenario) ~7% (‘5-year-late retrofitting’ scenario), suggesting that with early retrofitting emissions from iron and steel plants would peak before 2030.

Figure 3j, 3k, 3l show the detailed annual CO_2 emissions reductions from iron and steel plants by processing types under the three retrofitting strategies from 2020 to 2050, illustrating the changes of processing types and related CO_2 reductions over the short-term to long-term. Overall, during the whole period from 2020 to 2050, the most substantial emissions reductions worldwide are achieved via coal-based BF-BOF integrated facilities, with up to 36,041.6 Mt-51,790.3 Mt CO_2 reduction, accounting for 74% of the total global reduction of all iron and steel plants over the same period. The second highest cumulative CO_2 emissions reduction can be achieved by the traditional separate EAF steelmaking plants, accounting for 52% of the remaining cumulative 6820.4 Mt-8963.1 Mt CO_2 reduction. However, our analysis shows that the CO_2 reduction potential of EAF plants is limited by the maximum stock of scrap resources available, as world steel production cannot solely rely on the recycled use of steel. This suggests that the combination of retrofitting by switching raw-materials with scrap-based EAF alongside the deployment of CCUS technologies for existing infrastructure is necessary in order to achieve the needed CO_2 emissions reduction from the iron and steel industry over the long-term. *See Supplementary Information section 1.6 for a detailed description of the decarbonization potential by region.*

The above results refer to emissions under the Shared Socioeconomic Pathways (SSP)2 socio-economic development scenario. We further examine the emissions under different socio-economic development scenarios, i.e., SSP1 and SSP5. Considering that the SSP1 has a narrative focused on deploying greener technologies, we have assumed that under SSP1 the deployment of deep decarbonization technologies in the iron and steel industry worldwide will be quite advanced (the default scenario under SSP1 is that the iron and steel plants will be retrofitted 5 years earlier than the planned retrofitting date), with cumulative CO_2 emissions ranging from 31.7 Gt~43.5 Gt (from 8-years-ahead retrofitting scenario to 2-years-ahead retrofitting scenario respectively). Considering that the SSP5 describes a future with high challenges to mitigation and low challenges to adaptation, we have assumed that under SSP5 deep decarbonization technologies will be deployed later (the default scenario under SSP5 is that the iron and steel plants will be retrofitted 5 years later than the planned retrofitting date), with the related cumulative CO_2 emissions ranging from 48.8 Gt~67.1 Gt (from 2-years-late retrofitting scenario to 8-years-late retrofitting scenario respectively). *(Supplementary Information section 1.7, Extended Data Figure 5)*

Early retrofit is key to 1.5C limit

Figure 4 shows the global future CO_2 emissions from the iron and steel plants over 2020-2050 under 4 different carbon reduction scenarios (a, b, c, d). From 2020 to 2050, if operated as historically (without any low-carbon technology, without intervention), the cumulative CO_2 emissions from the global iron and steel industry will be as high as 106.3 Gt (the gray area in Figure 4). Although the implementation of the low-carbon strategies to the existing iron and steel plants could save 50% or more cumulative emissions from 2020 to 2050, the remaining cumulative CO_2 emissions from the iron and steel plants under the 5-year-late retrofitting low-carbon scenario will still be as high as 57.2 Gt (Figure 4a), almost exhausting the 60.6Gt of remaining carbon budget for the global iron and steel industry as calculated for the Sustainable Development Scenario by the IEA[25], which may pose a threat to achieving the 1.5°C climate limit[10]. In comparison, the carbon mitigation potential will grow with the earlier adoption of low-carbon technologies, and the cumulative emissions from iron and steel plants over 2020-2050 could be compressed to 36.8 Gt under 5-year-ahead retrofitting low-carbon scenario (Figure 4c). Moreover, the advanced deployment of 100% hydrogen-based steelmaking technology together with CCUS technology can further reduce cumulative emissions to a minimum of 36.7 Gt (Figure 4d).

By developing the CEADs – GSEI dataset, a plant-level CO_2 emissions inventory covering 24,588 processing units in 5,194 iron and steel plants across the world, this study offers a comprehensive understanding of CO_2 emissions patterns associated with the operation of iron and steel plants. Our developed dataset is subject to uncertainties and limitations (see detailed description at *Supplementary Information section 1.10*）. In general, the average uncertainties of global CO2 emissions are estimated to be 20% to 28%, varying among operation-year groups and regions, with larger uncertainties for older plants and developing regions due to incomplete information. The projection of future steel demand in different economies may remain uncertain. We employed a state-of-art computable general equilibrium (CGE) model, i.e., G-RDEM, with default settings of different SSPs (see detailed description in *Supplementary Information section 1.11*) to provide the 'most-likely' estimate. But the future is full of varies, such as technological shocks, pandemics, geopolitical conflicts, etc., that may change the regular route of the global economy. The projection of steel demand in the future needs more detailed datasets and real-time economic dynamics to improve and update. By evaluating the effect of mitigation options in iron and steel plants worldwide, this study sheds light on the specific emissions reduction within the iron and steel industry. Our results lend vivid background for the possibility of achieving net-zero carbon emissions in iron and steel production in the future: firstly, the timely low-carbon retrofitting of existing plants; secondly, by improving scrap recycling and collection systems, enriching scrap resources and reuse rates in the short-term and promoting the adoption of deep decarbonization technologies such as CCUS technology in the long term. *See Supplementary Information section 1.8, 1.9 for further discussions.* Plants should adopt different strategies according to their processing routes, latest retrofitting time, operating lifetime, owner-country and so on.

Compared with overall emissions reduction at the country, or the industry level globally, targeted retiring or timely retrofitting with low-carbon technology according to the plant-specific characteristics would better fit with the operation of iron and steel plants (operating lifetime, potential CO_2 mitigation options, etc.). This also could allow for an efficient realization of emissions reduction while minimizing the lock-in cost brought by the remaining operating lifetime. Fundamental to achieve a substantial reduction of CO_2 emissions across the global iron and steel industry are both the accumulation of steel scrap resources and the implementation of deep decarbonization technologies. Given that adopting together CCUS and Hydrogen-based steelmaking in the same plant may not significantly increase emissions mitigation potential compared to adopting only one of the two technologies[6,26]. In this study we have selected the CCUS technology with more maturity[1,6] and potentially less cost[5,27] as the representative deep decarbonization technology to discuss in detail the importance of deep decarbonization in the global iron and steel industry for the realization of net-zero climate targets from 2020 to 2050.

The CEADs – GSEI presented here is subject to uncertainties and limitations. A detailed description of uncertainties is included in the Supplementary Information. In general, the average uncertainties of global CO_2 emissions are estimated to be 20% to 24% for plants with less than 25 years of operation, 22% to 28% for older plants (with more than 25 years of operation). Plant-level uncertainties vary among operation-year groups and regions, with larger uncertainties for older plants and developing regions due to incomplete information. CEADs-GSEI now estimates the annual actual output of each operating unit based on the country, type of processing unit, and capacity, but collecting actual operation-time data at plant level is challenging nowadays. Developing more accurate data reporting systems at the plant level for the global iron and steel industry under international cooperation could help deliver more comprehensive, granular, precise, and reliable data. CEADs-GSEI will be updated and improved as more and better data become available. In addition, we used default setting in the CGE model to project the steel demand. Although it is currently the best estimation we can do, the projection of steel demand in the future need more detailed and real-time economic dynamics to improve and update. *Supplementary Information section 1.10 for further details of uncertainty analysis.*

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Figure legends

Figure 1 Maps of iron and steel plants CO_2 emissions in 2019. (a), Location, processing routes and CO_2 emission of 4,883 iron and steel plants worldwide. (b)-(f), Iron and steel plants located in the United States (b), China (c), Japan (d), Europe (e), India and Iran (f). Iron and steel plants are classified into 17 types by iron and steel processing routes and sized grouped into 3 classes based on CO_2 emissions in 2019 (≤15 Mt, ≤ 30 Mt, ≤44 Mt). The color of the dots shows the iron and steel processing routes, and the size of the dots indicates the CO_2 emissions amount. The 17 processing routes presented in (a) are also shown in *Extended Data Figure 2*.

Figure 2 CO_2 emissions and iron and steel output from global plants in 2019, by region, age and the operation-years. a, d, Curves show the output of iron and steel products from each age group, and the cohort of coal/charcoal-fired iron and steel plants **(a)** and the other types of iron and steel plants **(d)**. **b, c,** Bars indicate the estimated distribution of CO_2 emissions across different regions, by operation-years (years since the commissioning or last refurbishment) and age, of coal/charcoal-fired iron and steel plants **(b)** and other types of iron and steel plants **(c)**. Colors of bars represent the regions in which iron and steel plants are located, and the changes of hue represent the retrofitting status of iron and steel plants in the corresponding region from light (retrofitted iron and steel plants) to dark (original iron and steel plants). Note that this chart only covers CO_2 emissions from 3,184 iron and steel plants with known commissioning time, whereas CO_2 emissions from the remaining 1,717 iron and steel plants (about 12.2% of the total crude steel capacity) are not considered due to the lack of information about the commissioning time. In this study, the year 0 means that the relevant iron and steel plant began operating from 2019. The definition of the ten world regions in this study is available at *Extended Data Figure 3*. A detailed description of the classifications of the iron and steel processing units in this study is shown in *Supplementary Table S1*.

Figure 3 Cumulative mitigation of CO_2 emissions from iron and steel plants assuming different improving strategies from 2020 to 2050. Maps (a-c) show cumulative emissions (from all plants) without any intervention for three periods, namely, 2020-2030, 2031-2050, and 2020-2050. Maps (d-i) show results by period (rows of panels) from 3 emission reduction scenarios with different combinations of **the retrofitting schedule of the iron and steel plants (columns of panels), plant-specific planned retrofitting year, proposed CO_2 mitigation options and the regions** (see ***Methods***, proposed scenario sets of carbon mitigation for the analysis). Numbers at the bottom of each map indicate the global cumulative CO_2 emissions reductions during each period under each scenario; shading denotes the regional distributions of these reductions. The area charts (j-l) summarize the annual CO_2 emissions reduction from 2020 to 2050 by processing types (color of stacked areas), showing the changes of CO_2 emissions reductions from the iron and steel plants under different CO_2 mitigation options.

Figure 4 Remaining CO_2 emissions budget under the 2°C and 1.5°C climate limits and cumulative CO_2 emissions from iron and steel plants under different scenarios from 2020 to 2050. a, b, c, d Trends of annual CO_2 emissions reduction from iron and steel plants under the 5-year-late retrofitting scenario (a), default (on-time) retrofitting scenario (b), 5-year-ahead retrofitting scenario (c), 5-year-ahead retrofitting with CCUS + Hydrogen-based scenario (d) against the range of annual net CO_2 emissions under the 2°C and 1.5°C climate limits. The light green and light purple areas represent the 10% and 90% quartiles of the 2°C and 1.5°C scenarios, respectively. Green line and purple line show the median value of the net carbon dioxide emissions in all pathways limiting global warming to below 2°C and 1.5°C at the end of the century, respectively. Emissions from coal/charcoal-based iron and steel plants are shown with lighter shading, and total emissions from all types of iron and steel plants are shown with darker shading. Numbers indicate the total cumulative CO_2 emissions reductions from 2020 to 2050 under each scenario.

Methods

Global database of emissions from iron and steel plants

We develop a global database of emissions from iron and steel plants including 24,588 processing units (see *Extended Data Figure 6*) in 5,194 iron and steel plants located in 127 countries. We integrate multi-source data providing detailed information on iron and steel processing units by plants and their developments worldwide.

We start with the Steelonthenet steel industry database (https://www.steelonthenet.com/maps.html) to compile unit-based information of iron and steel plants in service as of 2019 (for example, unit capacity, start and stop year of operation, physical address, plant status, ownership). Then, we geo-locate and cross-check one-by-one 5,148 iron and steel plants (99% from the 5194 iron and steel plants) using data from Google Maps, the website of TianYanCha (https://www.tianyancha.com/), the website of Bloomberg (https://www.bloomberg.com/) and the websites of some iron and steel companies (for example, Sanyo (http://www.sanyo-steel.co.jp/english/company/project.php/), Arab Iron and Steel Union (https://aisusteel.org/en/company-directory); the geographical locations of the remaining 46 iron and steel plants could not be identified due to lack of detailed physical address information. Details of the data sources and a summary of the different iron and steel processing units are shown in *Supplementary Table S4*. Of the 24,588 iron and steel processing units included in our database, as of the end of 2019, 20,206 were operating, whereas 4,382 were ‘closed’.

We then classify, depending on the iron and steel manufacturing process, all the units into 14 types according to their technology and specific output, including 1,397 coking units, 28 powder units, 653 sintering units, 1858 iron making and casting units, 4,855 primary steelmaking units (crude steel making), 1,419 secondary steelmaking units (steel refining), 3,177 steel casting and forging units, 10,969 steel rolling units, 53 power supply units, 139 reheat furnaces, 29 oxygen producing units, 7 coal recovery units, 2 air separation plant, 2 other units.

Of the 5,194 iron and steel plants included in the database, 4,883 plants, or 94% of all the plants, were active in 2019 with known producers of major steel products (covering 19,678 individual iron and steel processing units), whereas the remaining 6% were downstream processing plants, such as bar finishing plants. Finally, through the identification of process units in iron and steel plants, we classify those 4,883 iron and steel plants into 17 types according to their processing flow indicated by the iron and steel manufacturing units installed.

Unit-based CO_2 emissions estimation

We estimate the annual CO_2 emissions of the 4,883 iron and steel plants operating in 2019 according to the production-based emissions accounting methodology as detailed in the Intergovernmental Panel on Climate Change (IPCC) guidelines[28], using the following equation:

$$E_{i,t} = E_{\text{combustion}i,t} + E_{\text{process}i,t} \quad (1)$$

Where *i*, *t*, represent the iron and steel plant, and year, respectively. *E* represents unit-based total CO_2 emissions (t), $E_{\text{combustion}}$ represents unit-based CO_2 emissions (t) from stationary combustion, E_{process} represents unit-based CO_2 emissions (t) from industrial process.

CO_2 emissions from stationary combustion represent the largest share of the overall emissions from an iron and steel plant. Stationary combustion sources belong to four main types: re-heating furnaces (other coal and oil use), coke production, pig iron making, crude steel making. We estimate the combustion-related CO_2 emissions from iron and steel plants based on the consumption of fuel as in the following equation:

$$E_{\text{combustion}i,t} = E_{\text{reheating furnaces}} + E_{\text{coke-onsite}i,t} + E_{\text{coke-offsite}i,t} +$$

$$E_{\text{pig iron not covered to steel}i,t} + E_{\text{crude steel}i,t} \quad (2)$$

Where $E_{\text{reheating furnaces}}$, $E_{\text{coke-onsite}}$, $E_{\text{coke-offsite}}$, $E_{\text{pig iron not covered to steel}}$, $E_{\text{crude steel}}$ represent the energy-related CO_2 emissions (t) from re-heating furnaces (other coal and oil use), coke production onsite, coking coal combustion, pig iron making, and crude steel making, respectively. In the case of the integrated iron and steel plants that typically include coking, Blast Furnaces ironmaking, and BOF/OHF steelmaking, we have included CO_2 emissions from coke production on-site and the pig iron produced in Blast Furnaces (as feedstock for BOF and OHF crude steelmaking) in the CO_2 emissions from BOF and OHF crude steel making, and therefore those emissions should not be double accounted.

As for iron and steel industrial process, CO_2 emissions come mainly from processing sources. Industrial processing sources belong to four main types: sinter making, pig iron making, direct reduced iron (DRI) making, crude steel making. We estimate the process-related CO_2 emissions in iron and steel plants based on the output of each industrial process as in the following equation:

$$E_{\text{process}i,t} = E_{\text{sinter}i,t} + E_{\text{DRI}i,t} \quad (3)$$

Where E_{sinter}, E_{DRI} represent the non-energy related CO_2 emissions (t) from sinter making, and DRI making, respectively.

Activity rates

Because detailed activity data for each iron and steel producing units are not available, we estimate unit-based fuel consumption data from country-level fuel consumption by the iron and steel industry as reported by the International Energy Agency (IEA)[29] and unit-based output data from country-level throughput by the iron and steel industry as reported by the World Steel Association [30]. Both unit-level fuel consumption and unit-level output are a function of installed capacity, annual operating hours and the detailed iron and steel processing units, but of these, only data about installed capacity are readily available.

We, therefore, make the simplifying assumption that the annual average operating hours of iron and steel producing units are consistent with country-level average values. Thus, we calculate unit-level fuel consumption from country-level fuel consumption and unit-level output from country-level throughput, respectively by the equations:

$$F_{i,j,t} = F_{k,j,t} \times \frac{C_{i,p}}{\sum C_{i,p}} \quad (4)$$

$$A_{i,p,t} = A_{k,p,t} \times \frac{C_{i,p}}{\sum C_{i,p}} \quad (5)$$

Where *k*, *j*, and *p* represent the country, fuel type, and product type, respectively. *F* represents specific fuel consumption for each unit; *A* represents the specific iron and steel product output for each unit; *C* represents the specific installed capacity of iron and steel processing units.

However, the share of the installed capacity of iron and steel processing units in the same plant over the total installed capacity at country level ($\frac{C_{i,p}}{\sum C_{i,p}}$) varies with the process type. Therefore, in order to estimate the fuel-specific consumption of each unit, we use the share of crude steel production capacity over the total crude steel production capacity of the country.

CO$_2$ emissions

CO$_2$ emissions from Reheating Furnaces were estimated based on the carbon content of the consumed fuel using the following equation:

$$E_{\text{reheating furnaces},CO_2,i,t} = F_{i,j,t} \times HV_j \times F_{carbon,j} \times F_{ox} \times \frac{44}{12} \quad (6)$$

Where HV_j represents the heating value of fuel (thousand Btu/lb); F_{carbon} represents the carbon content of fuel on a heating value basis (kg carbon/GJ); F_{ox} represents the carbon oxidation factor; 44/12 is the ratio of the molecular weight of carbon to that of CO$_2$. In this study, the carbon oxidation factor was assumed to be 1, the carbon contents and heating value data for each fuel type were obtained from the Intergovernmental Panel on Climate Change (IPCC) guidelines[28].

CO$_2$ emissions from metallurgical coke manufacturing were estimated according to the IPCC guidelines [28] using the following equation:

$$E_{\text{coke}-\text{onsite},CO_2,i,t} = A_{\text{coke}-\text{onsite},i,t} \times EF_{\text{coke},CO_2} \quad (7)$$

Where $A_{\text{coke}-\text{onsite}}$ represents the quantity of metallurgical coke produced on site in the integrated iron and steel plants (t), EF_{coke,co_2} represents the CO$_2$ emissions factor of metallurgical coke (t CO$_2$/ t coke) as proposed by the IPCC [28].

$$E_{\text{coke}-\text{offsite},CO_2,i,t} = F_{\text{coking coal},i,t} \times HV_{coking\ coal} \times F_{carbon,coking\ coal} \times F_{ox} \times \frac{44}{12} \quad (8)$$

Where $F_{\text{coking coal}}$ represents the quantity of coking coal consumed in the integrated iron and steel plants (t), $HV_{coking\ coal}$ represents the heating value of coking coal (thousand Btu/lb); $F_{carbon,coking\ coal}$ represents the carbon content of coking coal on a heating value basis (kg carbon/GJ); F_{ox} represents the carbon oxidation factor; 44/12 is the ratio of the molecular weight of carbon to that of CO$_2$.

CO$_2$ emissions from the iron and steel producing process were estimated according to the guidelines from the IPCC [28] as follows:

$$E_{CO_2,i,p,t} = A_{i,p,t} \times EF_{CO_2,p} \quad (9)$$

Where $E_{CO_2,p}$ represents the product-specific CO$_2$ emissions from the iron and steel processing units (sintering, pig iron, DRI, crude steel), A_p represents the quantity of product *p* produced on site for each unit; $EF_{\text{co}_2,p}$ represents the product-specific non-energy related CO$_2$ emissions factor of iron and steel processing *p* (t CO$_2$/ t product), as proposed by the IPCC[28], see *Supplementary Table S5*.

Potential changes in iron and steel plants CO$_2$ emissions estimation

Due to data limitations, we have assessed potential changes in the estimation of CO_2 emissions from iron and steel plants based on the projection of crude steel production from 2020 to 2050. Such projection is based on the tight relationship between economic development and iron and steel development using a computable general equilibrium (CGE) model.

Specifically, we utilize G-RDEM to predict the outputs of iron and steel sector for different countries. G-RDEM is a well-designed computable general equilibrium tool for long-term counterfactual analysis and economic baseline generation from given gross domestic product (GDP) and population projections. It has been improved in many ways specifically for the generation of long-term scenarios[31]. It encompasses an implicitly directly additive demand system with non-linear Engel curves, debt accumulation from foreign saving and introduces sector specific productivity changes, endogenous aggregate saving rates, as well as time-varying cost shares for value added and individual intermediates. Parameters for these relationships are econometrically estimated based on latest available data or taken from published work[31]. For more discussion of G-RDEM, please refer to *Supplementary Information section 1.11*.

Plant-level crude steel production estimation

Steel production reflects global economic development; previous studies have shown that the complex influence of economic growth on the production of crude steel varies across countries[1,32], due to the difference in factors such as industrial structure, level of investment, and so on. In this study, we first employ a CGE model to project the future country-level output of the iron and steel industry across the world.

Then, we narrow down the projected country-level output to the plant-level output based on the share of the current crude steel capacity in each iron and steel plant over the national crude steel capacity of the country where plants are located.

CGE models are widely used for both short-term policy assessment and long-term climate change-related analysis [33,34]. One of the main advantages of CGE models is that they consistently consider the manifold interrelations occurring within the economy, while providing the often-needed sectoral detail[31]. Projecting the future level of output of the steel sector with a CGE model, therefore, considers not only the overall future economic development, but also the interaction of the steel sector with upstream and downstream industries.

Specifically, the CGE model used here is a well-developed GTAP-based recursive dynamic CGE model, i.e., G-RDEM[31], which is especially suitable to generate long-term baselines and analyses (see Britz and Roson[31] for more details). The G-RDEM is a computable general equilibrium tool for long-term counterfactual analysis and baseline generation from given gross domestic product (GDP) and population projections. It encompasses an implicitly directly additive demand system (AIDADS) with non-linear Engel curves, and debt accumulation from foreign saving; it introduces sector specific productivity changes, endogenous aggregate saving rates, as well as time-varying cost shares for value added and individual intermediates. Based on the general equilibrium principle and the above assumed/estimated mechanism, the dynamics of investment, consumption, and consumption structure is calculated endogenously, driven by changes in GDP and population. For a complete description of the model, please refer to (Corong, et al. [35]), (Van der Mensbrugghe [36]) and (Britz and Roson [31]).

To initialize the CGE model, we need a benchmark (a dataset that describes the current status of the economic system) and long-term GDP and population projections. The benchmark of our CGE model is built on the wildly-used GTAP database (v9)[37]. This dataset provides the input-output relationship among 57 industrial sectors (including Ferrous Metals, Metals n.e.c., and Metal Products) of 140 countries/regions and the trade flows among these regions. We calibrated our model based on this data set. For the long-term GDP and population projections, we use the estimates derived from the SSP1, SSP2, SSP5[38-40].

Then, we use the initialized CGE model to generate the long-term baseline and derive the output of the steel sector from it. Finally, as shown in equation 10, we project crude steel production at the plant-level by narrowing down the projected output at country-level to the plant-level according to the share of crude steel capacity of the plants over the national crude steel capacity of the country where the plants are located.

$$PA_{i,t} = PA_{k,t} \times \frac{CrudeC_i}{\sum CrudeC_{i,k}} \quad (10)$$

Where *i, k,* and *t* represent the iron and steel plant, country, and year, respectively. *PA* represents the country-level projection of the specific iron and steel plants; *CrudeC* represents the current installed crude steel capacity of iron and steel plants. We project how the structure of iron and steel plants change using equation 11:

$$PA_{i,k} = U_{\alpha}(t) * PA_{i,k,\alpha} + U_{\beta}(t) * PA_{i,k,\beta} + \cdots + U_{\gamma}(t) * PA_{i,k,\gamma} \quad (11)$$

Where *U(t)* represents the proportion of output coming from the specific iron and steel processing units (such as BOF, EAF, steelmaking units, DRI, BF ironmaking units) for each plant; such proportion changes with the market demand over the period. α, β, γ represent the processing units.

Proposed scenario sets of carbon mitigation for the analysis:

To evaluate CO_2 emissions from the iron and steel industry in the future, we propose four scenario sets that are organized according to a tiered structure. Basically, **Tier 1** scenario sets deal with the planned year of retrofitting, the proposed CO_2 mitigation options of the iron and steel plants, and the region the plants are in, whereas **Tier 2** scenario sets deal with the choice of actual retrofitting schedule. We treat each scenario set as the different combination of the individual parameters in the model, such that we will have 4 scenario sets with the combination of eight parameters (*P, Y, L, T, W, N, C, S*). Meanings of the eight parameters are as follows:

1) ***P*** refers to the type of processing routes of the iron and steel plants; 2) ***Y*** refers to the year of the latest retrofitting; 3) ***L*** refers to the average operating lifetime; 4) ***T*** refers to the potential low-carbon technology of the iron and steel plants; 5) ***W*** refers to the time window of the low-carbon technology adoption; 6) ***N*** refers to the number of times the iron and steel plants are retrofitted between 2020 and 2050; 7) ***C*** refers to the order of countries adopting low-carbon technology. 8) ***S*,** a parameter in Tier 2, refers to the retrofitting schedule of the iron and steel plants.

We vary the value of each parameter by considering different sub-scenarios within each scenario set. This analysis aims to investigate the effects of the different portfolios of CO_2 mitigation options and their impacts in terms of CO_2 reductions in the iron and steel industry across the globe.

Tier 1 includes 3 scenario sets:

Scenario set 1: the planned year of retrofitting. Scenario set 1 defines the planned year of the retrofitting of each iron and steel plant according to 3 parameters: the type of the iron and steel plants, the latest retrofitted year, and the average operating lifetime.

Parameter 1: Type of processing routes of the iron and steel plants. Parameter set 1 defines the type of iron and steel plants that require the adoption of low-carbon technologies according to the processing unit of each plant. The acronym *P* means 'Type of processing routes of the iron and steel plants'.

- ***P1***: steelmaking plants with coal-based or charcoal-based blast furnaces.
- ***P2***: ironmaking plants with coal-based or charcoal-based blast furnaces.
- ***P3***: iron and steel plants with coal-based Directed reduced iron processing units.
- ***P4***: separately steelmaking plants with oxygen or electric steelmaking units.
- ***P5***: iron and steel plants with gas-based blast-furnaces or gas-based Directed reduced iron processing units or electric blast furnaces.

Parameter 2: Year of the latest retrofitting. Parameter set 2 defines the latest retrofitted **year** of iron and steel plants. The acronym *Y* means 'the Year of the latest retrofitting' and varies across the iron and steel plants worldwide.

Parameter 3: Average operating lifetime. Parameter set 3 defines the average operating lifetime of each iron and steel plant according to the year of the plant type. It was the average value of retrofitting-cycle (total number of years from the commissioning years to the latest retrofitting years). The acronym *L* means 'the Average operating lifetime' and varies across the iron and steel plants worldwide.

The combination of each variation of the above 5 parameter sets gives a distribution strategy. We will have 5 x 1 x 1 =5 sub-scenarios in scenario set 1.

Scenario set 2: Proposed CO_2 mitigation options for the iron and steel plants. Scenario set 2 defines the potential low-carbon technology of the first retrofitting according to 3 parameters: potential low-carbon technology of the iron and steel plants, the time window of the low-carbon technology adoption, number of times retrofitting is implemented

Parameter 4: potential low-carbon technologies for the iron and steel plants**.** Parameter set 4 defines the low carbon technologies that the iron and steel plants will adopt. The acronym *T* means 'technology'.

- ***T*1**: fuel switch. We assume that the switch of fuel in the iron and steel plants will be realized based on existing mature low-carbon technologies. Fuel switching is defined as the full substitution of coal and non-economic charcoal energy inputs with less carbon-intensive natural gas. We assume that the switching of the coal-based BF to the natural gas-based one can reduce CO_2 emissions by 20%[1], while the switching of the coal-based DRI to the natural gas-based one can reduce CO_2 emissions by 55%[1].
- ***T*2**: transformation of the iron and steel processing route. We assume that the transformation of the processing route will be within the scope of existing commercial technologies. We assume that the production of pig iron will be changed from blast furnace ironmaking to direct reduction one, whereas the production of crude steel will tend to be electrified to the processing route of direct reduction iron-electric arc furnace or the secondary processing route of electric furnace based on scrap steel. We assume that the transformation of the long-route BF-BOF steelmaking process into short route scrap-based EAF can reduce direct CO_2 emissions by 97%[1]. In addition, we assume that the upgrade of oxygen furnaces and the traditional electric arc furnaces in the separate steelmaking plants with advanced scrap-preheating technology will reduce direct CO_2 emissions by 80% and 73%, respectively based on our global dataset of emissions from iron and steel plants.
- ***T*3**: implementation of the Carbon capture, use and storage (CCUS) technology. We assume that CCUS technology will be implemented in the iron and steel plants to reduce CO_2 emissions. We assume that this proposed CCUS scenario to retrofit the coal/charcoal related iron and steel plants can reduce CO_2 emissions by 60% according to Axelson et al[24].

- ***T*4**: combination of the coal to natural gas fuel shifting (***T*1**) and the implementation of the CCUS technology (***T*3**). We assume that CCUS technology and coal-to-natural gas fuel switching will be combined to retrofit iron and steel plants in order to reduce CO_2 emissions. We assume that the combination of coal-to-natural gas fuel conversion and the implementation of CCUS technology can reduce CO_2 emissions by 95% according to Bataille et al[41].

- ***T*5**: implementation of the Hydrogen-based steelmaking technology. We assume that Hydrogen-based steelmaking technology will be implemented in the iron and steel plants to reduce CO_2 emissions. We assume that the Hydrogen-based steelmaking scenario to retrofit the coal/charcoal-related iron and steel plants can reduce CO_2 emissions by 26%, 82%, 95% over the period 2020~2050, according to Axelson et al[24].

- ***T*6**: combination of the coal to natural gas fuel shifting (***T*1**) and the adoption of the Hydrogen-based steelmaking technology (***T*5**). We assume that Hydrogen-based steelmaking technology and coal-to-natural gas fuel switching will be combined to retrofit iron and steel plants in order to reduce CO_2 emissions. We assume that the combination of coal-to-natural gas fuel conversion and the implementation of Hydrogen-based steelmaking technology can reduce CO_2 emissions by 95% according to Axelson et al[24].

- **Parameter 5: Time window of the low-carbon technology adoption.** Parameter set 5 defines the time window of the low-carbon technology adoption. The acronym *W* means 'Time window'.

- ***W*1**: short-term from 2020 to 2030
- ***W2***: long-term from 2031 to 2050

Parameter 6: Number of times the iron and steel plants are retrofitted. Parameter set 6 defines the number of times the iron and steel plants are retrofitted between 2020 and 2050 according to their retrofitting schedule. The low-carbon technologies used in each round of retrofitting may be different. The acronym *N* means 'number'.

- ***N*1**: the first time of retrofitting
- ***N2***: the second time of retrofitting

The combination of each variation of the above 3 parameter sets gives a distribution strategy. We will have 6 x 2 x 2 =24 sub-scenarios in **scenario set 2**.

Scenario set 3: Iron and steel plants regions. Scenario set 3 divides the world iron and steel industry into different regions according to parameter 7. We assume priority will be given to the installation and commissioning of the iron and steel plants located in the regions that planned to achieve carbon neutrality earlier.

Parameter 7: Country committed to achieve carbon neutrality. Parameter set 7 defines the order of countries adopting low-carbon technology. The acronym *C* means 'country'.

- ***C*1**: countries plan to achieve carbon neutrality earlier than 2050 or by 2050: European Union countries, the United States, Canada, Japan, South Korea, New Zealand, Fiji, Chile, South Africa, Costa Rica, Uruguay, Cambodia.
- ***C*2**: countries not listed in ***C*1** that plan to achieve carbon neutrality by 2060 or later.

The combination of each variation of the above 1 parameter set gives a distribution strategy. We will have 1 sub-scenario in scenario set 3.

Tier 2 includes 1 scenario sets:

Scenario set 4: Retrofitting schedule of the iron and steel plants. This scenario determines the retrofitting year of each iron and steel plant according to one parameter. The acronym *S* means 'retrofitting schedule'.

Parameter set 8 defines the actual retrofitting year of each iron and steel plant. The planned retrofitting date is the year by which the iron and steel plant reaches the average service life of its type since the latest retrofitting (**Parameter *Y***). Based on the planned retrofitting date, iron and steel plants will be retrofitted under 3 sub-scenarios:

- ***S*1** (Faster retrofitting case): the iron and steel plants will be retrofitted 5 years earlier than the planned retrofitting date.
- ***S*2** (Default): the iron and steel plants will be retrofitted at the planned retrofitting date.
- ***S*3** (Slower retrofitting case): the iron and steel plants will be retrofitted 5 years later than the planned retrofitting date.

The combination of each variation of the above 3 parameters gives a distribution strategy. We will have 3 sub-scenarios in scenario set 4.

The combination of each variation of the above 8 parameters gives a distribution strategy. In this analysis, we will have 5 x (6 x 2 x 2) x 1 x 3 = 360 scenarios. We list four typical plants in different countries to explain the detailed implementation of the low-carbon pathways mentioned in the above scenario sets in the *Supplementary Information section 1.5 (Extended Data Figs. 7 and 8)*.

Sensitivity Analysis

The cumulative emissions (36.8 Gt) under the 5-year-ahead retrofitting scenario represent 7.1% of the remaining budget across all sectors to achieve the 1.5°C climate limit (520.5 Gt). A sensitivity analysis of cumulative emissions of the iron and steel industry under the 2~8-year-ahead retrofitting scenarios and 2~8 year-late retrofitting scenarios suggests that 1) retrofitting existing iron and steel facilities as planned or five years earlier (under the proposed low-carbon retrofit scenarios) may be more likely to ensure that emissions from the iron and steel sector remain in line with the climate limits and avoid contributing to the growth of CO_2 emissions worldwide; 2) the early implementation of deep decarbonization technologies (transformation of the long-route BF-BOF steelmaking process into short route scrap-based EAF in *T2*, *T3*, *T4*) will make it easier for the iron and steel industry to achieve sustainable and necessary CO_2 emissions reduction and advance towards the near-zero carbon emissions goal *(Supplementary Information section 1.7, Supplementary Table S6*).

Data availability

The numerical results plotted in **Figures 1–4** are provided with this paper. CO_2 emissions for global iron and steel plants can be found at https://doi.org/10.5281/zenodo.7895711. Our analysis mainly relies on six different data sets, each used with permission and/or by license. Data for individual iron and steel plants worldwide are available in the website of Steelonthenet: https://www.steelonthenet.com/. Users can purchase the relevant database and merge with CEADs-GSEI to get complete information at plant level. Data for global iron and steel production by country are available in the website of World Steel Association: https://worldsteel.org/steel-topics/statistics/. Data for energy consumption for iron and steel industry by fuel type are available in the IEA World Energy Statistics Datasets: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics. Users need to register IEA accounts, agree to data use terms, and subscribe to this dataset. Data for geolocation of global iron and steel plants are available in the website of Google Maps: https://www.google.com/maps/place/. Users can search the plant's information using the name of the iron and steel plants. Data for information and location of Chinese iron and steel plants are available in the website of TianYanCha: https://www.tianyancha.com. Users need to register TianYanCha accounts, agree to the data use terms, and search the plant's information using the name of the iron and steel plants. Data for ownership information of some steel manufacturing companies are available in the website of Bloomberg: https://www.bloomberg.com/. Users can search the related plant's information using the name of the iron and steel plants.

Code availability

Data processing code for the plant-level CO_2 emissions can be found at https://doi.org/ 10.5281/zenodo.7895709.

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Author contributions

DABO GUAN, and TIANYANG LEI designed the study. TIANYANG LEI performed the analyses, with support from DAOPING WANG, WEICHEN ZHAO, CAN CUI on datasets, from SHIJUN MA, WEICHEN ZHAO, JING MENG, and SHU TAO on analytical approaches, and from XIANG YU on discussions. TIANYANG LEI led the writing with input from all coauthors.

Competing interest declaration

The authors declare that they have no competing interests

Additional information

Supplementary information

This file contains Supplementary Description Section 1-11 and Supplementary Tables 1-6.

Corresponding author

Correspondence to Dabo Guan

Extended Data figure legends

Extended Data Figure 1 Schematic diagram of building the CEADs-GSEI.

Extended Data Figure 2 Maps of iron and steel plants crude steel capacity in 2019. Iron and steel plants are classified into 17 types by iron and steel processing routes and annual crude steel capacity in 2019 (⩽9 Mt, ⩽ 17 Mt, ⩽26 Mt). Color of point shows the iron and steel processing routes and size of points indicates the capacity size.

Extended Data Figure 3 Definition of 10 regions in this study

Extended Data Figure 4 Cumulative annual CO_2 emissions in the current operating round from all existing iron and steel plants by region. Annual CO_2 emissions under the 25-year retrofitting cycle are shown with darker shade, and annual CO_2 emissions under the corresponding average retrofitting cycle are shown with lighter shade.

Extended Data Figure 5 Cumulative CO_2 emissions of iron and steel industry under SSP1, SSP2, SSP5 by region from 2020 to 2050

Extended Data Figure 6 Map of global iron and steel processing units' capacity. Color of point shows the processing type of each units, including 14 types, namely: iron making and casting, steelmaking (BOF, EAF, others), steel refining, coking, powdering, sintering, steel casting and forgings, steel rolling, coal recovery plants, oxygen producing plants, power supply units, reheating furnaces, air separation plants and other plants, size of points indicates the capacity size.

Extended Data Figure 7 Parameters setting of low-carbon pathways for iron and steel plants in countries plan to achieve carbon neutrality earlier than 2050 or by 2050 (C1).

Extended Data Figure 8 Parameters setting of low-carbon pathways for iron and steel plants in countries plan to achieve carbon neutrality by 2060 or later(C2).