

Plant-by-plant decarbonization strategies for the global steel industry

In the format provided by the
authors and unedited

Table of Contents

Supplementary Texts	2
Supplementary Figures	22
Supplementary Tables	50
References	64

Supplementary Text 1. Introduction to the processes and routes in iron and steel industry

The multi-processes in the iron and steel industry can be categorized into three stages: pretreatment including coke production (i.e. coking) and iron ore processing (i.e. sintering and pelletizing) is to prepare important sources of iron and reducing agents for manufacturing iron; ironmaking represents iron smelting for manufacturing steel using blast furnace (BF), direct reduction (DRI furnace), and other minor facilities; steelmaking finally represents crude steel production by basic oxygen furnace (BOF), electric arc furnace (EAF), and open hearth furnace (OHF) from iron and steel scrap (Supplementary Table 1). The above-mentioned processes can be combined to BOF/OHF primary, EAF primary, and secondary steelmaking routes (Extended Data Fig. 1). Specifically, the two primary routes make crude steel by raw iron through aforementioned pretreatment, ironmaking, and steelmaking processes, among which the BOF/OHF primary steelmaking route mainly relies on pig iron from BF, while the EAF primary steelmaking route generally use DRI. The secondary steelmaking route makes crude steel by steel scrap in EAF. The combination of processes results in different plant types as defined in Supplementary Table 2.

Supplementary Text 2. Sensitivity tests of mitigation potential

Sensitivity for indirect CO₂ emissions

Supplementary Figure 5 shows the comparisons of CO₂ mitigation potential between the base estimate (only considering direct CO₂ emissions as shown in Fig. 4) and two sensitivity tests in which indirect CO₂ emissions are included (estimated using carbon intensities derived from all types of electricity generation (i.e., EF_{avg}) and fossil-fuel electricity generation (i.e., EF_{fossil}), respectively). The methodology of indirect emission accountings can be found in *Methods* Section. When the mitigation strategies are related to efficiency improvement (i.e. blue and purple bars in Supplementary Fig. 5), the effects of including indirect emissions are generally insignificant owing to the dominance of direct CO₂ emissions in primary steelmaking. Thus, the impacts on mitigation potential related to transformation towards secondary steelmaking are focused here.

Globally, when indirect emissions are included, mitigation potential related to secondary steelmaking transformation obviously declines in almost all cases with different indicators and percentiles (Supplementary Fig. 5a). For example, when the 75th and 50th quantiles are used, the reduction of mitigation potential reaches 4%-9% and 8%-12%, respectively, in comparison with the base estimate. This is because EAF is much more electricity-intensive than general facilities in the prevalent BF-BOF route (Supplementary Table 5), cutting down the benefits if electricity-related emissions are considered. But it should be noted that in most cases, considerable mitigation can still be expected even if indirect emissions are included, confirming the promising effects of secondary steelmaking transformation. Moreover, when EF_{fossil} is used for indirect emission accountings, the impact on offsetting mitigation potential becomes more significant compared to EF_{avg} , because electricity consumption becomes more carbon-intensive. The relative differences of using EF_{fossil} and EF_{avg} reach up to ~4% in some cases. This reflects that the mitigation benefits can likely be amplified by increasing the shares of low-carbon power (i.e., decreasing the shares of carbon-intensive electricity generation by fossil-fuel-based autoproductors on site).

The regional effects of considering indirect emissions are broadly similar to those at global scale (Supplementary Fig. 5b-5i). But in very few cases, mitigation potential can instead slightly increase when indirect emissions are included, since some plants with DRI-EAF primary steelmaking route, which is originally more electricity-intensive than EAF secondary steelmaking, are identified as the targeted ones. In addition, when retirement of overcapacity is considered in mitigation strategies, the production shift of retired plants towards some less electricity-intensive primary steelmaking plants can sometimes slightly increase mitigation potential. However, such minor cases do not affect the major impact of indirect emissions — the overall decrease of mitigation potential in terms of secondary steelmaking transformation compared to base estimate.

The effects of considering indirect emissions on cost effectiveness are quite similar to those on mitigation potential (Supplementary Figs. 6-7), since the estimated costs (capital, stranded, or upgrading costs) are not affected by electricity consumption here. Globally and regionally, the inclusion of indirect emissions results in obvious increases of abatement cost metrics related to secondary steelmaking transformation, and the changes are more remarkable when EF_{fossil} is used in indirect emission accountings in comparison to EF_{avg} . When the 90th quantile is used for identification, the increases are generally slight (<5%), but can reach 5%-20% when the 75th and

50th quantiles are used. In very few cases, abatement cost metrics can instead decrease when indirect emissions are included as explained by the changes of mitigation potential above. But in such cases the mitigation potential in base estimates are actually very small (See Supplementary Fig. 5), and thus the changes have negligible impact on overall mitigation benefits.

Sensitivity of upgrading costs

Supplementary Figure 8 shows the abatement cost metric if upgrading costs are significantly higher, for comparison with the base estimate in Fig. 4. This sensitivity test is designed because different from capital costs compiled from literature, upgrading costs are assumed as half of capital costs (referring to the costs of BF relining process¹⁻³) in the base estimate, which can be subject to larger uncertainty. Upgrading of plants is complicated and case-by-case to some extent. Upgrading may be completed by adding advanced installation on the existing facilities (corresponding to the case in base estimate); But sometimes upgrading requires the decommission of part of existing facilities for equipment of new ones, which may result in certain loss of capital costs and make the actual upgrading costs higher (i.e., upgrading cost plus potential stranded capital cost). Therefore, here we add this sensitivity test, assuming much higher upgrading costs (i.e., the same as capital costs) to assess the impact on cost effectiveness.

The results show very significant influence on mitigation strategies related to efficiency improvement. Globally, the abatement cost metrics of efficiency improvement increases by ~50% in comparison with that in base estimate (Fig. 4a and Supplementary Fig. 8a; since upgrading costs are doubled). Similar to global changes, the gaps of cost effectiveness between efficiency improvement and secondary steelmaking transformation are significantly widened in most regions (Supplementary Fig. 8b-8i), especially those with large mitigation potential (e.g., India and Eastern Europe and Russia). This points to an important consideration: if upgrading costs of efficiency improvement are moderate, it can be an attractive strategy economically and also create new primary steelmaking assets with lower value (thus lower stranded risks in the future); however, if upgrading costs are significantly higher, transformation towards secondary steelmaking become much more appealing if available.

Sensitivity of indirect emission decarbonization

As the share of secondary steelmaking increases, more decarbonization burden will gradually be transferred to power industry. An analysis is performed here to assess the impact on abatement costs if indirect emissions from electricity consumption are further decarbonized based on the strategies. The abatement costs of indirect emission by three technologies (i.e., wind power, solar PV power, and fossil fuel with CCS) are considered here as shown in Supplementary Table 8.

As shown in Supplementary Fig. 9-10, if the electricity consumption of iron and steel industry is further decarbonized by wind or solar PV power, which are mature technology with low abatement costs, the total CO₂ abatement costs (i.e., costs per unit CO₂ mitigation potential) generally decrease in most cases, especially those strategies related to secondary steelmaking transformation. Globally, the relative cost reduction ranges from around 5-15%, and cost increases are only found in very few regional cases when the abatement costs of direct

emissions are very low as overcapacity is retired. This shows that decarbonizing electricity for the iron and steel industry can very likely increase the cost-effectiveness especially when electricity consumption from secondary steelmaking grows. However, if some developing technologies with high costs like CCS are used for indirect emission decarbonization, the cost effectiveness tends to be deteriorated, but its share of technology application is expected to be very low for short-term mitigation focused in this study. In summary, further decarbonizing electricity based on direct emission mitigation is generally worth considering in policymaking for deeper decarbonization of iron and steel industry.

Supplementary Text 3. Trends in capacity and CO₂ emissions

Trends in capacity

The past thirty years have witnessed substantial growth in the global iron and steel industry. Extended Data Figure 2 shows global and regional trends in steelmaking capacity from 1990 to 2019. Global steelmaking capacity doubled from 1,195 Mt in 1990 to 2,342 Mt in 2019 (i.e. 2.3% annual growth), with a total of ~1,600 plants commissioned worldwide over the time period (Supplementary Figs. 11-12). Moreover, the growth has largely been in emerging economies, thereby shifting the majority of global steel production to those countries (Supplementary Fig. 13). For example, the U.S. and Western Europe accounted for 11.0% and 20.4% of global steelmaking capacity, respectively, in 1990 (in the same year China and India accounted for 11.4% and 2.3%, respectively). But after rapid growth, the steelmaking capacity in India in 2019 (120 Mt) was nearly as much as the U.S. (125 Mt). Meanwhile, more recent growths in the iron and steel industry of countries such as Vietnam, Indonesia, Turkey, and Iran suggest they are emerging hotspots of steel-related CO₂ emissions.

The capacity evolution is also reflected by the age distributions (Supplementary Fig. 14). The rapid expansion of steelmaking plants in emerging economies results in the large fleets of iron and steel infrastructure², and in 2019, the average ages of steelmaking and ironmaking furnaces are both ~23 years globally (Supplementary Fig. 14a). In some emerging economies (e.g. Iran and Vietnam), the steelmaking fleets are young with average ages below 15 and even 10 years in 2019. Despite young facilities, China has eliminated ~300 Mt of excess or outdated capacity in the recent decade related to efforts to improve air quality, which targeted small furnaces with higher energy intensity⁴ (Supplementary Fig. 14b). By contrast, in the U.S. and Western Europe, 58.2% and 79.8% of operating steelmaking capacity in 2019 was commissioned prior to 1990, respectively. Developed countries also gradually retired outdated (e.g. OHF) or energy-intensive capacities in recent decades to streamline their industrial structure, with increasing shares of EAF for secondary steelmaking.

Trends in direct CO₂ emissions

Supplementary Figure 15 shows 30-year trends in direct CO₂ emissions by region and process. Overall, in contrast to 96% increase of steelmaking capacity, global direct CO₂ emissions of iron and steel industry soared from 1,152 Mt to 2,751 Mt with an increase of 139% during the period 1990-2019 (Supplementary Fig. 15a). The disproportionately high emissions were mainly due to the expansion of energy-intensive primary steelmaking via the blast furnace-basic oxygen furnace (BF-BOF) route, especially in emerging economies⁵. Consequently, the processes related to BF-BOF route, such as coking, sintering, pelletizing, BF ironmaking, and BOF steelmaking, all showed considerable emission growths in 1990-2019, ranging from 70%-200%. Striking emission increases by over 300% were observed for DRI ironmaking as DRI-EAF route gradually prevailed in India and the Middle East. In contrast, steelmaking in developed countries was increasingly by secondary routes based on electric arc furnaces (EAFs, mainly relying on electricity to generate indirect emissions)⁶. Thus, direct CO₂ emissions in India's iron and steel industry grew from 48 Mt to 277 Mt (+477%) over the time period while emissions from the U.S. and Western Europe steadily decreased by 43% and 49%, respectively. In 2019, the BF-BOF (primary) route accounted for roughly 70% of crude steel

produced worldwide, and BF alone accounted for ~75% of total direct CO₂ emissions given its requirements of coke and injected coal^{7,8}. When pretreatment processes are included, primary steelmaking routes strikingly accounted for >95% of global iron and steel direct CO₂ emissions (Supplementary Fig. 15b).

Supplementary Figure 16 further shows the process-based direct CO₂ emissions by region. Similar to the global pattern in Supplementary Fig. 15, the contributions from blast furnaces dominated in every region (generally >65%). In some regions, direct reduction iron (DRI) process is also a large emission source. For example, DRI furnaces account for 25% and 27% of direct CO₂ emissions in India and Rest of World (mainly attributed to the Middle East) in 2019, respectively. The share of DRI furnaces exceeded 10% in Canada and Latin America as well. These regions are generally characterized by high-quality mines for DR pellet production and abundant natural gas resources, but India mainly relies on energy-intensive coal-based DRI process. As the processes to pretreat iron ores, sintering has larger direct CO₂ emissions than pelletizing in most regions because of lower requirements for raw materials and thus more production. But as a representative exception, the emissions from pelletizing outweighed sintering in the U.S. mainly owing to the quality of local mines⁹. From a country-based perspective, the shift of direct CO₂ emission hotspots from developed countries to emerging economies stood out in 1990-2019 (Supplementary Fig. 17).

Trends in indirect CO₂ emissions

Supplementary Figure 18 shows 30-year trends in indirect CO₂ emissions by region and process. Global indirect CO₂ emissions of iron and steel industry climbed from 131 (214) Mt to 285 (428) Mt in 1990-2019 when carbon intensity of electricity generation EF_{avg} (EF_{fossil}) is used for estimates (See *Indirect emission accountings* in *Methods* Section for details of carbon intensity considerations). Overall, the magnitude of indirect emissions was much smaller than that of direct emissions, and the relative growth in 1990-2019 was slower as well because the rapidly expanding BF-BOF route in emerging economies contributed much more to direct emissions. Compared to direct emissions, the shares of regions heavily relying on BF-BOF route, such as China, significantly decreased (41%-42% in 2019 depending on electricity carbon intensity), while the contributions from developed regions like the U.S. and Western Europe grew (5-6% and 4-8% in 2019), as the iron and steel industry there transited towards more electricity-dependent EAF secondary steelmaking (Supplementary Fig. 18a). The shares of India and Rest of World also showed increasing trends as EAF-based primary steelmaking fed by DRI (which is more electricity-intensive than blast furnace ironmaking) boosted there.

From a process-based perspective, the patterns are distinct with those in direct emissions (Supplementary Fig. 18b). EAF dominated indirect CO₂ emissions (50%-60%) as highly electricity-intensive facility. This emphasizes that although transition towards secondary steelmaking can significantly reduce direct emissions, the impact of indirect emissions should be carefully assessed by sensitivity tests in the mitigation analyses (See Supplementary Text 2). As key processes in BF-BOF route, blast furnace ironmaking, sintering, and BOF steelmaking accounted for ~17%, ~10%, and ~8% of indirect CO₂ emissions in 2019, but considering the large production of related products, the indirect emission intensities of such processes are actually moderate and even low (e.g. 0.02-0.03 tonne indirect CO₂ per tonne steel in BOF compared to 0.29-0.43 tonne CO₂ in EAF in 2019 globally when only steelmaking process is

considered).

Supplementary Text 4. Global and regional drivers of direct CO₂ emissions

Extended Data Figure 3 shows global and regional underlying drivers contributing to changes of direct CO₂ emissions. Globally, increases in production are the main driver of increases in CO₂ emissions (yellow bars in Extended Data Fig. 3a), with changes in energy efficiency (defined as CO₂ emissions per unit crude steel production) limiting such increases of CO₂ emissions more in some time periods than others. For example, from 2000 to 2010, rapid increases in steel demand in developing countries led to expansion of less-efficient facilities that raised the average energy intensity worldwide (blue bars in Extended Data Fig. 3a). Meanwhile, steady increases in BF-BOF (primary) steelmaking in emerging economies since 2000 meant that shifts in production routes consistently urged emissions upwards (orange bars in Extended Data Fig. 3a).

Regional drivers of direct CO₂ emissions were broadly similar to those affecting global emissions (Extended Data Fig. 3b-3i). However, improvements in the energy efficiency of steel production consistently reduced emissions in China, benefitting from the country's efforts to retire inefficient plants^{4,10}, and the promotion of secondary steelmaking—especially since 2010—was effective as well¹¹. In contrast, relatively constant demand in high-income countries and regions meant that production route shift and efficiency improvement were more important to emission changes (e.g., the U.S. in Extended Data Fig. 3e and Western Europe in Extended Data Fig. 3g)^{12,13}.

Supplementary Text 5. Disproportionalities of plants and facilities

Supplementary Figure 20 shows the relationship between crude steel capacity and age, and that between crude steel production and annual direct CO₂ emissions from secondary steelmaking plants in 1990 and 2019. Different from the striking growth of young and large plants in developing countries for primary steelmaking (Fig. 1 and Supplementary Fig. 19), the age-to-capacity patterns of secondary steelmaking are dominated by the plant aging in developed countries in 1990-2019. In 2019, the pattern is much more scattered than that of primary steelmaking plants, and the average age of those identified plants (n=122), accounting for 0.3% of capacity, reaches 56.3 years. Distinct gaps of emission intensity are also found among secondary steelmaking plants, and the gaps have been widened in 1990-2019 because the emergence of more relatively inefficient plants in developing countries such as Southeast Asia. Globally, in 2019, 21.1% of global CO₂ emissions from secondary steelmaking plants were disproportionally produced by 5.8% of secondary steel production, showing large gaps towards the benchmark level.

For the age-capacity relationship of facilities, the patterns are very similar to those of primary steelmaking plants (Supplementary Fig. 21). The fleets of young (< 15 years) and large (> 1,000 kt) sintering/pelletizing and ironmaking facilities are striking, with most facilities located in developing countries/regions such as India and the Middle East. In contrast, the large but older facilities are mostly located in developed countries/regions (e.g., the U.S., Western Europe, and Japan) and Eastern Europe and Russia where industrialization was initiated early during the Former Soviet Union period. Using the 90th quantiles of age-to-capacity ratio as thresholds, a very small proportion of facilities (< 1% of capacity) are identified as potential targeted facilities. More small-sized but young facilities (24.1 years on average) are identified for sintering/pelletizing in comparison with ironmaking.

Distinct gaps of emission intensity are also observed for sintering/pelletizing and ironmaking facilities (Supplementary Fig. 22). The emission intensity of pelletizing facilities is generally lower than that of sintering facilities (0.11 tCO₂/t vs. 0.16 tCO₂/t for global average; Supplementary Fig. 22a); similarly, the emission intensity of DRI furnaces is moderately lower than that of blast furnaces (1.1 tCO₂/t vs. 1.6 tCO₂/t for global average; Supplementary Fig. 22b). This indicates some mitigation opportunities by optimizing the processes within primary steelmaking routes (e.g., increasing the shares of pellets for ironmaking if available). In each case, a number of inefficient facilities exist (shaded area beyond the 90th quantile of emission intensity). Globally, 8.8% and 8.3% of CO₂ emissions from sintering/pelletizing and ironmaking facilities were respectively emitted from 5.3% and 4.8% of production. Significant gaps are shown when compared to the given benchmark intensities (the average intensity of top 25% efficient facilities). For example, for ironmaking facilities, the 90th percentile of emission intensity is 108% higher than the benchmark value, and even the 50th percentile is 76% higher.

The facility-level disproportionalities are further revealed by historical evolutions at regional scale (Supplementary Fig. 23-24), which are overall consistent with those of primary steelmaking plants (see Fig. 3). The age-to-capacity ratio generally showed increasing trends especially in developed regions like Western Europe, as facilities aged without active new commission (Supplementary Fig. 23). However, the large-scale BF relining in 1990s resulted in slight decrease or stable changes of age-to-capacity ratio for ironmaking in developed region

during 1990-2000. In China, striking decreases of age-to-capacity ratio were observed in 2000-2010. The variations of age-to-capacity ratio are relatively steady in India, reflecting a trade-off between newly-built facilities (but many of them are small- or medium-sized) and aging of older ones.

Facility inefficiency is particularly noteworthy in some regions (Supplementary Fig. 24). The efficiency of sintering/pelletizing and ironmaking facilities has both gradually improved worldwide as energy-saving technologies developed and inefficient facilities were decommissioned. As a representative, the average energy intensity of sintering/pelletizing and ironmaking facilities in China declined by 38% and 39% in 1990-2019, respectively. Significant efficiency improvement was observed in India as well, although the facilities there still maintained the most carbon-intensive level on average. Additionally, the transition from BF-BOF route to DRI-EAF route (i.e., using DR pellet to produce DRI and then manufacturing steel) promoted the energy intensity in some regions like the rest of world (as compared above, pelletizing and DRI are generally less carbon-intensive than sintering and BF, respectively). Globally, efficiency improvement was not very obvious in the past three decades, as less efficient facilities in developing countries expanded tremendously.

Supplementary Text 6. Discussions on different indicators and mitigation strategies

A few important aspects of the advantages and disadvantages of different indicators and mitigation strategies are highlighted and briefly discussed in the *Discussion* Section of main text. Here, some aspects are further illustrated to reveal underlying mitigation risks, and some additional factors are considered to enrich the analyses. The supplementary discussions can be potentially essential for mitigation decision-making in governments and industries.

New assets and related lock-in effects

Two components are mainly considered in mitigation strategies (with combination of retirement): efficiency improvement and transformation towards secondary steelmaking. Despite comparable cost effectiveness as shown in Fig. 4, an important aspect should also be seriously considered: the new assets and related lock-in effects. Admittedly, efficiency improvement by upgrading/partly replacing primary steelmaking plants can effectively reduce CO₂ emissions especially in some developing countries, but meanwhile it results in new assets and capital costs. A few analyses have showed the need to speed up deep decarbonization of iron and steel industry, e.g. as early as late 2020s or early 2030s for net-zero steel industry by 2050^{14,15}. In this context, the new primary steelmaking assets may likely negatively affect the process of rapid transition, leading to potential risks of stranded capital costs one investment cycle later^{16,17}. According to latest estimates, however, the investment lifetime of primary steelmaking plants is 15-25 years on average^{1,2}, and thus probably most of new capacity built by 2030 has small or even no burden of stranded assets by the mid-century. The strategy of secondary steelmaking transformation has much smaller burdens in this aspect, since EAF is very low-carbon itself with decarbonization difficulties mostly transferred to power industry (i.e., indirect emissions). The comparison above emphasizes that new mitigation investments should be carefully evaluated according to both short-term and long-term decarbonization planning.

But importantly, this does not mean that efficiency improvement is a pessimistic strategy in the long run. The enterprises can upgrade the plants with technologies that are more energy-saving but also more compatible with future zero-carbon transition. For instance, upgrading to an oxygen blast furnace (OBF) can allow high CO₂ capture potential if CCS technology is installed in the future; upgrading to an advanced DRI furnace can likely be adapted to 100% hydrogen operation with minor equipment retrofit in the future⁷. Such smooth transition towards net-zero steel industry can likely avoid large-scale decommissioning of existing facilities and a large amount of stranded assets.

Operating costs and competitiveness

In the cost effectiveness analysis, upgrading costs, stranded capital costs, and new capital costs are considered. In reality, operating costs and competitiveness can be other factors to assess. For inefficient plants, they generally consume more fuels per unit production and have higher related operating costs in this aspect; for older plants, more expenses may be spent on maintenance and repair. These can very likely deteriorate their competitiveness. But competitiveness can also be influenced by many factors, such as local market demand (e.g.,

some plants serve very specific markets), geolocation (e.g., the distance towards iron ore mines, railway, and harbors), and supply-/demand-side policies. Thus, competitiveness may be case-by-case in reality, but can be involved in targeted decarbonization policymaking. Market policy can probably be implemented to promote the retirement, upgrading, or replacement of less competitive plants to improve the mitigation performance. This also points to the opportunities for the penetration of advanced low-carbon and zero-carbon producing technologies. For instance, H2 Green Steel, an enterprise in Sweden, has pre-sold over 1.5 million tonnes of green steel to customers¹⁸, showing the potential competitiveness for commercialization. To include operating costs and competitiveness can improve the practicality and flexibility of mitigation strategies, and likely boost more ambitious decarbonization through market mechanism.

Scrap availability and price

In the analyses, the term “mitigation potential” is conservatively used because the implementation and effects of the mitigation strategies are also constrained by some resource factors, which are beyond the plant-level quantitative scope in this study but important to clarify here. Typically, scrap availability can be an essential factor that determines the process of targeted mitigation by secondary steelmaking transformation. The scrap supplies are inadequate or unstable in many developing countries, i.e. the most urge-to-abate economies. For example, when the plants beyond the 50th quantile of emission intensity indicator are targeted, ~430 Mt of crude steel production in China should be transformed towards secondary steelmaking route to achieve the maximum potential, roughly requiring 470 Mt of steel scrap (assuming a ratio of 1.1 between scrap and steel¹⁹). Currently, annual scrap generation in China is ~250 Mt²⁰, a large proportion of which has been used by China’s iron and steel industry and is thus far from enough to meet the mitigation demand. But fortunately, projections show that scrap generation will rapidly increase and approach 800 Mt in China by 2050 (while steel demand and production will keep stable and then gradually decline)⁵; scrap availability will also further increase as the recycling system is improved²¹. These all likely support more aggressive secondary steelmaking transformation in China. The scrap shortage can be more challenging in India and other countries with less steel stock now²², and expansion of scrap import can probably be a temporary solution (e.g., India will import about 30 Mt of ferrous scrap per year by 2030²³).

Scrap price can be another important factor to affect the cost effectiveness of mitigation strategies. Scrap price is tightly linked with its supply and demand^{24,25}. As secondary steelmaking expands, the demand of scrap may surge. If the supply of scrap struggle to meet the demand, scrap price can likely be raised, which deteriorates the cost effectiveness of secondary-steelmaking-related mitigation strategies (i.e., increase the operating costs of secondary steelmaking plants and deteriorate the competitiveness as discussed above). To tackle the problem, some policies from governments may be necessary to monitor, manage, and regulate the local scrap market, and the development of international scrap trade may be of help as well. The discussion here shows that to achieve the targeted mitigation potential is not a “one-step” but “step-by-step” process as the compatibility resource utilization is gradually optimized.

Retirement of global excess capacity

We look into where the capacity retirement take place as well as the stranded assets as shown in Supplementary Figure 25. When the emission intensity indicator is used, the retirement mainly occurs in developing regions, including some large plants with massive stranded assets. Identified by the age-to-capacity ratio indicator, the retirement is more widely distributed, and the majority is smaller plants with less stranded assets. Importantly, whichever indicator is used, developing regions would bear most of the stranded assets (i.e., over 80%) because more identified plants are large and/or relatively young there. The imbalance of stranded asset distribution may be a challenge of accelerating global overcapacity retirement, which in turn requires regional differentiated planning. Some international financial compensation can likely encourage the decommissioning especially for developing countries, but the source of such funding will be a difficult political issue that should be addressed by joint efforts of decision makers in governments and enterprises (e.g., the negotiations of Global Arrangement of Sustainable Steel and Aluminum between the U.S. and EU²⁶). Given steel is highly traded, global steel market should probably be optimized as well, to allow the retirement of plants in some regions but meet the local demand at the same time. Overall, retirement of global excess capacity is an essential challenge that should be comprehensively evaluated, negotiated, and promoted from socio-economic, political, and environmental perspectives.

In this study, the mitigation policy via retirement of global excess capacity occurs based on the 2019-year production. Here, the “baseline” decarbonization potential that accords with the current production, structure, and resource is provided, targeting short-term decarbonization. But plant retirement can be an important aspect for developing countries in the future pathways, which relies on future demand changes generally projected by Integrated Assessment Models (IAMs). Such analysis is not included in this study (i.e., the global production level is assumed to be maintained here), and more efforts can probably be made to perform pathway-dependent retirement research especially for developing countries using the GISD database in the future.

The relationship with net-zero goals

Short-term decarbonization strategies are focused in this study, but it is important to assess whether the proposed strategies are congruent with long-term net-zero goals. Thus, we compare the CO₂ mitigation potential with the emission reduction of global iron and steel industry in 2030 projected by IEA’s Net Zero Emission Scenario as shown in Supplementary Table 9²⁷. It is found that the CO₂ mitigation potential in some strategies are largely consistent with the foreseen emission reduction in 2030, especially when the 50th percentile is used. When the 50th percentile of emission intensity indicator is used for plant identification, the CO₂ mitigation potential exceeds the projected reduction no matter what strategy is adopted. This shows that the proposed strategies may serve as the near-term choice within the net-zero scenarios, or are basically compatible with the short-term requirement of net-zero goals.

Technical innovation for further decarbonization

Besides the current mature strategies (i.e., retirement, efficiency improvement, and transformation towards secondary steelmaking), technical innovation is a key measure to further decarbonize iron and steel industry. A supplementary analysis is performed here from

the plant-by-plant perspective to reveal the effects of innovative technologies in the short term. According to the IEA Net Zero Scenario²⁷, about 100 Mt of steel can be produced by innovative technologies (i.e., hydrogen-based ironmaking and production with CCUS) in 2030. Besides the plants identified by the 50th percentiles of the indicators, we sort the remaining plants according to their rankings by each indicator and further identify some plants in order until the production scale reaches that proposed by IEA Net Zero Scenario, to quantify the mitigation potential if they are applied with innovative technologies (Supplementary Fig. 3). The results show that globally, around 150-160 Mt of CO₂ emissions can be further reduced by applying innovative technologies with their estimated production scale in 2030. The global mitigation potential can increase by 11%-17% and 28%-34% when emission intensity and age-to-capacity ratio indicators are used to target plants, respectively. Regionally, mitigation potential can be obviously improved in most cases as well. This highlights the importance of developing, demonstrating, and applying innovative low-carbon technologies for deep decarbonization.

The feasibility of low-carbon strategies

In this study, it is estimated that 16% and 28% of global steel production capacity would be targeted in the short term when the 50th percentiles of age-to-capacity ratio and emission intensity indicators are used, respectively. Such capacity transition identified here is basically consistent with the short-term magnitudes presented in other studies as the key start for the achievement of deep decarbonization (i.e., net-zero steel pathways) by 2050 (e.g., assessments by Net Zero Steel¹⁵ and IEA Net Zero Scenario²⁷). Therefore, aggressive transformation may be essentially needed in such a 30-year process if net zero steel production is pursued by mid-century. Despite beyond the environmental scope of this study, the engineering issues (e.g., approval, design, decommissioning, construction, upgrading, and launch) of such 16%-28% capacity transformation may be a key challenge for global steelmakers especially in developing countries, which must be cautiously evaluated by local engineering research and demonstrated by the leading projects, to ensure the ambitious but smooth transition within such a short period.

Other considerations on mitigation indicators and strategies

In this study, an indicator called age-to-capacity ratio is introduced besides emission intensity (which is commonly used) to identify targeted plants, and its meaning is described in detail here. Age of plants is an important and objective dimension for decarbonization, because older plants tends to have less stranded capital if they are retrofitted or retired. However, ranking the plants with the same age for retirement or upgrading needs another dimension, and thus plant capacity is introduced as an objective variable. Smaller plants generally represent less investment and embodied capital costs, and are preferentially included in climate and environmental strategies in many cases. Finally, the ratio between age and capacity is used as an indicator, which mainly points to decarbonization burdens from a cost-based perspective. This is different from emission intensity that emphasizes the emission-based perspective.

It can be found in this study, efficiency improvement is excluded for age-to-capacity ratio indicator. This is because that the strategy is basically not cost-effective, or inconsistent with the meaning of the indicator. The cost effectiveness of this strategies is shown in Supplementary

Figure 26 in comparison with other strategies. It is clearly shown that the abatement costs are much higher than the others globally (about 25-60%). Specifically, when the age-to-capacity ratio indicator is used, it targets older and smaller plants with less stranded capital without consideration of efficiency, and thus some of identified plants can still have good performance on energy efficiency especially in developed regions, significantly reducing the mitigation potential of efficiency improvement. Based on the assessment, it is not included in the strategies presented in the main text.

Supplementary Text 7. Limitations and uncertainty analysis

Uncertainty quantification

Emission estimates are subject to uncertainty because of incomplete information of activity rates and emission factors²⁸. In order to more completely assess the uncertainties of our emission estimates, both national and facility-level uncertainty analysis was conducted following the methodology demonstrated by previous studies²⁹⁻³¹. The term “uncertainty” here refers to the lower and upper bounds of the 95% confidential interval (CI) around the central estimate. Input parameters of activity rates and emission factors, with corresponding statistical distributions, were placed in a Monte Carlo framework, and 10,000 simulations were performed to analyze the uncertainty of direct CO₂ emissions. The probability distributions of input parameters are shown in Supplementary Table 10. Our result shows that global average emission uncertainty is -14% to 16% based on the aggregation of uncertainties of individual countries (Supplementary Fig. 27), which is close to the CO₂ emission uncertainty level in previous studies on power sector and cement industry^{29,30}.

For the uncertainties of facility/plant-level emission estimates, previous studies commonly selected one or several different-sized or representative facilities or plants to assess the uncertainties^{29,30}. In this study, we followed this method and selected representative steelmaking plants for analysis. The primary steelmaking plants correspond to two plant types in the eight regions (see Extended Data Fig. 1 and Supplementary Table 2): plants based on BOF/OHF primary route and plants based on EAF primary route. We assume a larger coefficient of variation (CV) for facility-level activity rates compared to national emissions due to lack of direct data source of facility-level fuel consumption, and facility-level uncertainties of emission factors are assumed to be the same as national estimates following previous studies^{29,30}. As a result, the emission estimate uncertainties range from around -(19-20) % to +(20-22) %. The uncertainties can probably be underestimated because of plant-level variations of fuel quality, annual operating hours, and applied technologies etc., which are difficult to obtain and include in the current framework but comprehensively discussed in the section below.

Discussions on limitation and uncertainty

Capacity utilization. The capacity utilization rates by process are assumed as consistent within a country following previous studies^{29,30,32}, which can be a limitation in the accounting methodology. But importantly, CISP that includes real statistical production (i.e., real capacity utilization rates) is used in the analyses for the facilities in China. Since China produces 53% of global crude steel and 63% of global pig iron in 2019⁶ (as the base year of decarbonization analyses), this should considerably improve data quality and alleviate the impact of the assumption.

Furthermore, a comparative test is conducted to assess the impact. The direct CO₂ emissions of China's primary steel plants are estimated based on the assumption of consistent capacity utilization rate, and then compared with the results using real statistical data in 2019. Overall, in terms of direct CO₂ emissions, the relative differences are within $\pm 30\%$ for plants accounting for 68% of total emissions; in terms of emission intensity, the share also reaches 71%. For plant-level estimates, such differences are generally acceptably moderate (e.g., the uncertainties of country-level emissions always reach $\sim 15\%$). Further, when identifying targeted plants by the

indicator of emission intensity, 72% of targeted plants in China are overlapped in the two estimates (i.e., real statistics and consistent utilization) using the 50th percentile, with relative difference of mitigation potential of ~8% in China. Thus, it is reasonably reckoned that the effects of the assumption are acceptable when more reliable local data sources are not available.

Based on the assessments above, the assumption is conservatively used for emission accountings, to avoid introducing more complicated treatments and related uncertainties. If more reliable facility-level data outside China is available in the future, it can probably be incorporated to improve emission representativeness.

Energy intensity. The effect of capacity size on facility energy intensity is mainly considered because it is directly supported by some sectoral research^{10,33} as well as studies in other industries³⁴. Some other factors may also influence facility energy intensity but are hard to quantify, which is presented as a noteworthy limitation here.

Detailed technology can be an important factor, but unfortunately the availability of facility-level technical details hardly supports its inclusion in the current model. Taking blast furnaces as an example, the installation of Pulverized Coal Injection (PCI) system, design of charging system, waste heat recovery, and other technical details can play a role in the performance. But such detailed information is only available for a very small part of the facilities in GISD concentrated in developed countries, and it is also difficult to compile statistics or literature to support representing the differences of such detailed technologies. To include such consideration at this stage would bring more uncertainties that are hard to assess. Therefore, now the technological differences are only considered at more rough technical level (e.g., the differences between BF and DRI are considered). This is a limitation that will likely be improved as more facility-level technical information and statistics are available in the future.

Indirect emissions. The basic information in GISD only covers the facilities directly related to iron and steel making without records on onsite autoproducers or source and structure of electricity consumption. Therefore, to better represent indirect emissions, two carbon intensities of electricity are used and compared: (1) average carbon intensity of all types of electricity generation in the country (representing the cases that more proportions of clean power are consumed) and (2) average carbon intensity of fossil-fuel electricity generation in the country (representing the cases that only fossil fuels are consumed). The combination of the two intensities basically represents a range of indirect emissions. The inclusion of indirect emissions has been comprehensively analyzed in Supplementary Text 2, but some limitations are still clearly presented here.

First, autoproducers are generally less efficient than infrastructure connected to public power grid when they generate electricity from fossil fuels³⁵. Hence, even if the national average carbon intensity of fossil-fuel electricity generation is used, the indirect emissions from autoproducers may still be underestimated. Since there have been a few well-established plant- or unit-level databases for global power industry that include at least some captive power plants^{29,36}, they can probably be linked with GISD in the future, to identify the autoproducers onsite in the iron and steel plants to better represent plant-level indirect CO₂ emissions. Second, some accounting factors can probably be improved. For instance, the process-based electricity intensity is consistent worldwide, which can be replaced with e.g. region- or country-specific

values when more detailed information is available.

Minor sources. Direct CO₂ emissions from fossil fuels and indirect CO₂ emissions from electricity consumption are estimated and used in analyses. But some minor sources in iron and steel industry are not included now. For example, some process emissions that arise from limestone uses are not considered; the CO₂ emissions from chemical reaction between carbon in iron and oxygen in BOF are not systematically included but are likely partly captured by the methodology (i.e. combustion of BOF off-gases in iron and steel industry is included). Such sources are hard to quantify at plant- or facility-specific level, but only account for a very small part of CO₂ emissions from iron and steel industry². It is reasonably reckoned that their impact should be very limited on the main analyses and finding in this study.

Other potential limitations and expected improvements

Our study is also subject to several additional uncertainties and limitations, and some of them are expected to be fully or partly overcome in the future. First, although we have tried our best to collect related information, the GISD database might be still incomplete given the tremendous amount of detailed information. We compared the facility information of China in the MCI database with the CISC, and found that many small plants and pretreatment plants were missing, suggesting that MCI may have also omitted small plants in other regions especially the developing countries. Second, facility-level CO₂ emission measurements are scarce, hampering our ability to cross-check and validate our estimates; we will continue to pursue such data for comparison and thereby improve data quality. Regardless of these considerations, the database we have compiled and made freely- and publicly-available (GISD version 1.0 at <http://gidmodel.org.cn/>) provides estimates of unprecedented detail into the global iron and steel industry, which can strongly support sector-specific targeted mitigation policies. The GISD database and related data products will be maintained and updated regularly in the future to improve the estimate accuracy, extend the temporal coverage, and cover more aspects of emissions.

Supplementary Text 8. Methodological supplementary information

Facility-level energy intensity treatment

In this study, we consider the differences of energy intensity ($e_{i,m}$) between large and small facilities when deriving facility-level fuel consumption (see equation (3) in *Methods* Section). It has been demonstrated by previous studies that facilities with larger capacity generally have lower energy intensity in power and industrial sectors^{29,33,34}. Here the process-based facilities in each country were classified into several groups, i.e. mini, small, medium, large, and super-large groups. The facilities are first sorted ascendingly by capacity and then separated by 20%, 40%, 60%, and 80% of cumulative capacity (In this way, the median facility that crosses the 50% threshold of total capacity must be in the medium group). The country-level process-based energy intensity can be directly derived from process-based fuel consumption obtained in equation (2) and process-based production for each country, and then it is assumed that the medium-size facilities had the same intensity level as country-level energy intensity. The energy intensities of other capacity groups were further distinguished based on the facility-level intensity statistics collected and compiled from previous studies (see Supplementary Table 4; some facility-level CO₂ emission intensity data was also included here due to data availability to improve data representativeness). Generally we could only obtain the ranges (i.e. minimum and maximum) of facility-level intensity rather than piecewise values, and thus linear interpolation was applied to derive the relative differences among all the groups. Based on the intensity of the medium-size group, the energy intensities of all the size groups can then be obtained by using the relative differences. The results show that significant capacity effect exist in terms of facility intensity. For instance, the energy intensity difference between mini- and super-large-size facilities can be over 50% in some processes. The above method may underestimate or overestimate facility differences due to scarce data and has large uncertainty at facility level, so we also conduct uncertainty analysis with comprehensive discussions on facility-level uncertainties as shown in Supplementary Text 7. More efforts will be made to collect more capacity-dependent facility data to improve the method in the future (e.g. to build a fitting curve when data points are statistically enough).

Drivers decomposition

We quantified the contributions from three drivers to the CO₂ emission changes at global and regional scale, including production growth, technology shifts reflected by primary and secondary steelmaking proportions, and energy intensity (energy efficiency) here. In this study, the logarithmic mean Divisia index (LMDI) method was used for driver decomposition^{37,38}. The LMDI method gives perfect decomposition without residual term, and the decomposition results follow simple additive property. It has been widely applied in previous studies to analyze the emission drivers of different sectors at different scales³⁹⁻⁴¹.

The components are decomposed as shown by equation (1)-(4) below:

$$\Delta E = E^T - E^0 = \Delta E_P + \Delta E_S + \Delta E_I \quad (1)$$

$$\Delta E_P = \sum_i \frac{E_i^T - E_i^0}{\ln E_i^T - \ln E_i^0} \ln \frac{P^T}{P^0} \quad (2)$$

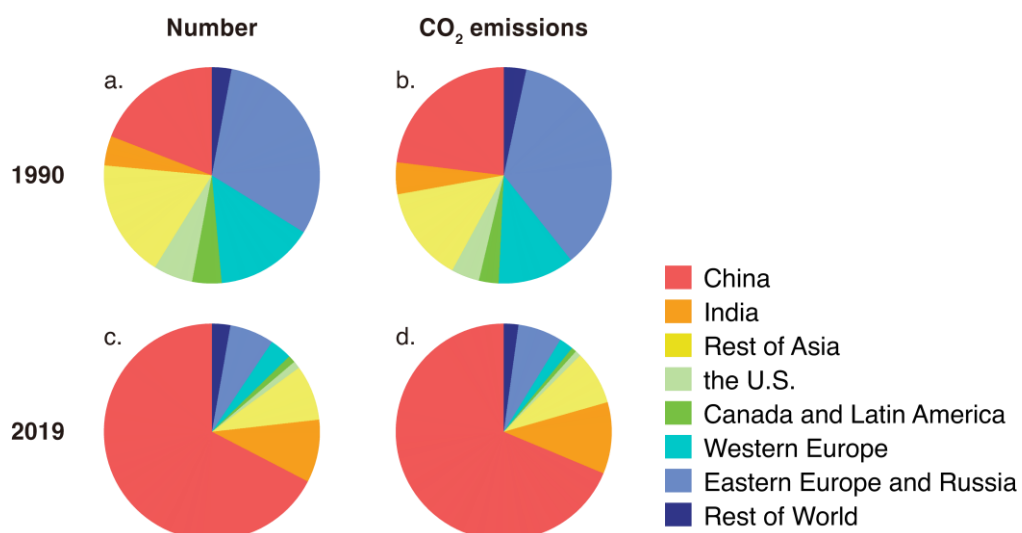
$$\Delta E_S = \sum_i \frac{E_i^T - E_i^0}{\ln E_i^T - \ln E_i^0} \ln \frac{S_i^T}{S_i^0} \quad (3)$$

$$\Delta E_I = \sum_i \frac{E_i^T - E_i^0}{\ln E_i^T - \ln E_i^0} \ln \frac{I_i^T}{I_i^0} \quad (4)$$

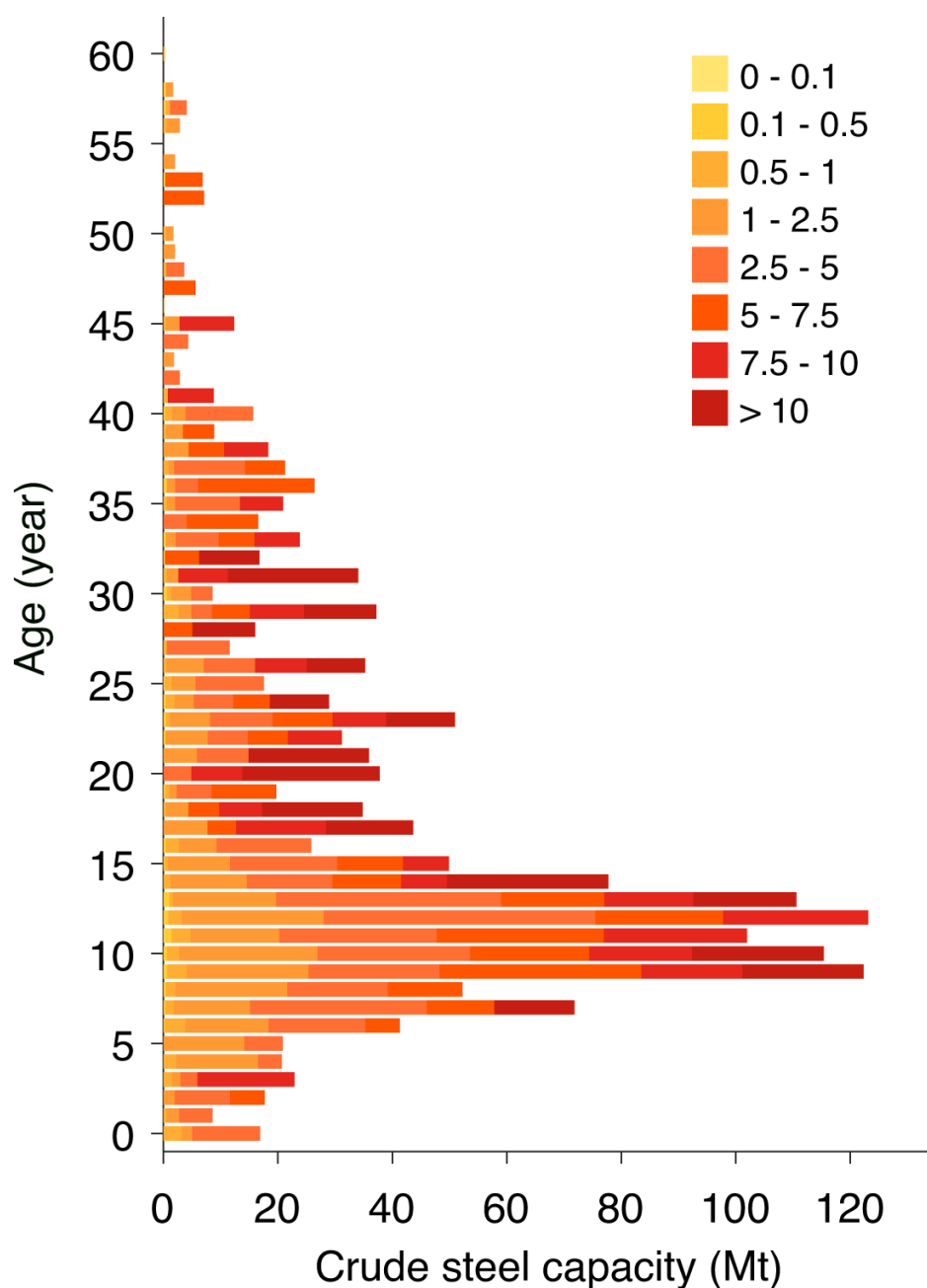
where i represents primary or secondary steelmaking route; 0 and T represent the first and last year of a period; E represents CO₂ emissions; ΔE_P , ΔE_S , and ΔE_I represent emission drivers of production growth, production route shift, and efficiency improvement, respectively; P , S , and I represent crude steel production, shares of primary or secondary steelmaking routes, and emission intensity of primary or secondary steelmaking routes, respectively.

Uncertainty analysis

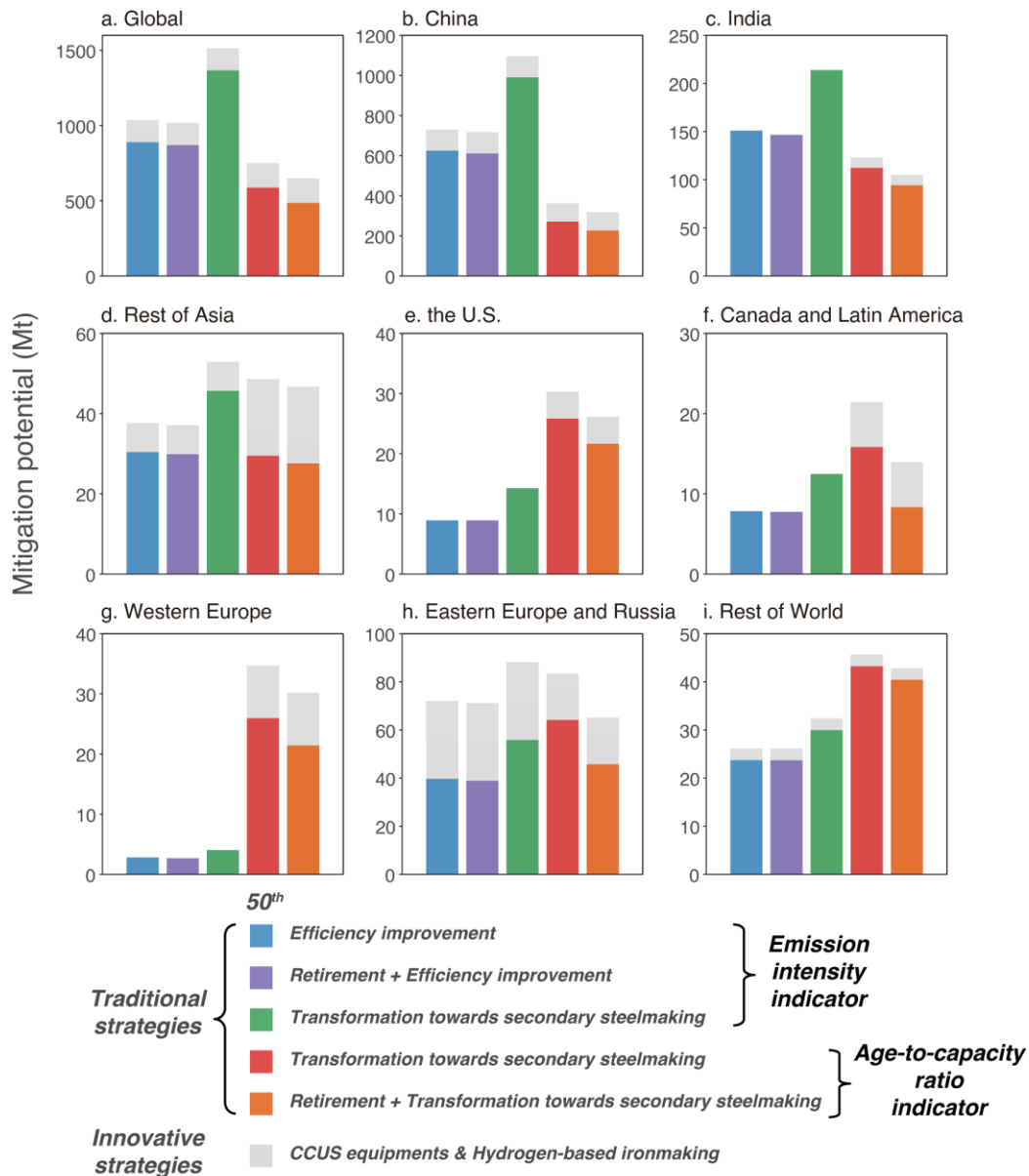
We performed uncertainty analysis for the emission estimates at country and plant/facility level based on a Monte Carlo approach, following the methodology applied on power and cement sectors in previous studies^{29,30}. The uncertainty range was calculated by the 95% confidential interval (CI) around the central estimate from 10,000 Monte Carlo tests with specific probability distributions of input parameters including activity rates (fuel consumption) and emission factors. The probability distributions of the parameters were obtained from previous studies as shown in Supplementary Table 10. For facility-level uncertainties, the probability distributions of some parameters were different from national level estimates as listed in Supplementary Table 10 as well. We analyzed the emission uncertainty of global iron and steel industry, individual countries, and representative plants/facilities in each process and route (See Supplementary Text 10 for more details).



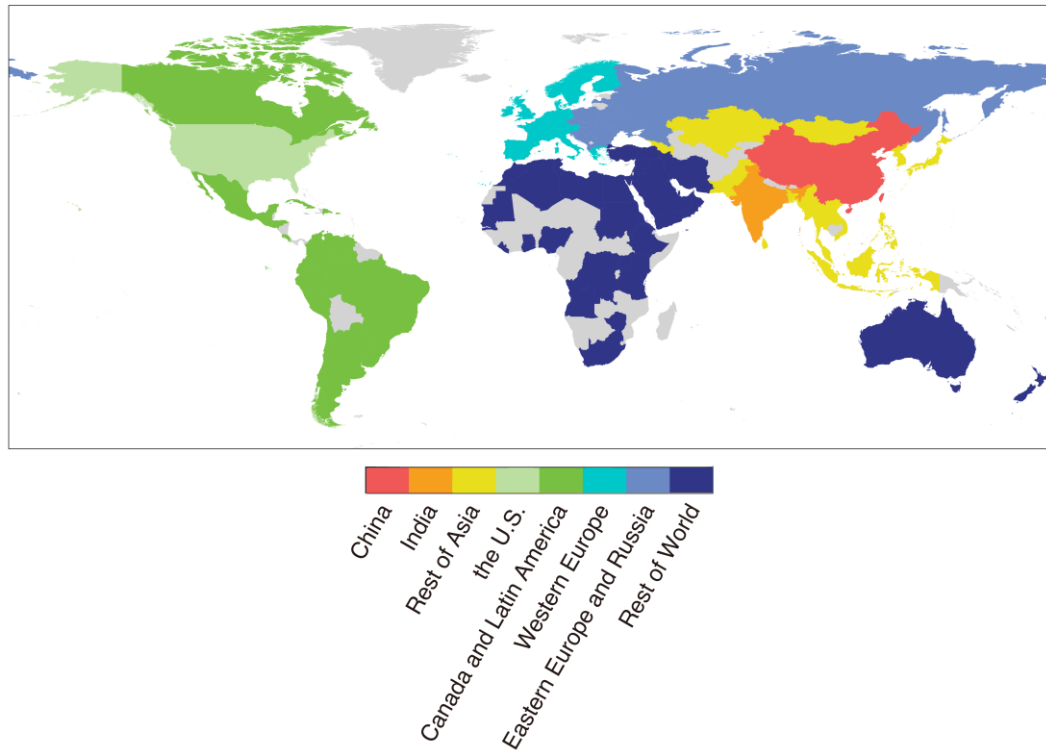
Supplementary Figure 1 | The shares of direct CO₂ emission hotspots (plants with CO₂ emissions $\geq 5,000$ kt) by region. The left and right columns show the shares of number and CO₂ emissions in 1990 (top panel) and 2019 (bottom panel), respectively.



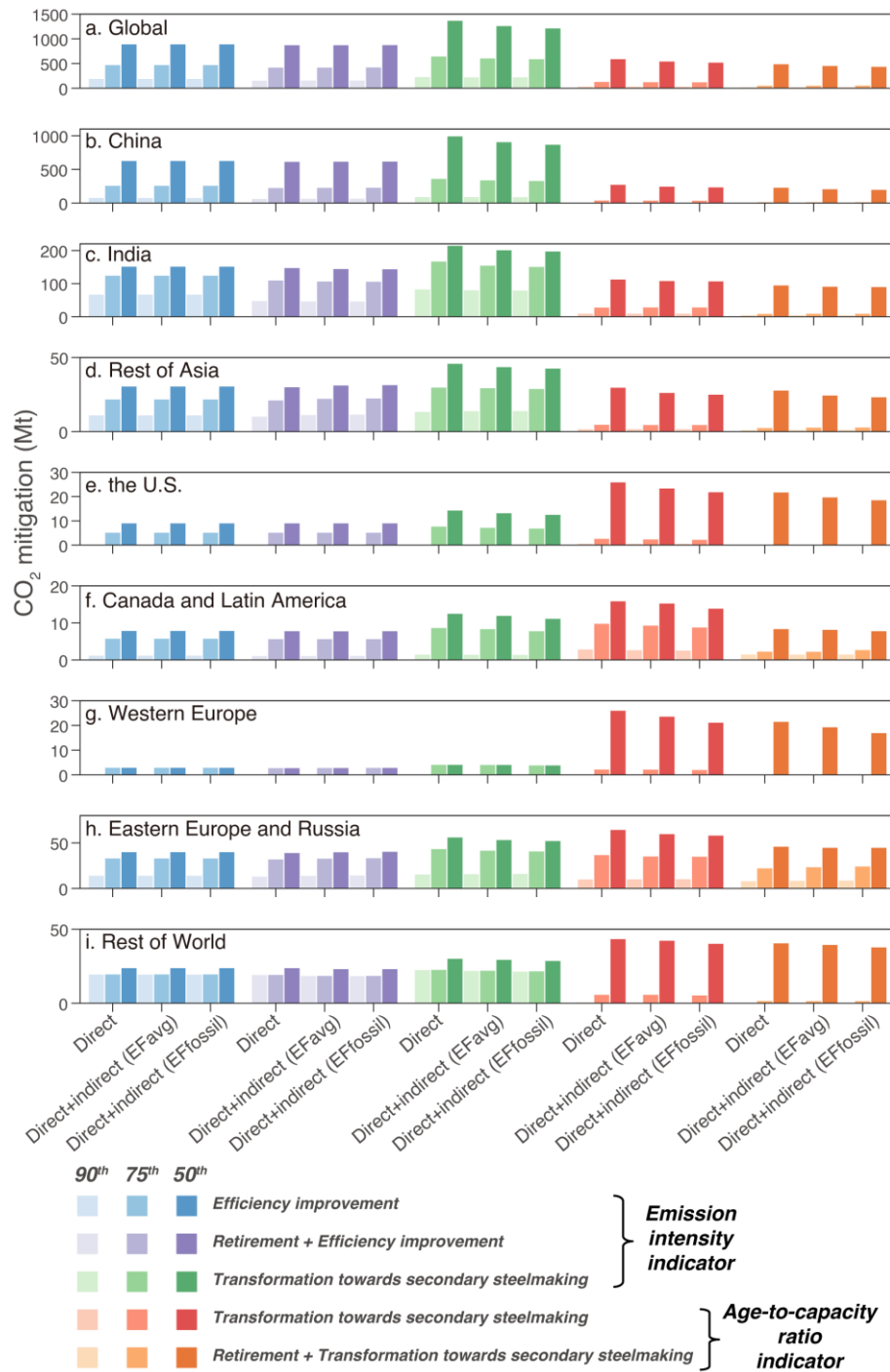
Supplementary Figure 2 | The capacity demographics (i.e., capacity composition by age and capacity size) of primary steelmaking plants in 2019. The y-axis labels represent the intervals between operating year and 2019, and 0 year indicates that the plant starts operating in 2019. The bars are accumulated by group of plant capacity size. The introduction to demographics can be found in previous literature⁴².



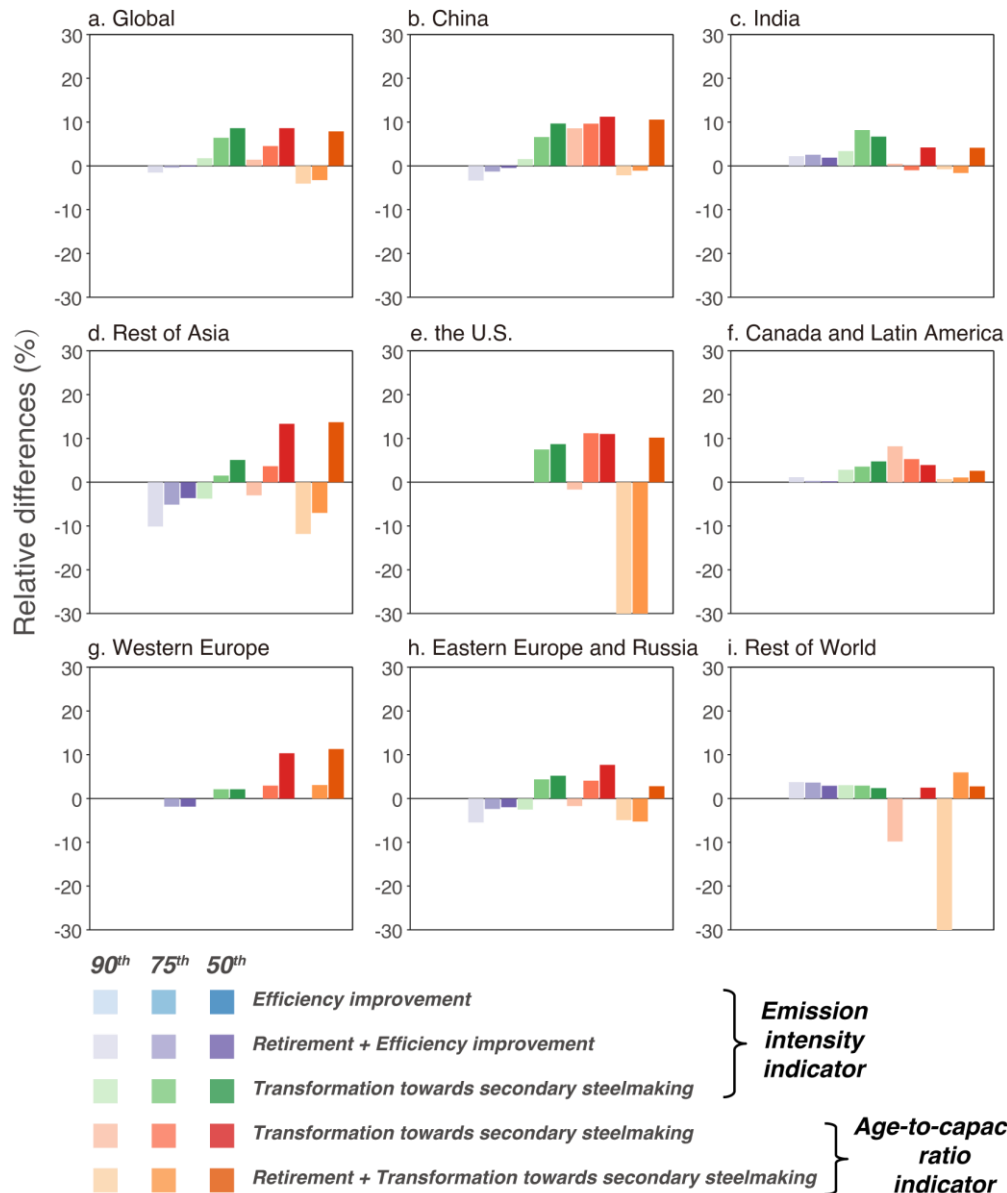
Supplementary Figure 3 | Effects on mitigation potential if innovative technologies are further applied. The bars show the mitigation potential of traditional strategies when the 50th percentiles of emission intensity and age-to-capacity ratio indicators are used to identify the targeted plants (blue, purple, green, red, and orange bars) as well as the mitigation potential when innovative strategies are further applied beyond the 50th percentiles (grey bars). The projected production scale of innovative technologies (i.e., production equipped with CCUS and hydrogen-based ironmaking) is obtained from IEA Net Zero Scenario (i.e., the production in 2030)²⁷, and a number of plants are identified according to the rankings by the indicators beyond the 50th percentiles to be applied with innovative technologies for further decarbonization.



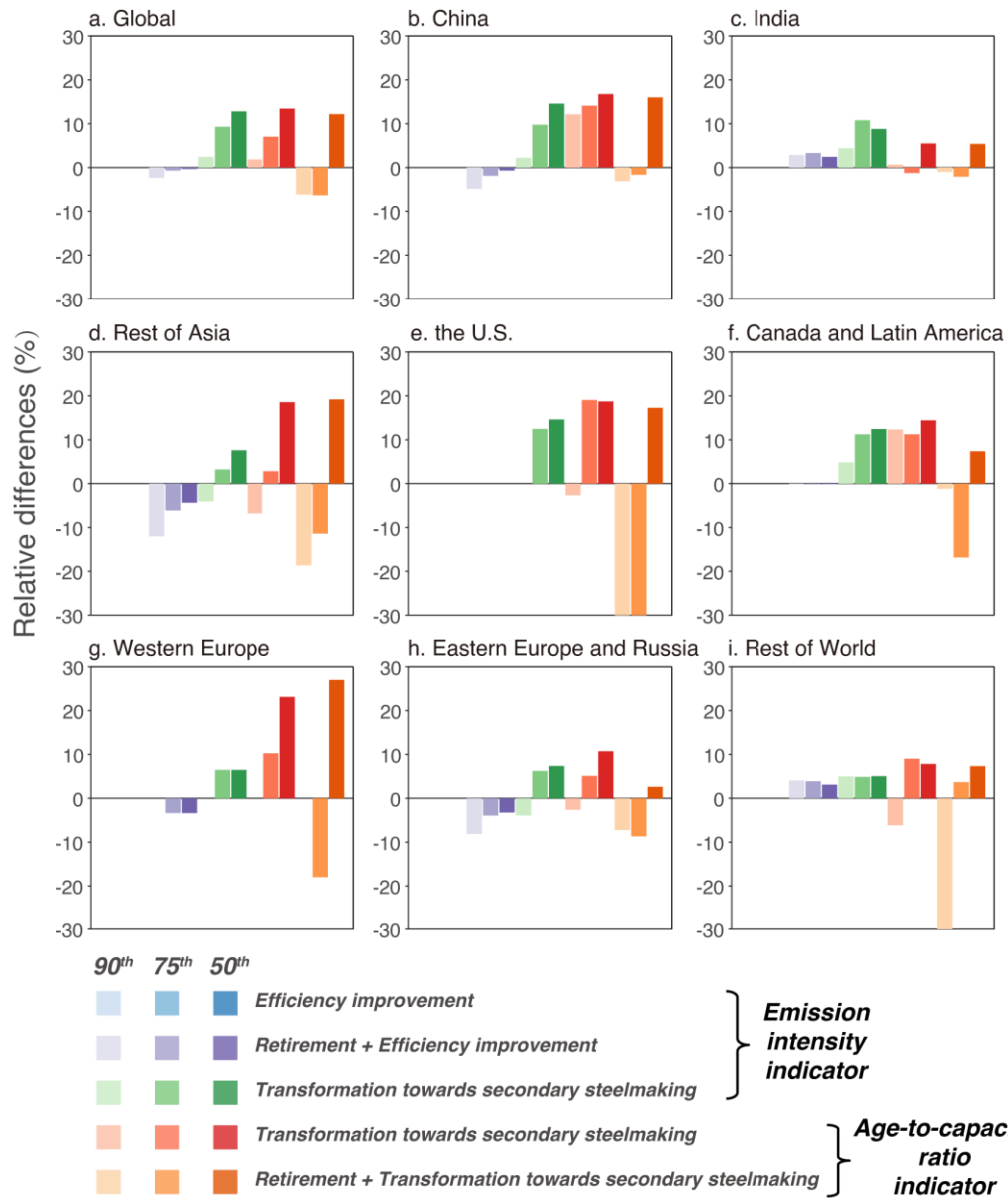
Supplementary Figure 4 | Maps of regions in this study. All countries are divided into eight regions.



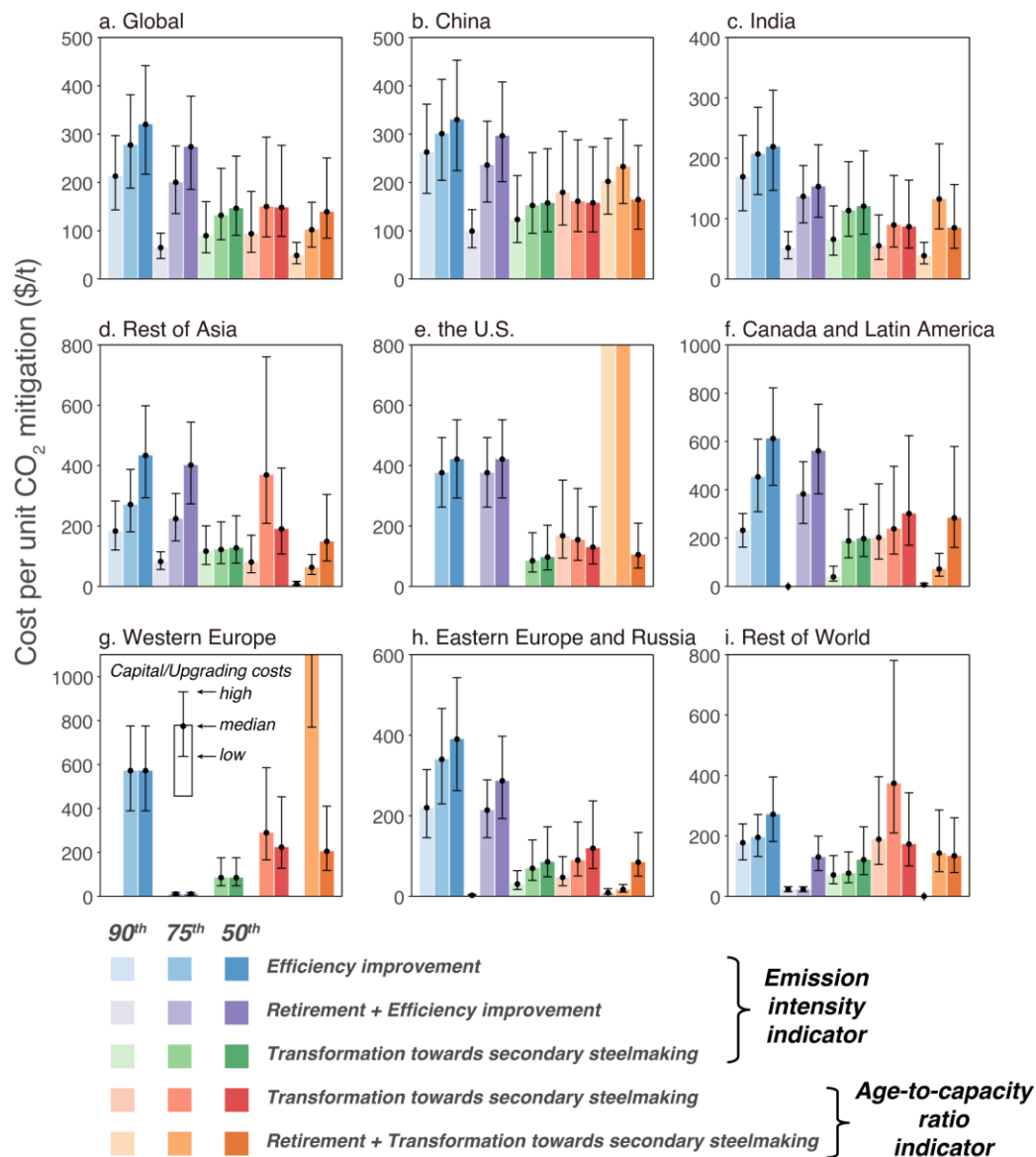
Supplementary Figure 5 | Sensitivity test of CO₂ mitigation potential for indirect CO₂ emissions. The CO₂ mitigation potential with different quantiles of indicators (age-to-capacity ratio and emission intensity) and mitigation strategies is shown when indirect CO₂ emissions (estimated using carbon intensities derived from all types of electricity generation (EF_{avg}) and fossil-fuel electricity generation (EF_{fossil}), respectively) are included in the analyses, to compare with the case when only direct emissions are considered as shown in Fig. 4.



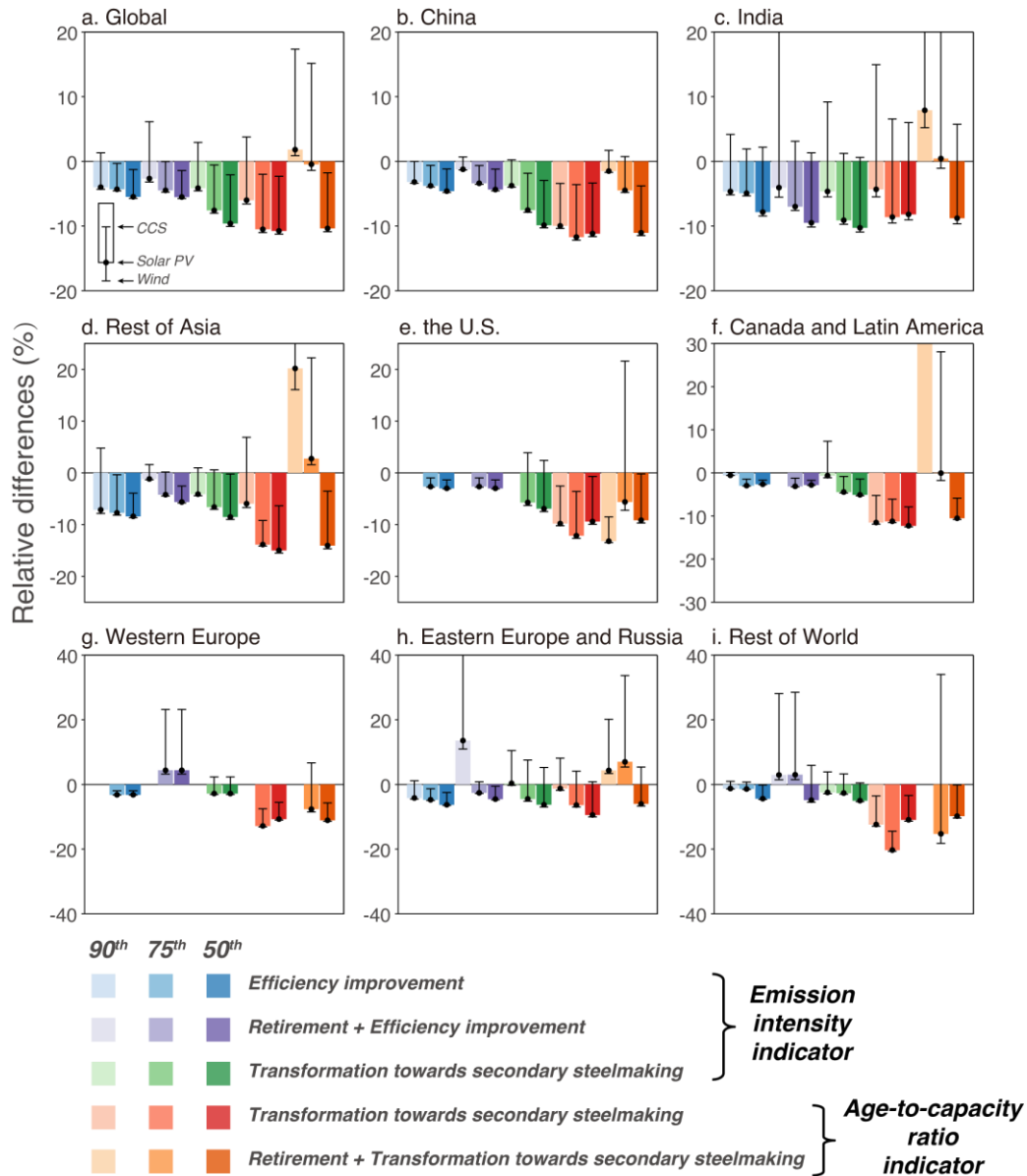
Supplementary Figure 6 | Sensitivity test for cost effectiveness if indirect CO₂ emissions are considered. The same as Fig. 4 but shows the relative differences of CO₂ mitigation potential per unit cost between the case in which indirect CO₂ emissions are included and the case in which only direct CO₂ emissions are considered. Here indirect CO₂ emissions are estimated using carbon intensities derived from all types of electricity generation (EF_{avg}).



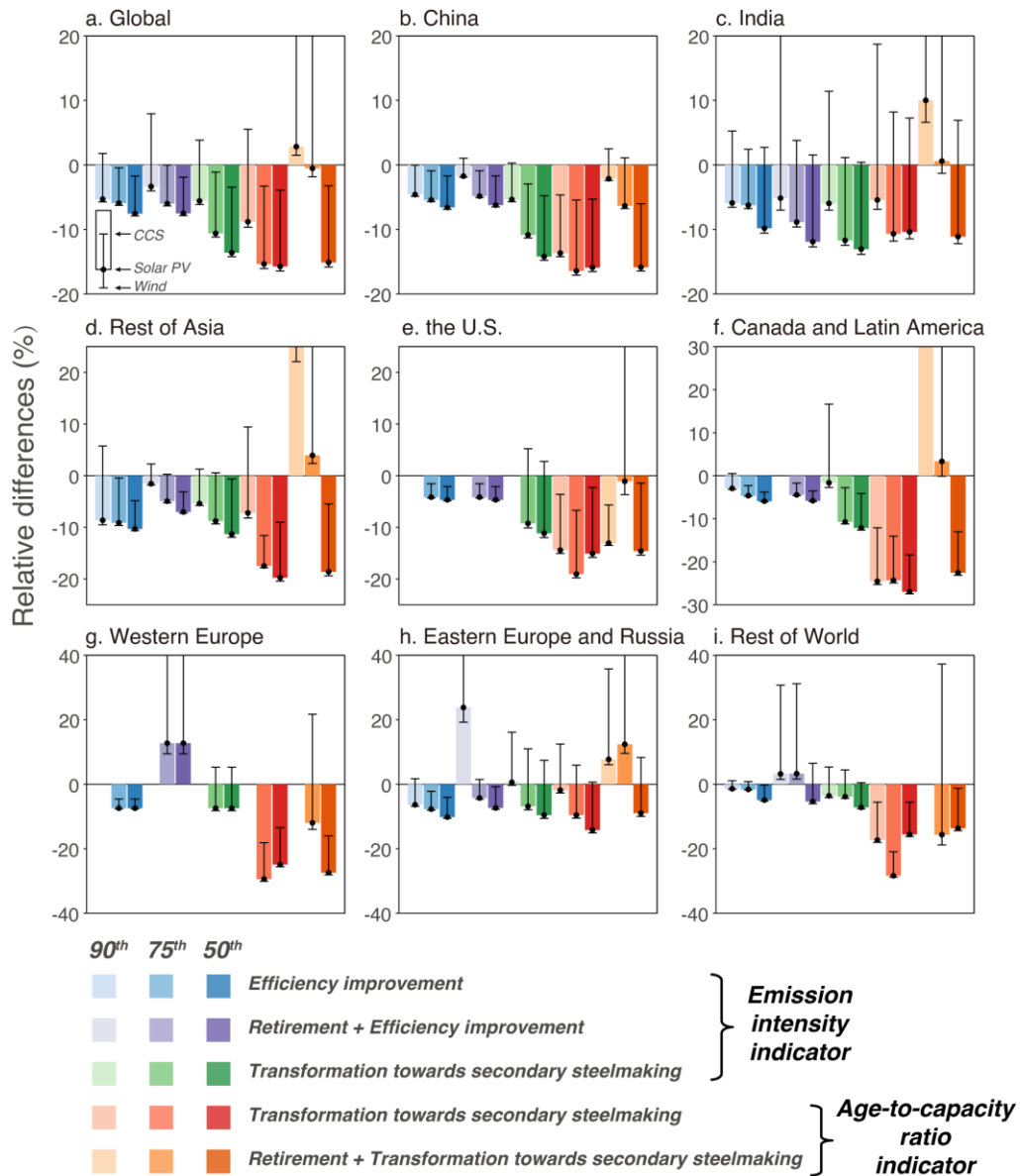
Supplementary Figure 7 | Sensitivity test for cost effectiveness if indirect CO₂ emissions are considered. The same as Supplementary Figure 6 but here indirect CO₂ emissions are estimated using carbon intensities derived from fossil-fuel electricity generation (EF_{fossil}).



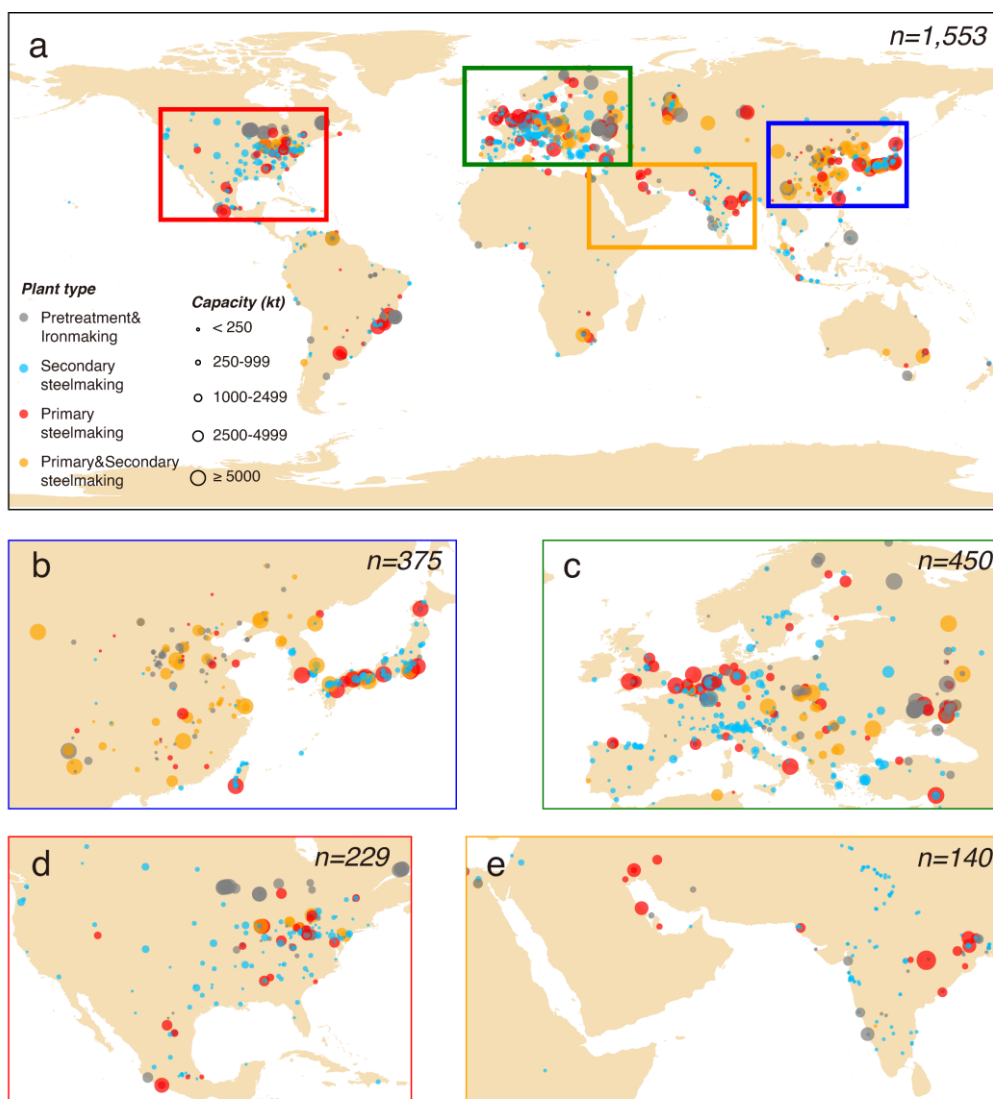
Supplementary Figure 8 | Sensitivity test for cost effectiveness if upgrading costs are assumed higher. The same as Fig.4 but here upgrading costs are assumed to be the same as capital costs as shown in Supplementary Table 6.



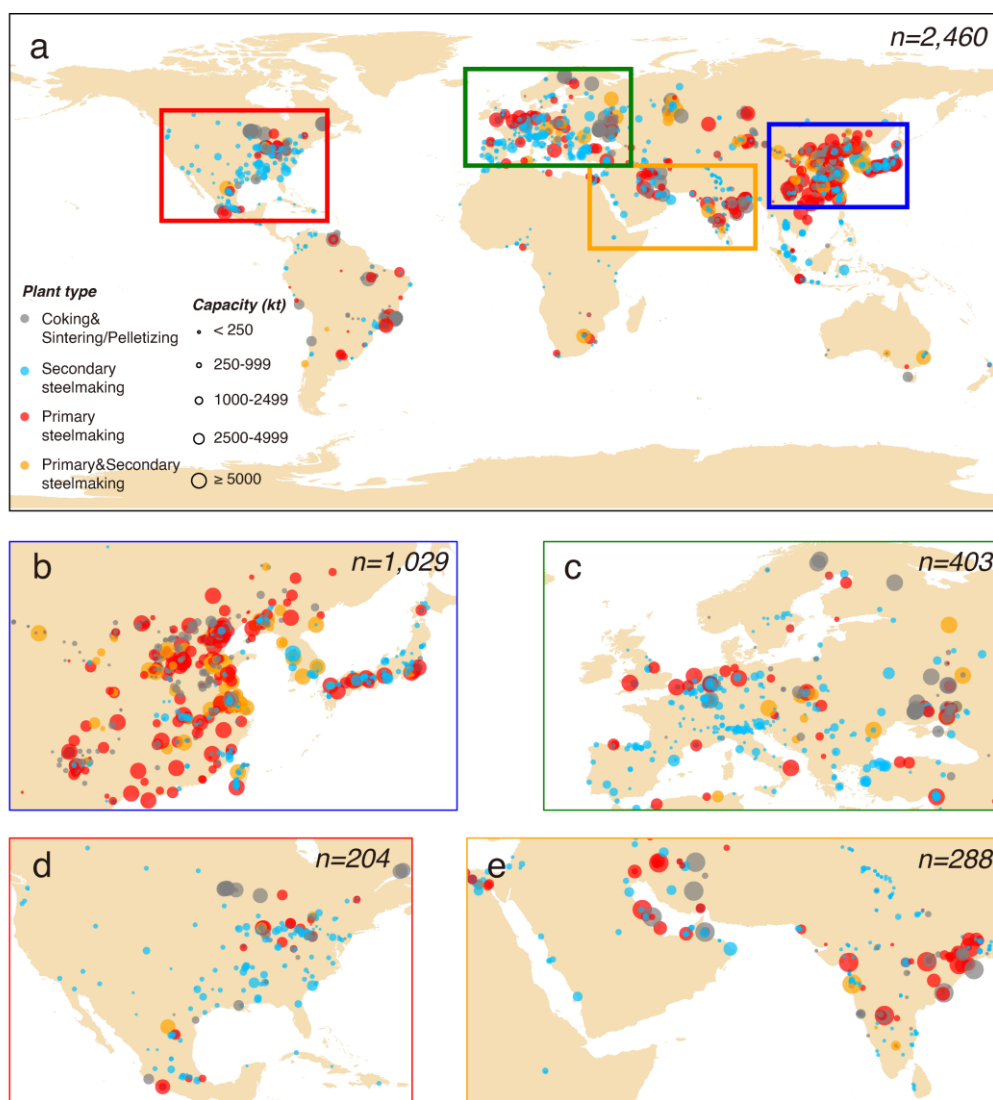
Supplementary Figure 9 | Sensitivity test for cost effectiveness if indirect CO₂ emissions are further decarbonized by wind power, solar PV, or CCS. The same as Fig. 4 but shows the relative differences of costs per unit CO₂ mitigation potential between the case in which indirect CO₂ emissions are included and decarbonized and the case in which indirect CO₂ emissions are included but not decarbonized. The errorbars show the ranges determined by different decarbonization technology (the centers represent the case where solar PV is used for decarbonization and the whiskers represent the cases where wind power and CCS are used, respectively). Here indirect CO₂ emissions are estimated using carbon intensities derived from all types of electricity generation (EF_{avg}).



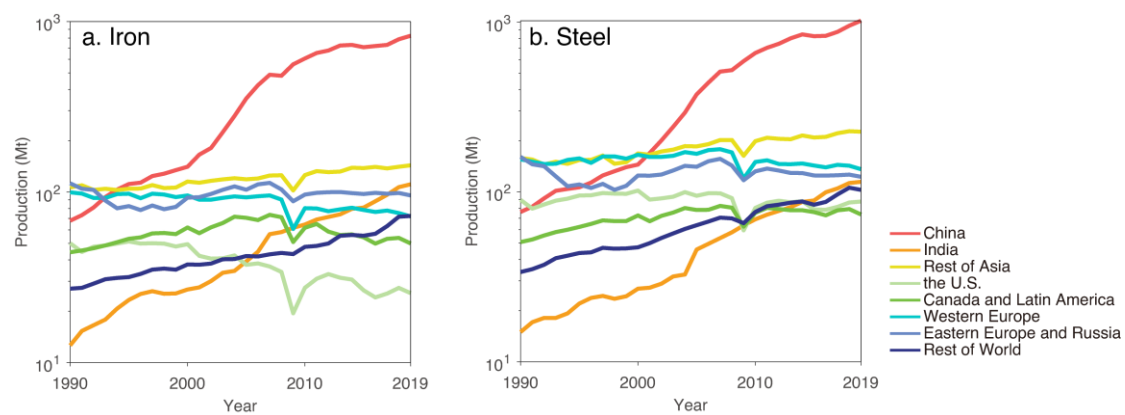
Supplementary Figure 10 | Sensitivity test for cost effectiveness if indirect CO₂ emissions are further decarbonized by wind power, solar PV, or CCS. The same as Supplementary Fig. 9 but here indirect CO₂ emissions are estimated using carbon intensities derived from all types of electricity generation (EF_{fossil}).



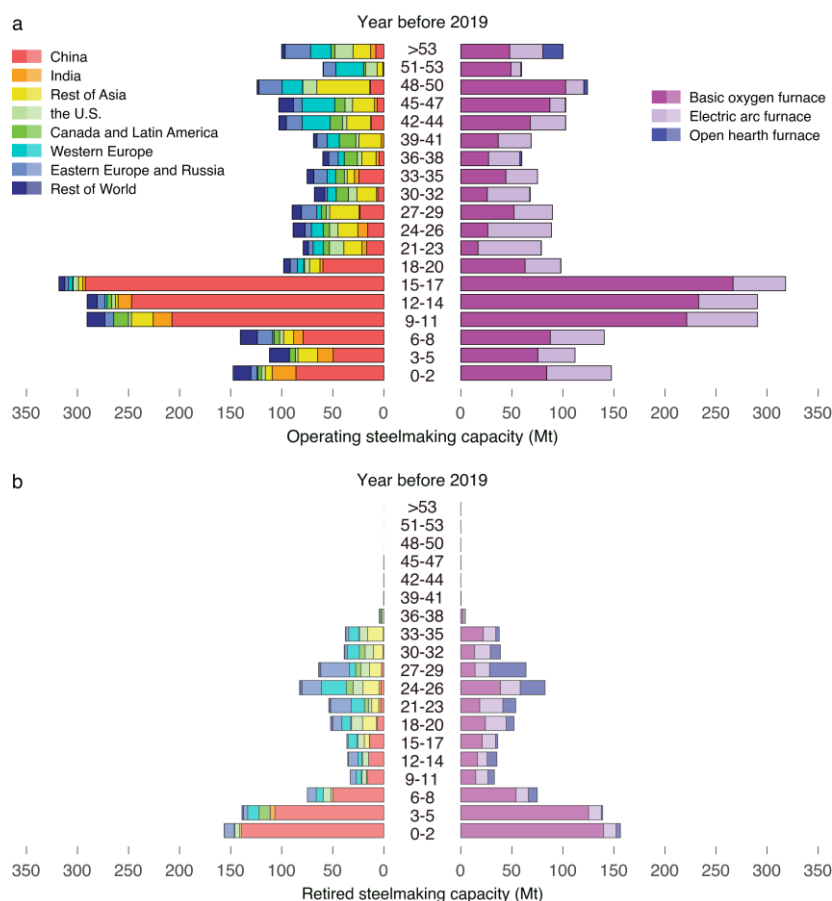
Supplementary Figure 11 | Maps of iron and steel plants worldwide in 1990. Location, plant type, and capacity of operating plants (a) globally, in (b) East Asia, (c) Europe (d) North America, and (e) South Asian Subcontinent and the Middle East. The plants are classified by capacities (<250 kt, 250-999 kt, 1,000-2,499 kt, 2,500-4,999 kt, and ≥ 5,000 kt) and production types. The plant types are defined in Supplementary Table 2.



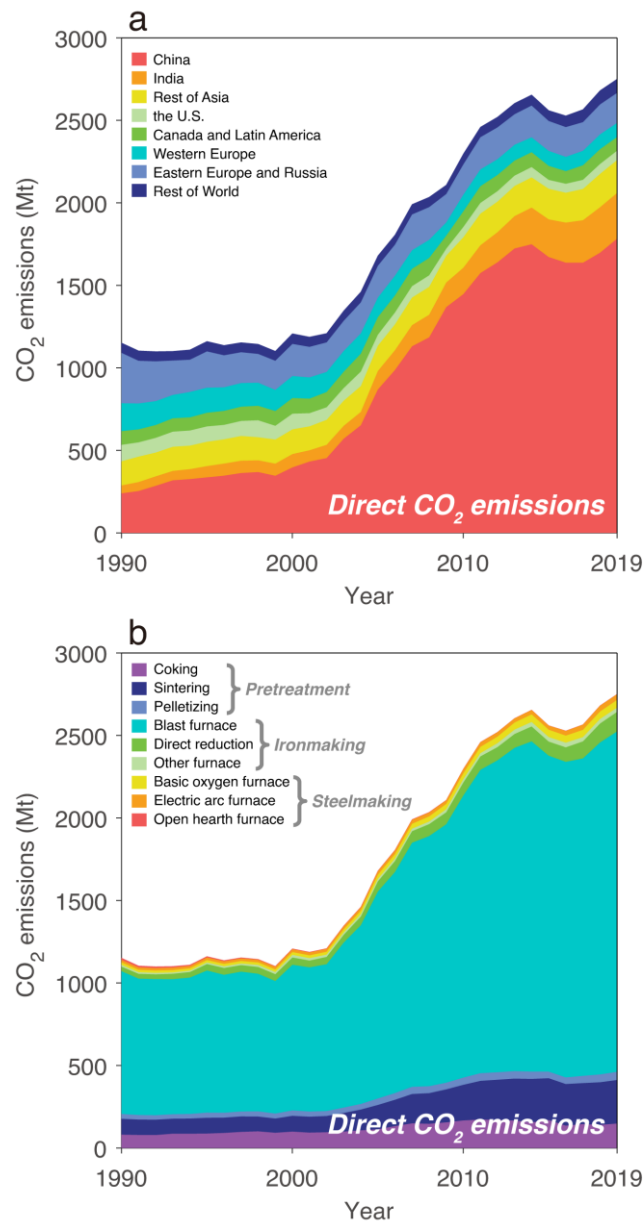
Supplementary Figure 12 | Maps of iron and steel plants worldwide in 2019. The same as Supplementary Figure 11 but for the operating plants in 2019.



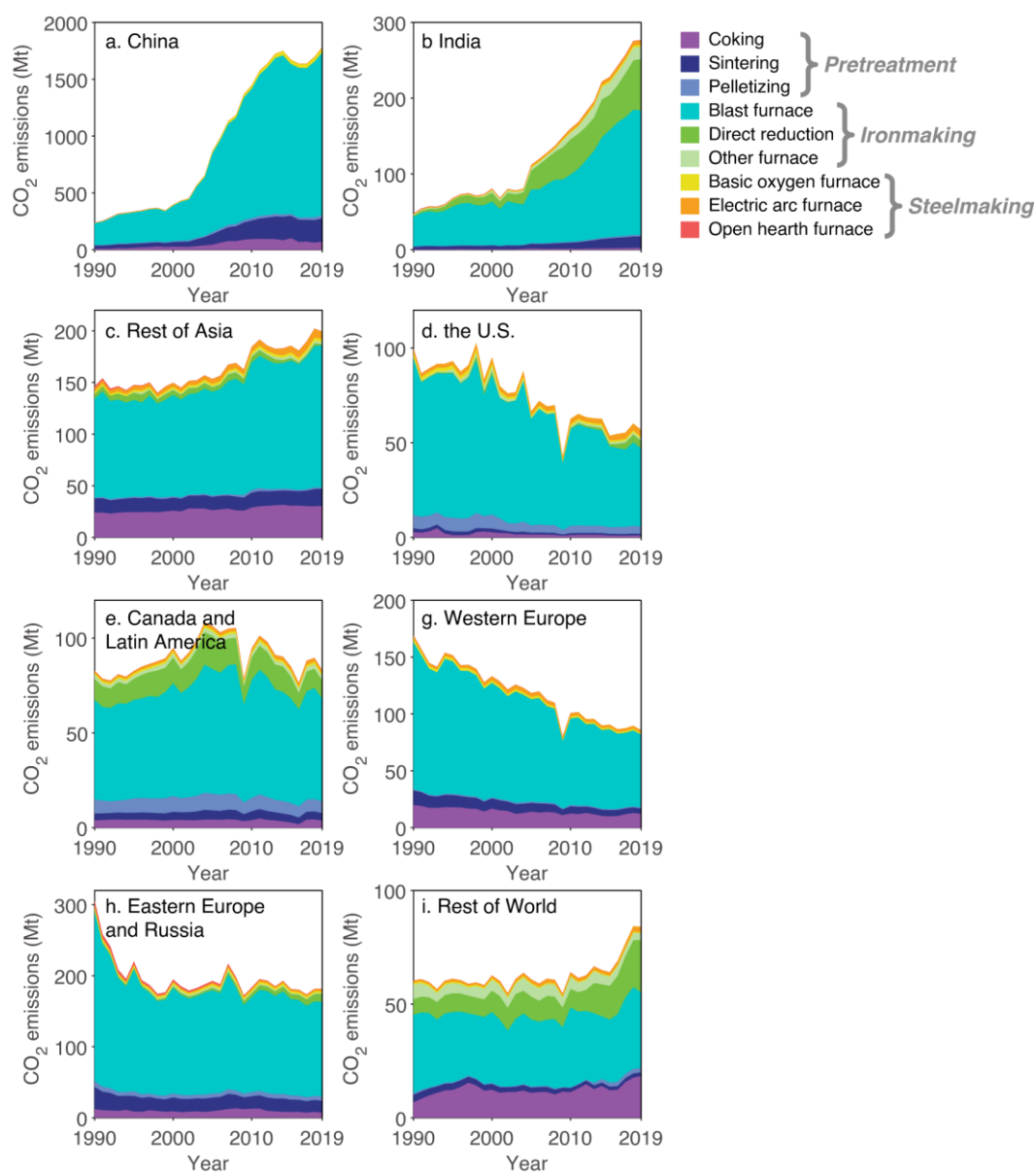
Supplementary Figure 13 | Historic production of global iron and steel industry.
Production of (a) iron and (b) steel by region from 1990 to 2019.



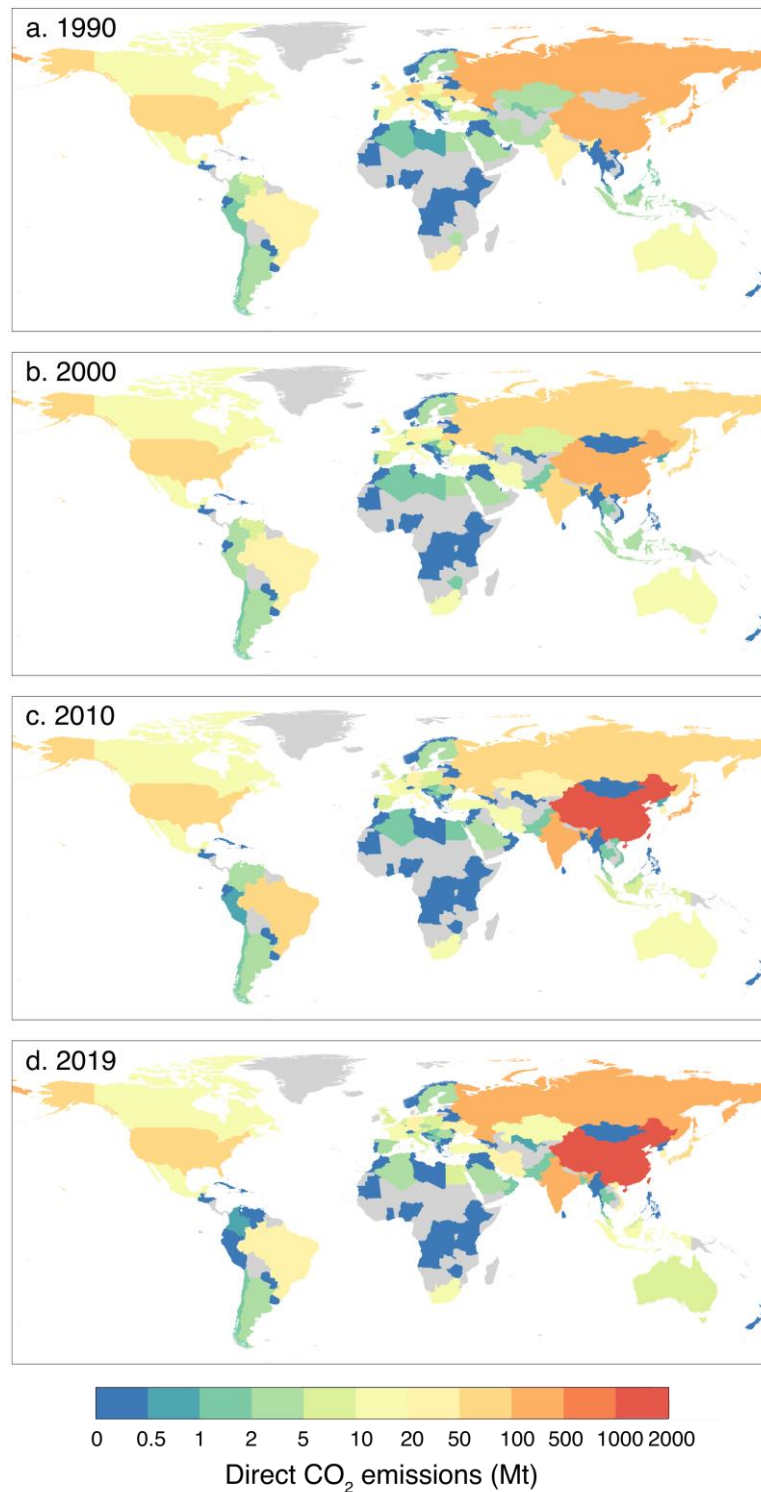
Supplementary Figure 14 | Operating- and retired-year distributions of global steelmaking capacity. The (a) operating- and (b) retired-year distribution of steelmaking capacity as of 2019 by region and steelmaking furnace type. The youngest existing facilities and the most recent retired facilities are at the bottom. The y-axis labels represent the intervals between operating/retired year and 2019, and 0 year indicates that the facility starts operating or is retired in 2019.



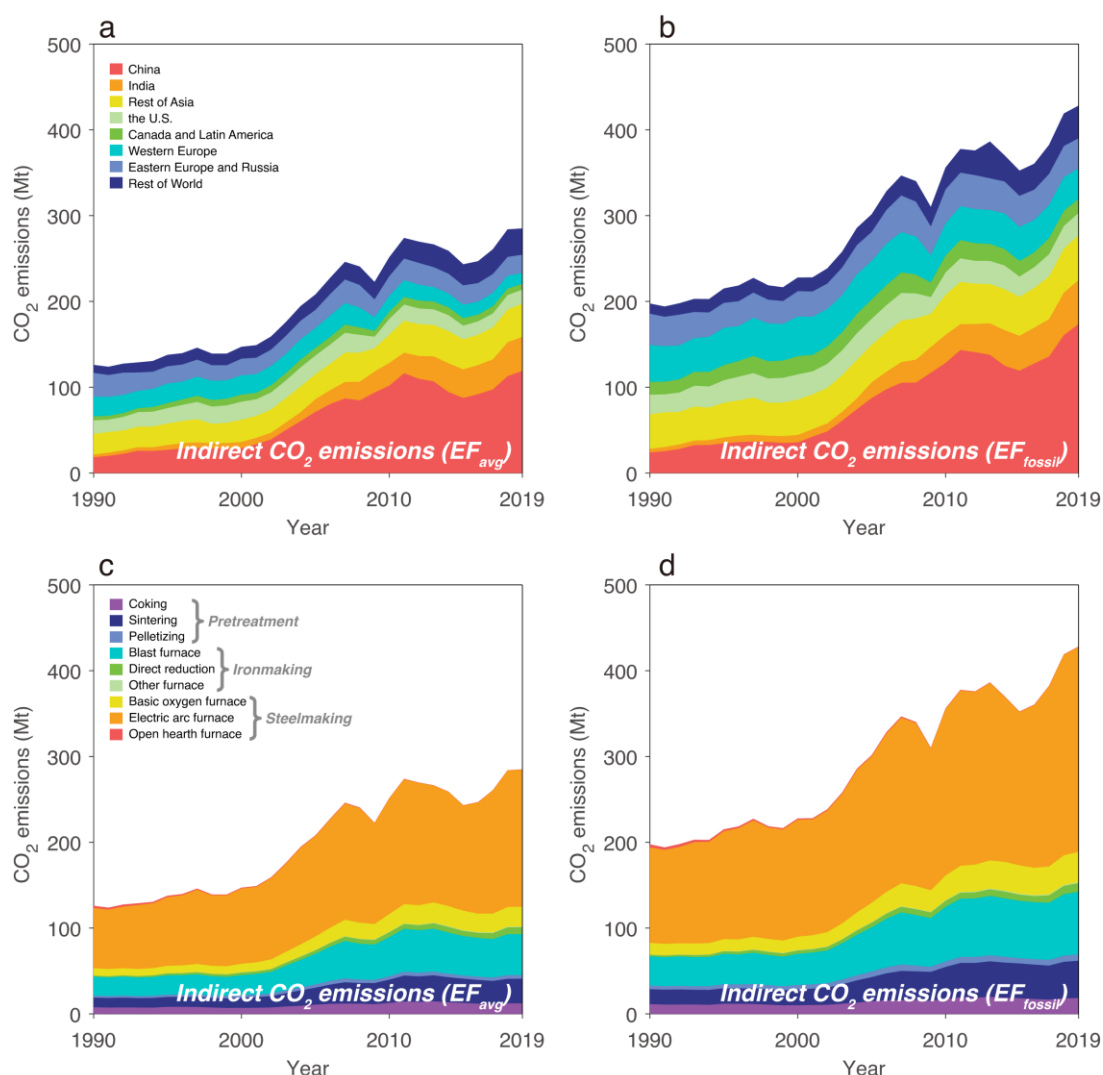
Supplementary Figure 15 | Annual direct CO₂ emissions from global iron and steel industry. The annual CO₂ emissions by (a) region and (b) process from 1990-2019. Other furnace of ironmaking corresponds to e.g. direct smelting by Corex technology.



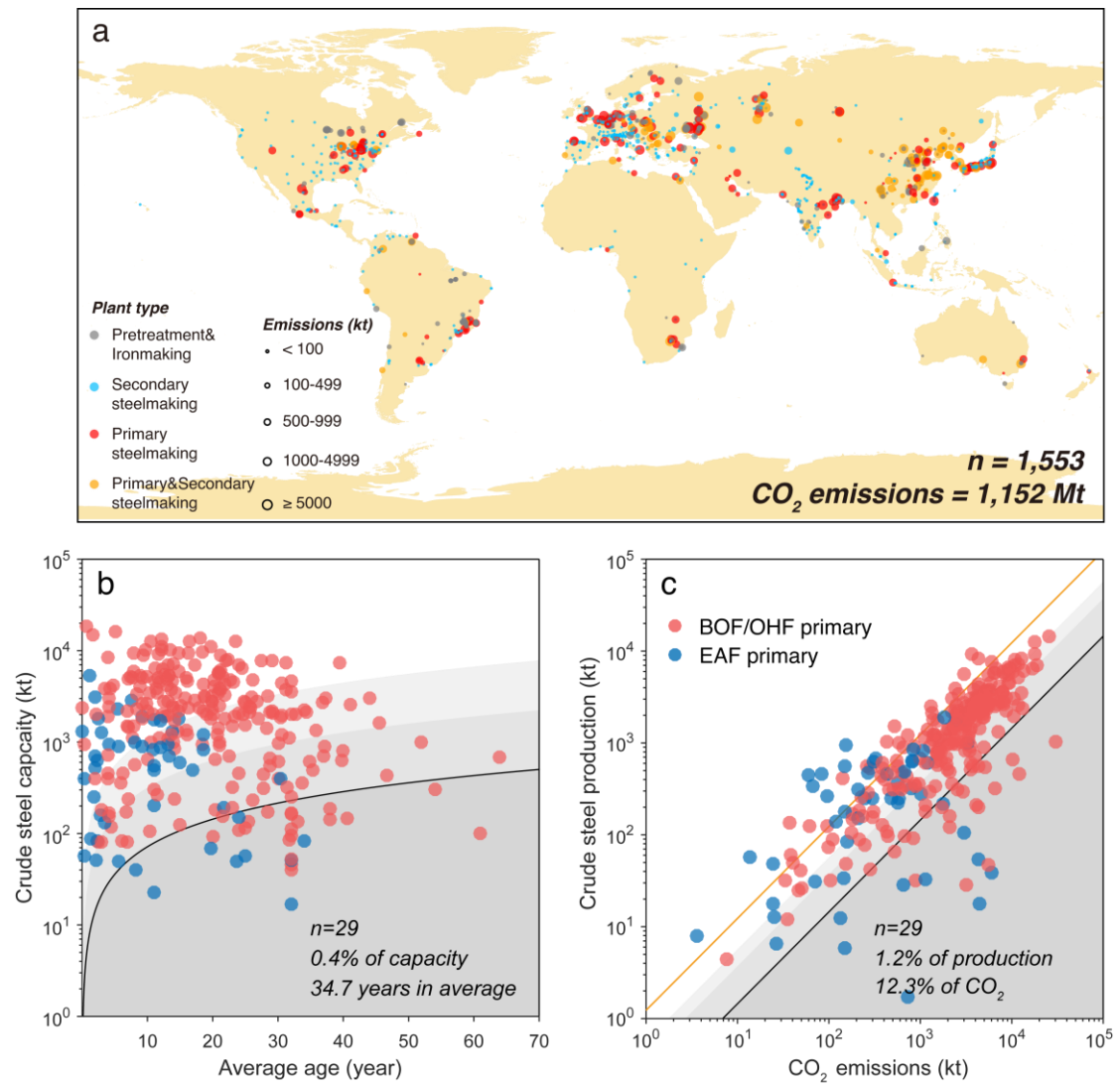
Supplementary Figure 16 | Annual direct CO₂ emissions from iron and steel industry by region. The annual CO₂ emissions by region from 1990-2019.



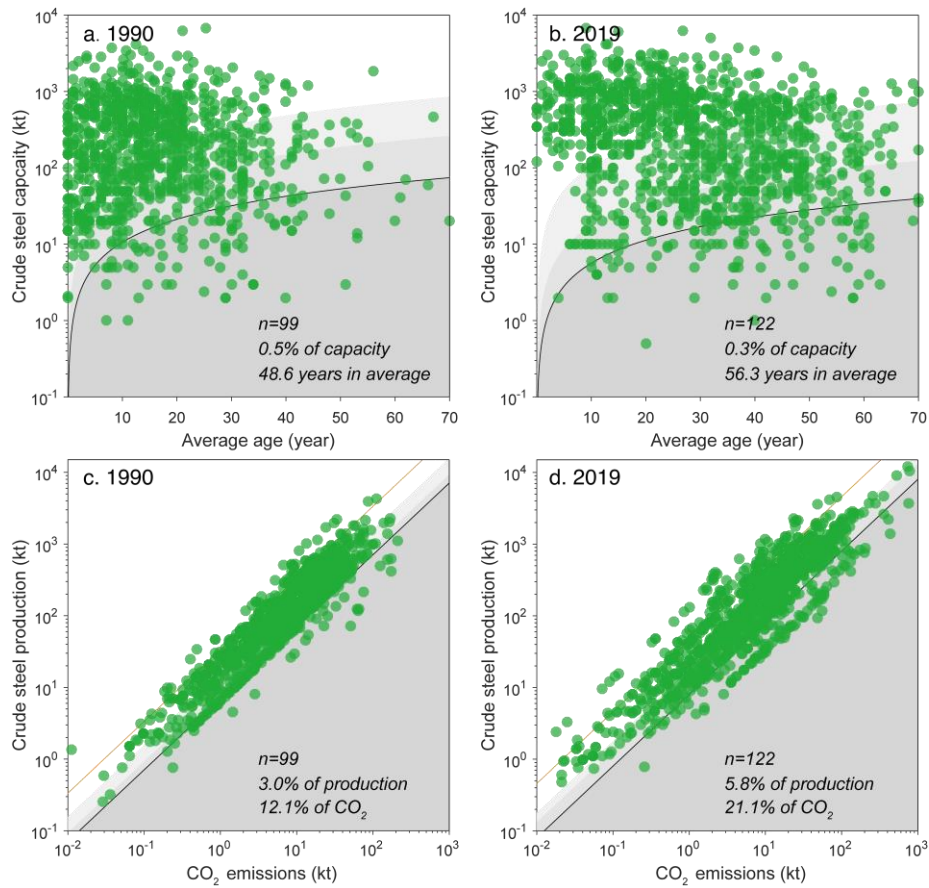
Supplementary Figure 17 | Maps of direct CO₂ emissions from global iron and steel industry. Direct CO₂ emissions maps of each country or region in (a) 1990, (b) 2000, (c) 2010, and (d) 2019.



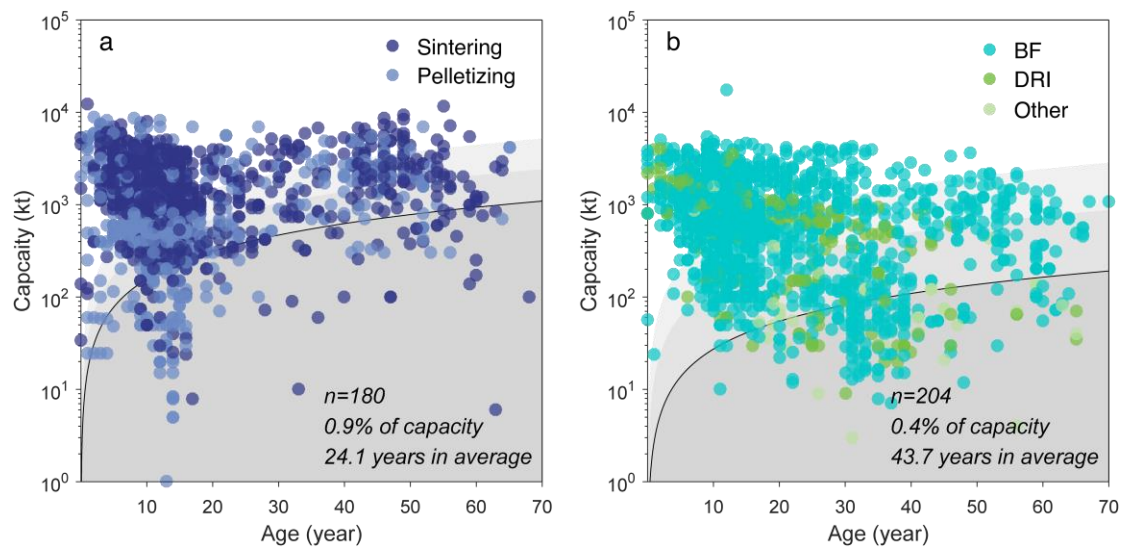
Supplementary Figure 18 | Annual indirect CO₂ emissions from global iron and steel industry. The annual CO₂ emissions by region (top panel) and process (bottom panel) from 1990-2019. The left and right columns show the estimates using carbon intensities derived from all types of electricity generation (EF_{avg}) and fossil-fuel electricity generation (EF_{fossil}), respectively (See *Indirect emission accountings* in *Methods* Section for details of indirect emission estimates).



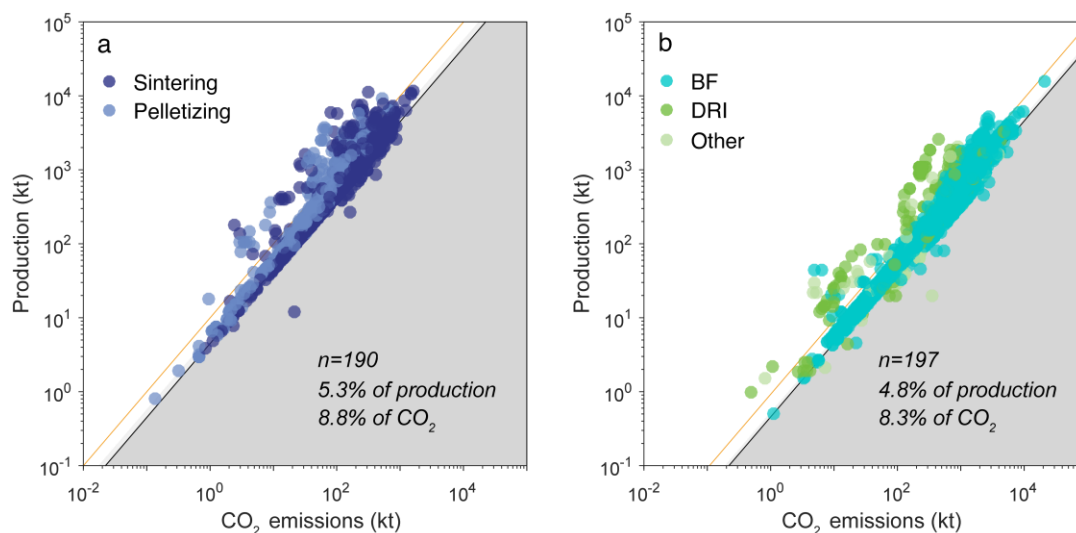
Supplementary Figure 19 | Maps of direct CO₂ emissions from iron and steel plants worldwide and disproportionalities of age-to-capacity ratio and emission intensity of primary steelmaking plants in 1990. The same as Fig. 1 but for 1990.



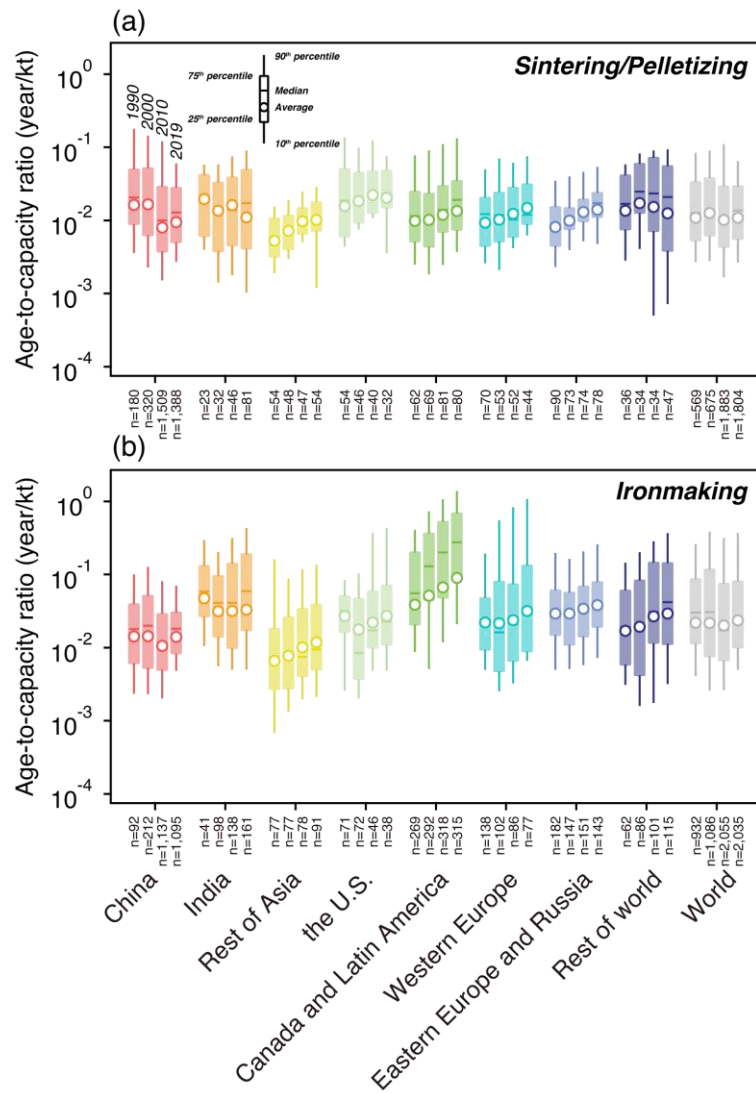
Supplementary Figure 20 | Age-to-capacity ratio and emission intensity disproportionalities of secondary steelmaking plants. The same as Fig. 2 and Supplementary Fig. 19 but for secondary steelmaking plants.



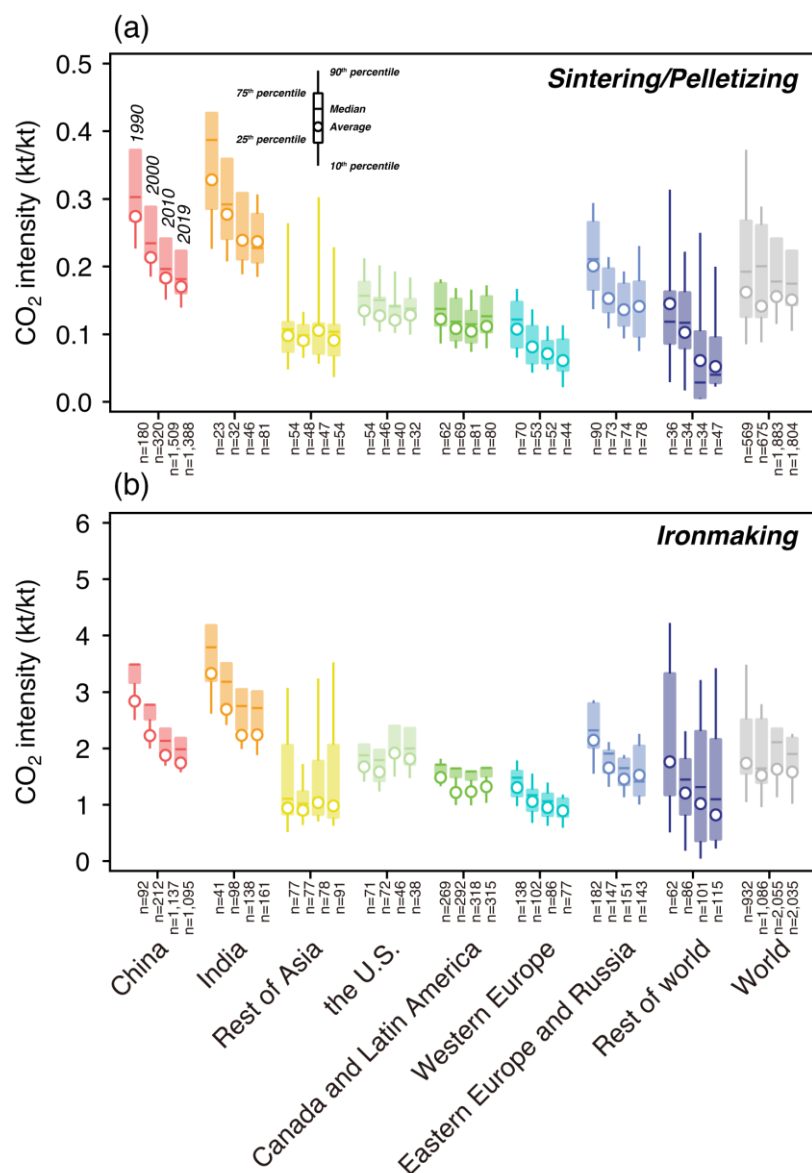
Supplementary Figure 21 | Age-to-capacity ratio disproportionalities of (a) sintering/pelletizing and (b) ironmaking facilities. The scatters represent individual facilities of (a) sintering/pelletizing and (b) ironmaking in 2019, respectively, in each case plotted according to crude steel capacity (y axis) and average age (x axis). The black solid diagonal lines represent the 90th quantiles of age-to-capacity ratio, and the numbers, shares of capacity, and ages on average for facilities beyond the 90th quantiles are shown at the bottom right corner. The gray shades represent the areas beyond 90th, 75th, and 50th quantiles as the shades become lighter. Ironmaking facilities include blast furnace (BF), direct reduction iron (DRI) furnace, and other minor ironmaking facilities.



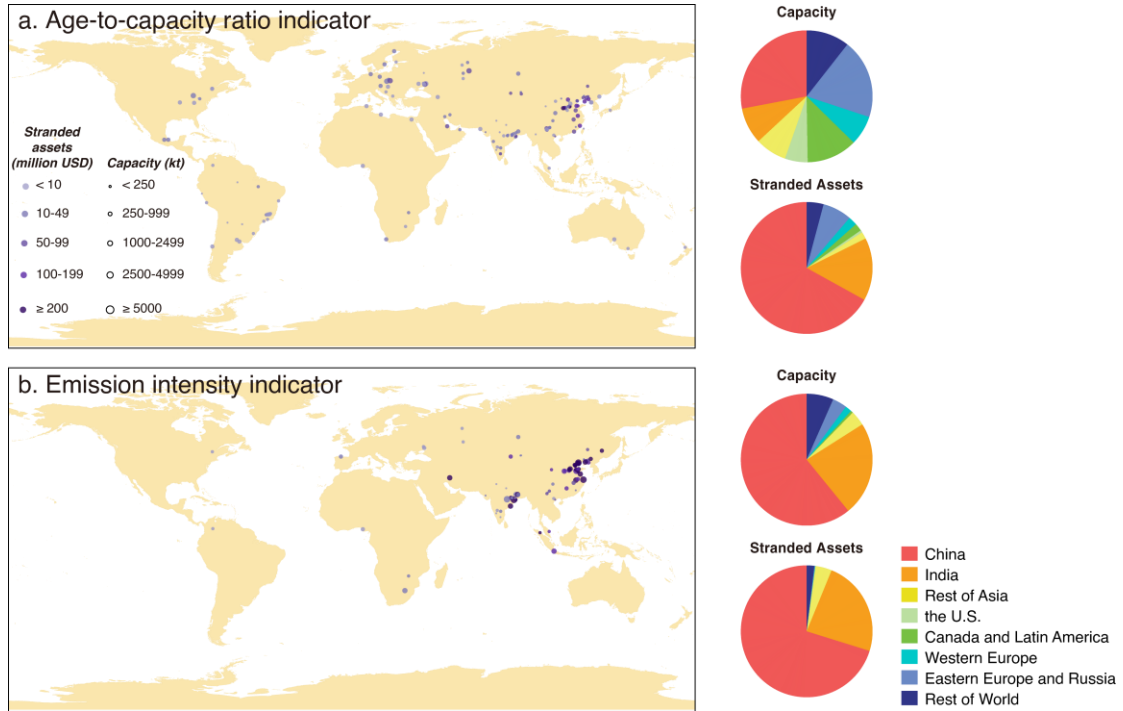
Supplementary Figure 22 | Emission intensity disproportionalities of (a) sintering/pelletizing and (b) ironmaking facilities. The same as Supplementary Figure 21 but in each case plotted according to crude steel production (y axis) and direct CO₂ emissions (x axis) (bottom panel).



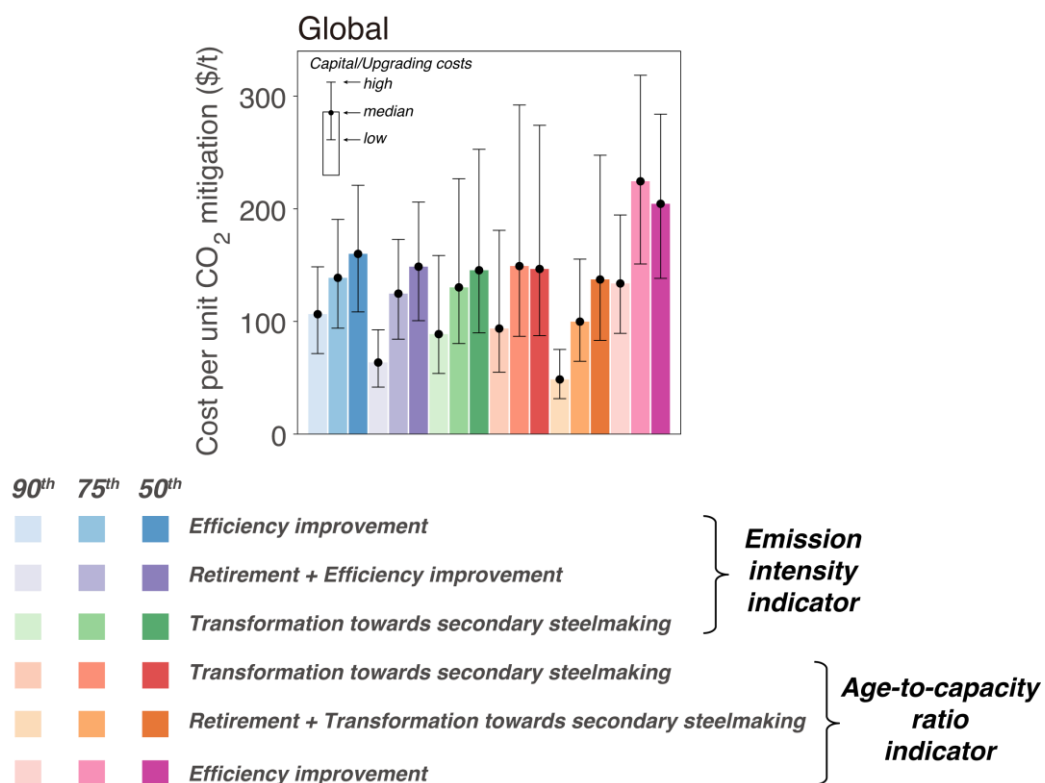
Supplementary Figure 23 | Regional and global evolutions of age-to-capacity ratio for (a) sintering/pelletizing and (b) ironmaking facilities. The facility-level age-to-capacity ratio of (a) sintering/pelletizing and (b) ironmaking facilities in 1990, 2000, 2010, and 2019 in different regions and at global scale. In each case, the boxes show the range from 25th to 75th percentiles; the whisker show the 10th and 90th percentiles; the lines and scatters show the median and average values, respectively.



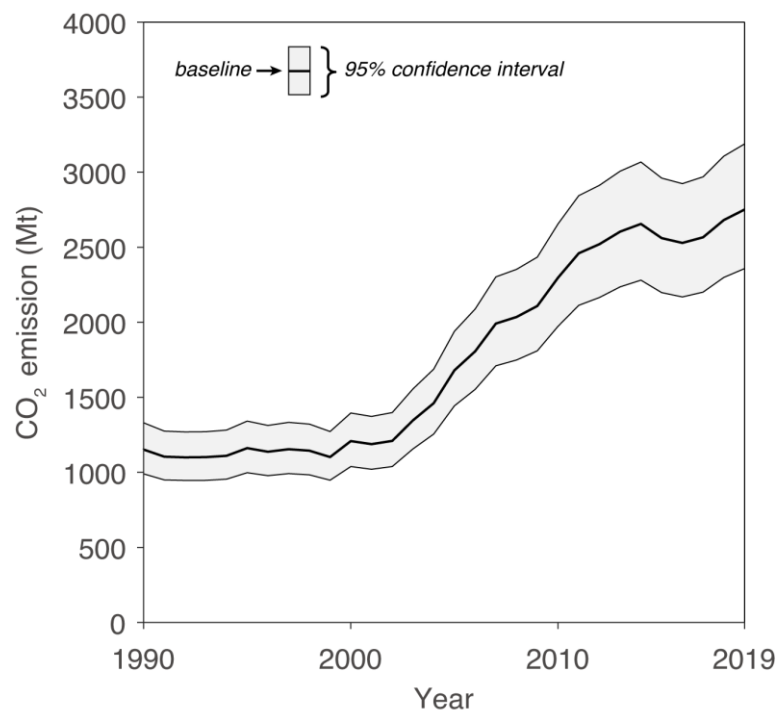
Supplementary Figure 24 | Regional and global evolutions of direct CO₂ emission intensities for (a) sintering/pelletizing and (b) ironmaking facilities. The same as Supplementary Figure 23 but for direct CO₂ emission intensity.



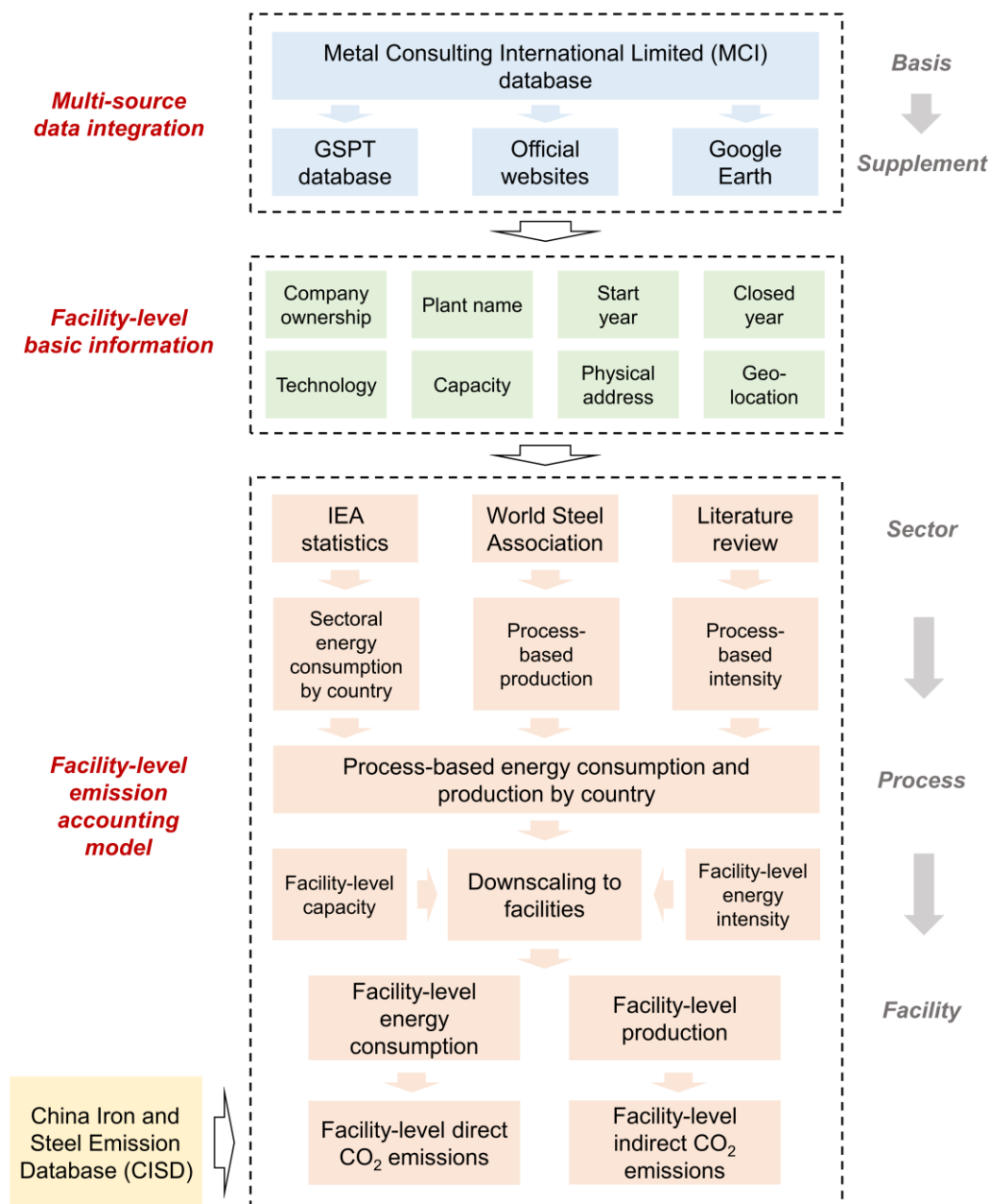
Supplementary Figure 25 | The plant-level distributions of global overcapacity retirement identified by the 50th percentiles of (a) age-to-capacity ratio and (b) CO₂ emission intensity indicators, respectively. The plants are classified by stranded assets (<10 million USD, 10-49 million USD, 50-99 million USD, 100-199 million USD, and ≥ 200 million USD) and capacity (<250 kt, 250-999 kt, 1,000-2,499 kt, 2,500-4,999 kt, and ≥ 5,000 kt). The regional shares of capacity and stranded assets are shown by the pie charts on the right.



Supplementary Figure 26 | Cost effectiveness of CO₂ mitigation by targeting primary steelmaking plants, identified stepwise by the indicators of age-to-capacity ratio or emission intensity with different mitigation strategies. The same as Fig.4 but for comparison, here efficiency improvement is also considered when the age-to-capacity ratio indicator is used.



Supplementary Figure 27 | Uncertainty range of direct CO₂ emissions from global iron and steel industry. Uncertainty of total direct CO₂ emissions from 1990 to 2019. The black line represents the baseline emission estimate using default activity rates and emission factors, and the gray shaded area represents the 95% confidence interval of the emission estimate.



Supplementary Figure 28 | Methodology framework. The framework of basic information compilation and emission estimates.

Supplementary Table 1 | Introduction to the processes of steel industry. The processes are categorized into three stages: pretreatment, ironmaking, and steelmaking.

	Process
Pretreatment	Coking
	Sintering
	Pelletizing
Ironmaking	Blast furnace (BF) ironmaking
	Direct reduction ironmaking (DRI)
	Ironmaking in other furnaces (minor ways, e.g. direct smelting by Corex technology)
Steelmaking	Basic oxygen furnace (BOF) steelmaking
	Electric arc furnace (EAF) steelmaking
	Open hearth furnace (OHF) steelmaking

Supplementary Table 2 | Definition of different types of plants in this study. The plants are categorized into three groups: pretreatment plants, ironmaking plants (probably with pretreatment processes but without steelmaking), and steelmaking (probably with pretreatment processes and/or ironmaking).

	Plant type	Description
Pretreatment & ironmaking plant	Coking	The plants only produce coke.
	Sintering/Pelletizing	The plants produce sinter and/or pellet.
	Coking&Sintering/Pelletizing	The plants produce both coke and sinter/pellet.
	Ironmaking only	The plants produce iron without pretreatment processes themselves (probably purchase coke and other materials from others) and do not subsequently produce crude steel.
	Pretreatment&Ironmaking	The plants produce iron with pretreatment processes themselves and do not subsequently produce crude steel.
Steelmaking plant	Primary steelmaking (BOF/OHF primary or EAF primary steelmaking)	The plants produce crude steel with ironmaking and/or pretreatment processes. The raw material is mainly iron ore.
	Secondary steelmaking	The plants produce crude steel using EAF fed by steel scrap. The raw material is mainly scrap.
	Primary&Secondary steelmaking	The plants produce crude steel using both primary and secondary routes above.

Supplementary Table 3. Energy intensities of each processes (energy consumption per unit product produced). The coking process has separated data in IEA statistics and thus its energy intensity is not used in the accounting methodology. The value of blast furnace ironmaking is used for minor ironmaking facilities besides blast furnaces and DRI furnaces.

Process	Energy intensity (MJ/tonne product)	Sources
Sintering	1,344	EU BREF, 2013 ¹⁹
Pelletizing	1,000	EU BREF, 2013 ¹⁹
Blast furnace ironmaking	13,207	EU BREF, 2013 ¹⁹ IPCC, 2006 ⁴³
Direct reduction ironmaking (DRI)	10,046	Tenova and Danieli, 2014 ⁴⁴ EU BREF, 2013 ¹⁹
Electric arc furnace (EAF) steelmaking	488	Echterhof, 2021 ⁴⁵ IPCC, 2006 ⁴³
Basic oxygen furnace (BOF) steelmaking	299	EU BREF, 2013 ¹⁹ IPCC, 2006 ⁴³
Open hearth furnace (OHF) steelmaking	578	EU BREF, 2013 ¹⁹ IPCC, 2006 ⁴³

Supplementary Table 4. Energy efficiency differences of small/large-capacity facilities.

Country/ Region	Process	Parameter	Min	Max	Relative differences	Sources
China	BF	CO ₂ intensity (kg CO ₂ /kg production)	1.09	1.37	25.69%	Wang et al., 2007 ³³
China	EAF	CO ₂ intensity (kg CO ₂ /kg production)	0.48	0.80	66.67%	Wang et al., 2007 ³³
EU	Sinter	Energy intensity (MJ/t)	1289	2019	56.63%	EU BREF, 2013 ¹⁹
EU	Coke	Energy intensity (MJ/t)	3200	3900	21.88%	EU BREF, 2013 ¹⁹
China	Sinter	Energy intensity (kgce/t)	52.06	108.6	108.61%	Guo and Fu, 2010 ¹⁰
China	BF	Energy intensity (kgce/t)	395.41	591.81	49.67%	Guo and Fu, 2010 ¹⁰
China	EAF	Energy intensity (kgce/t)	146.31	325.44	122.43%	Guo and Fu, 2010 ¹⁰
India	Plant- level	CO ₂ intensity (tonne CO ₂ /tonne crude steel production)	2.35	4.03	71.05%	Ministry of Steel, India, 2017 ⁴⁶
India	Plant- level	Energy intensity (Gcal/tonne crude steel)	5.83	8.82	51.34%	Ministry of Steel, India, 2017 ⁴⁶
Average					63.77%	

Supplementary Table 5. Electricity intensities of each process (electricity consumption per unit product produced). The value of blast furnace ironmaking is used for minor ironmaking facilities besides blast furnaces and DRI furnaces.

Process	Electricity intensity (kWh/tonne product)	Sources
Coking	34.7	EU BREF, 2013 ¹⁹
Sintering	34.3	EU BREF, 2013 ¹⁹
Pelletizing	21.3	EU BREF, 2013 ¹⁹
Blast furnace ironmaking	74.4	EU BREF, 2013 ¹⁹
Direct reduction ironmaking (DRI)	120.0	Nduagu et al., 2022 ⁴⁷
Electric arc furnace (EAF) steelmaking	576.0	EU BREF, 2013 ¹⁹
Basic oxygen furnace (BOF) steelmaking	34.9	EU BREF, 2013 ¹⁹
Open hearth furnace (OHF) steelmaking	34.9	EU BREF, 2013 ¹⁹

Supplementary Table 6. Capital costs (lower, medium, and upper values) by process. The value of blast furnace ironmaking is used for minor ironmaking facilities besides blast furnaces and DRI furnaces.

Process	Lower (\$/kt)	Medium (\$/kt)	Upper (\$/kt)	Sources
Coking	92,086 ^a	147,494	202,902	Steelorbis ⁴⁸ ; Dolvi Coke Projects Limited ⁴⁹
Sintering	24,000	40,000	67,647	MCI ⁵⁰
Pelletizing	22,866 ^b	38,110	64,451 ^b	SAIL ⁵¹
Blast furnace ironmaking	148,000	211,500	275,000	IEA ETSAP, 2010 ⁵²
Direct reduction ironmaking (DRI)	100,416 ^c	143,500	200,000	IEA ETSAP, 2010 ⁵² ; MCI ⁵³
Electric arc furnace (EAF) steelmaking	80,000	143,000	300,000	IEA ETSAP, 2010 ⁵⁴ ; MCI ⁵⁴ ; Steel Technology ⁵⁵
Basic oxygen furnace (BOF) steelmaking	69,976	100,000	130,024	IEA ETSAP, 2010 ⁵⁴
Open hearth furnace (OHF) steelmaking	69,976 ^d	100,000 ^d	130,024 ^d	IEA ETSAP, 2010 ⁵⁴

^a estimated based on the relative differences of medium and upper values.

^b estimated based on the relative differences of sintering.

^c estimated based on the relative differences of blast furnace ironmaking.

^d assumed to be the same as basic oxygen furnace (BOF) steelmaking.

Supplementary Table 7. The historical average campaign lifetimes by process. The lifetimes are derived from historical information of retired facilities and investment cycles in the database except for blast furnace, the lifetime of which is obtained from previous literature¹. The value of blast furnace ironmaking is used for minor ironmaking facilities besides blast furnaces and DRI furnaces.

Process	Lifetime (year)
Coking	33
Sintering	28
Pelletizing	32
Blast furnace ironmaking	17
Direct reduction ironmaking (DRI)	18
Electric arc furnace (EAF) steelmaking	27
Basic oxygen furnace (BOF) steelmaking	27
Open hearth furnace (OHF) steelmaking	42

Supplementary Table 8. Global average decarbonization costs of indirect emissions based on different technologies⁵⁶.

Technology	Decarbonization cost (\$/tCO₂-eq)
Wind power	27.10
Solar PV power	32.98
Fossil fuel power with CCS	130.85

Supplementary Table 9. Comparison of CO₂ mitigation potential of different strategies with the projected CO₂ emission reduction of iron and steel industry (in 2030 compared to the 2019 level) in IEA Net Zero Emission Scenario²⁷.

Indicator	Strategy	90 th	75 th	50 th	IEA Net Zero Emission Scenario 2030
Emission intensity indicator	Efficiency improvement	-6.8%	-17.0%	-32.3%	-29.0%
	Retirement + Efficiency improvement	-6.8%	-16.9%	-32.2%	
	Transformation towards secondary steelmaking	-8.2%	-23.3%	-49.7%	
Age-to- capacity ratio indicator	Transformation towards secondary steelmaking	-1.1%	-4.6%	-21.3%	
	Retirement + Transformation towards secondary steelmaking	-0.9%	-4.2%	-21.0%	
Combination of the two indicators above	Transformation towards secondary steelmaking	-3.8%	-14.8%	-31.9%	

Supplementary Table 10. Probability distributions of emission estimate-related parameters²⁹⁻³¹.

	Variables	Distribution
National level	Activity rate (fuel consumption)	Normal (CV: 5%)
	Carbon content	Lognormal (GSD=1.5%)
	Oxidation factor	Lognormal (GSD=0.2%)
	Heating value	Normal (CV: 5%)
Facility level	Activity rate (fuel consumption)	Normal (CV: 10%)

Supplementary Table 11. Global capacity by process in GISD in 1990 and 2019, in comparison with global statistical production^{6,57}.

Process	1990		2019	
	GISD capacity (Mt)	Production (Mt)	GISD capacity (Mt)	Production (Mt)
Coking	400	367	730	705
Sintering	806	582	2192	1639
Pelletizing	322	225	778	441
BF ironmaking	800	518	1717	1266
DRI ironmaking	35	19	146	111
Other ironmaking	8	1	20	16
EAF steelmaking	367	215	746	518
BOF steelmaking	699	422	1568	1344
OHF steelmaking	129	115	28	6

Supplementary Table 12. Global and regional steelmaking capacity in GISD in 2000 and 2019, in comparison with OECD Steelmaking Capacity Database⁵⁸.

Region	2000		2019	
	GISD capacity (Mt)	OECD (Mt)	GISD capacity (Mt)	OECD (Mt)
China	249	244	1077	1182
India	44	34	120	129
Rest of Asia	271	226	322	305
The U.S.	140	115	125	110
Canada and Latin America	107	89	129	117
Western Europe	231	196	203	185
Eastern Europe and Russia	192	158	192	170
Rest of World	87	71	173	165
Global	1320	1132	2342	2363

Supplementary Table 13. The regional and global coefficients of variation (CV) of age-to-capacity ratio for primary steelmaking plants in Fig. 3.

Region	1990	2000	2010	2019
China	1.7	1.7	9.9	2.7
India	2.0	3.4	4.6	4.8
Rest of Asia	3.9	3.6	3.4	3.6
The U.S.	3.0	3.7	3.5	3.0
Canada and Latin America	1.5	1.6	1.7	1.6
Western Europe	1.5	1.0	0.8	0.8
Eastern Europe and Russia	2.4	2.7	3.7	4.0
Rest of World	1.7	1.3	1.1	1.2
Global	2.8	2.7	6.4	6.3

Supplementary Table 14. The regional and global coefficients of variation (CV) of direct CO₂ emission intensity for primary steelmaking plants in Fig. 3.

Region	1990	2000	2010	2019
China	1.3	1.1	0.5	0.8
India	0.5	0.8	1.0	0.9
Rest of Asia	1.1	0.7	0.7	0.8
The U.S.	0.3	0.4	1.3	0.2
Canada and Latin America	1.0	1.0	1.0	0.7
Western Europe	0.4	0.6	0.6	0.5
Eastern Europe and Russia	0.6	0.4	0.7	1.5
Rest of World	0.7	0.8	0.7	1.1
Global	1.2	1.2	0.7	1.0

References:

1. Vogl, V., Olsson, O. & Nykvist, B. Phasing out the blast furnace to meet global climate targets. *Joule* **5**(10), 2646-2662 (2021).
2. International Energy Agency. *Iron and Steel Technology Roadmap: Towards More Sustainable Steelmaking* (International Energy Agency, 2020); <https://www.iea.org/reports/iron-and-steel-technology-roadmap>
3. Wörtler et al. *Steel's Contribution to a Low-Carbon Europe 2050* (Boston Consulting Group, 2013); <https://www.bcg.com/publications/2013/metals-mining-environment-steels-contribution-low-carbon-europe-2050>
4. Zhang, Q. et al. Drivers of improved PM_{2.5} air quality in China from 2013 to 2017. *Prod. Natl. Acad. Sci. USA* **116**, 24463 (2019).
5. Wang, P. et al. Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat. Commun.* **12**, 2066 (2021).
6. World Steel Association. *Steel Statistical Yearbook* (World Steel Association, 1990-2020); <https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html>
7. Fan, Z. & Friedmann, S. J. Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule* **5**(4), 829-862 (2021).
8. Zhang, W. et al. A review on explorations of the oxygen blast furnace process. *Steel Res. Int.* **92**, 2000326 (2021).
9. S&P Global Commodity Insights. *US Steel evaluates end-2020 restart at Keetac iron ore pellet mine* (S&P Global Commodity Insights, 2020); <https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/metals/103020-us-steel-evaluates-end-2020-restart-at-keetac-iron-ore-pellet-mine#article0>
10. Guo, Z. C. & Fu, Z. X. Current situation of energy consumption and measures taken for energy saving in the iron and steel industry in China. *Energy* **35**, 4356-4360 (2010).
11. *Measures for the Implementation of Capacity Replacement in the Iron and Steel Industry* (in Chinese) (Ministry of Industry and Information Technology of the People's Republic of China, 2021); https://www.miit.gov.cn/zwgk/zcjd/art/2021/art_91a274227d8f4e3191292d048a30abfe.html
12. Meijer, K. et al. ULCOS: ultra-low CO₂ steelmaking. *Ironmak. Steelmak.* **36**, 249-251 (2009).
13. Vehc, J. R. *Technology Roadmap Research Program for the Steel Industry* (American Iron and Steel Institute, 2010); <https://digital.library.unt.edu/ark:/67531/metadc831264/>
14. Agora Industry, Wuppertal Institute & Lund University. *Global Steel at a Crossroads. Why the global steel sector needs to invest in climate-neutral technologies in the 2020s* (Agora Industry, 2021); <https://www.agora-energie.wuppertal.de/en/publications/global-steel-at-a-crossroads/>
15. The Institute for Sustainable Development and International Relations (IDDRI). *Global facility level net-zero steel pathways: technical report on the first scenarios of the Net-zero*

- Steel Project* (IDDRI, 2021); <https://netzerosteel.org/publications/>
16. Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. & Caldecott, B. Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environ. Res. Lett.* **13**, 054019 (2018).
 17. Hirth, L. & Steckel, J. C. The role of capital costs in decarbonizing the electricity sector. *Environ. Res. Lett.* **11**, 114010 (2016).
 18. H2 Green Steel. *H2 Green Steel has pre-sold over 1.5 million tonnes of green steel to customers* (H2 Green Steel, 2022); <https://www.h2greensteel.com/latestnews/h2-green-steel-has-pre-sold-over-15-million-tonnes-of-green-steel-to-customers>
 19. Remus, R., Aguado-Monsonet, M. A., Roudier S. & Delgado Sancho, L. *Best Available Techniques (BAT) Reference Document for Iron and Steel Production: Industrial Emissions Directive 2010/75/EU: (Integrated Pollution Prevention and Control)* (Publications Office of the European Union, 2013); <https://op.europa.eu/en/publication-detail/-/publication/ea047e8-644c-4149-bdc9-9dde79c64a12>
 20. Mysteel. *Analysis of supply and demand balance of China's scrap steel market in 2022 (in Chinese)* (Mysteel, 2023); <https://baijiahao.baidu.com/s?id=1754688084513895613&wfr=spider&for=pc>
 21. Wübbke, J. & Heroth, T. Challenges and political solutions for steel recycling in China. *Resour. Conserv. Recycl.* **87**, 1-7 (2014).
 22. Pauliuk, S., Milford, R. L., Müller, D. B. & Allwood, J. M. The steel scrap age. *Environ. Sci. Technol.* **47**, 3448-3454 (2013).
 23. ArgusMedia. *India to import 30mn t/yr of ferrous scrap by 2030* (ArgusMedia, 2022); <https://www.argusmedia.com/en/news/2329560-india-to-import-30mn-tyr-of-ferrous-scrap-by-2030>
 24. Aylen, J. & Albertson, K. Markets in ferrous scrap for steelmaking. *Ironmak. Steelmak.* **33(3)**, 203-212 (2006).
 25. Gruver, G. & Giarratani, F. Modeling geographic ferrous scrap markets: regional prices and interregional transactions in the United States. *J. Reg. Sci.* **45(2)**, 313-341 (2005).
 26. European Commission. *Joint EU-US Statement on a Global Arrangement on Sustainable Steel and Aluminium* (European Commission, 2021); https://ec.europa.eu/commission/presscorner/detail/en/IP_21_5724
 27. International Energy Agency. *Net Zero by 2050: A Roadmap for the Global Energy Sector* (International Energy Agency, 2021); <https://www.iea.org/reports/net-zero-by-2050>
 28. Gurney, K. R., Huang, J. & Coltin, K. Bias present in US federal agency power plant CO₂ emissions data and implications for the US clean power plan. *Environ. Res. Lett.* **11**, 064005 (2016).
 29. Tong, D. et al. Targeted emission reductions from global super-polluting power plant units. *Nat. Sustain.* **1**, 59-68 (2018).
 30. Chen, C. et al. A striking growth of CO₂ emissions from the global cement industry driven by new facilities in emerging countries. *Environ. Res. Lett.* **17**, 044007 (2022).
 31. Liu, J. et al. Carbon and air pollutant emissions from China's cement industry 1990–2015:

- Trends, evolution of technologies, and drivers. *Atmos. Chem. Phys.* **21**, 1627-1647 (2021).
32. Lei, T. et al. Adaptive CO₂ emissions mitigation strategies of global oil refineries in all age groups. *One Earth* **4**, 1114-1126 (2021).
 33. Wang, K., Wang, C., Lu, X. & Chen, J. Scenario analysis on CO₂ emissions reduction potential in China's iron and steel industry. *Energy Policy* **35**(4), 2320-2335 (2007).
 34. Maruyama, N. & Eckelman, M. J. Long-term trends of electric efficiencies in electricity generation in developing countries. *Energy Policy* **37**, 1678-1686 (2009).
 35. S&P Global Commodity Insights. *The End of Cheap Electricity: China's government to take captive power away from big industries* (S&P Global Commodity Insights, 2018); <https://www.spglobal.com/commodityinsights/en/ci/research-analysis/the-end-of-cheap-electricity-china.html>
 36. Ummel, K. *CARMA revisited: an updated database of carbon dioxide emissions from power plants worldwide* (Center for Global Development, 2012). <https://www.cgdev.org/publication/carma-revisited-updated-database-carbon-dioxide-emissions-power-plants-worldwide-working>
 37. Ang, B. W. Decomposition analysis for policymaking in energy: Which is the preferred method? *Energy Policy* **32**, 1131-1139 (2004).
 38. Ang, B. W. The LMDI approach to decomposition analysis: A practical guide. *Energy Policy* **33**, 867-871 (2005).
 39. Liu, L.-C., Fan, Y., Wu, G. & Wei, Y.-M. Using LMDI method to analyze the change of China's industrial CO₂ emissions from final fuel use: An empirical analysis. *Energy Policy* **35**, 5892-5900 (2007).
 40. Wang, W. W., Zhang, M. & Zhou, M. Using LMDI method to analyze transport sector CO₂ emissions in China. *Energy* **36**, 5909-5915 (2011).
 41. Cansino, J. M., Sánchez-Braza, A. & Rodríguez-Arévalo, M. L. Driving forces of Spain's CO₂ emissions: A LMDI decomposition approach. *Renew. Sustain. Energy Rev.* **48**, 749-759 (2015).
 42. Serrenho A. & Allwood J. Material stock demographics: Cars in Great Britain. *Environ. Sci. Technol.* **50**(6), 3002-3009 (2016).
 43. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006); <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>
 44. Tenova and Denieli. *Energiron: DRI Technology by Tenova and Denieli* (Tenova and Denieli, 2014); Available at <https://www.energiron.com/>
 45. Echterhof, T. Review on the use of alternative carbon sources in EAF steelmaking. *Metals* **11**, 222 (2021).
 46. Ministry of Steel, Government of India. *Annual Report 2016-2017* (Ministry of Steel, Government of India, 2017); <https://steel.gov.in/annual-reports>
 47. Nduagu, E. I. et al. Comparative life cycle assessment of natural gas and coal-based directly reduced iron (DRI) production: A case study for India. *J. Clean. Prod.* **347**, 131196 (2022).
 48. SteelOrbis. *China's Nanjing Iron & Steel to invest in coke project in Indonesia* (SteelOrbis, 2020); <https://www.steelorbis.com/steel-news/latest-news/chinas-nanjing-iron--steel-to->

[invest-in-coke-project-in-indonesia-1174104.htm](https://documents.pub/document/30-mtpa-coke-oven-by-product-plant-at-3-mtpa-coke-oven-by-product-plant.html?page=1)

49. Dolvi Coke Projects Limited. *3.0 Mtpa coke oven & by-product plant at Salav, Dist. Raigad, Maharashtra, Project Report* (Dolvi Coke Projects Limited, Mumbai, 2014); <https://documents.pub/document/30-mtpa-coke-oven-by-product-plant-at-3-mtpa-coke-oven-by-product-plant.html?page=1>
50. Metal Consulting International (MCI) Limited. *Capital investment costs for plant and equipment in iron and steelmaking, Research Report* (Metal Consulting International Limited, 2010); https://www.steelonthenet.com/pdf/commerce/capex_exec_summary.pdf
51. The Hindu Businessline. *SAIL to set up 4 pellet plants at a cost of Rs 3,600 cr* (The Hindu Businessline, 2011); <https://www.thehindubusinessline.com/companies/SAIL-to-set-up-4-pellet-plants-at-a-cost-of-Rs-3600-cr/article20251863.ece>
52. International Energy Agency (IEA). *Technology Brief, Iron and Steel* (IEA, Energy Technology Systems Analysis Programme, 2010); <https://iea-etsap.org/E-TechDS/PDF/I02-Iron&Steel-GS-AD-gct.pdf>
53. Metal Consulting International (MCI) Limited. *Capex costs – DRI plant* (Metal Consulting International Limited, 2010); <https://www.steelonthenet.com/kb/steelmaking-capex-costs-dri-plant.html>
54. Metal Consulting International (MCI) Limited. *Capital Investment Costs - electric arc furnace* (Metal Consulting International Limited, 2010); <https://www.steelonthenet.com/capital-investment/eaf.html>
55. Steel Technology. *Basic Oxygen Furnace Steelmaking* (Steel Technology, 2023); <https://www.steel-technology.com/articles/oxygenfurnace>
56. International Energy Agency. *Sustainable Recovery* (International Energy Agency, 2020); <https://www.iea.org/reports/sustainable-recovery>
57. *Industrial Commodity Statistics Database* (United Nations Statistics Division, 2020); <https://unstats.un.org/unsd/industry/Commodity/>
58. *OECD Steelmaking Capacity Database* (OECD Steel Committee, 2020); <https://www.oecd.org/industry/steelcapacity.htm>