Net Zero Steel

FACILITY LEVEL GLOBAL NET-ZERO PATHWAYS UNDER VARYING TRADE AND GEOPOLITICAL SCENARIOS

FINAL TECHNICAL & POLICY REPORT FOR THE NET-ZERO STEEL PROJECT, PART II OF THE NET-ZERO STEEL PROJECT

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NET-ZERO STEEL PROJECT

The production of steel generates significant greenhouse gas emissions, the largest single industrial global emitter after cement. In our efforts to move to a net zero-carbon world, steel has been treated as "hard to abate" or part of the "last 20% of emissions." The objective of the Net Zero Steel Project is to counter this assumption and show instead that several global decarbonization pathways for steel by 2050 are possible using technologies that are currently commercial, near-commercial and at the advanced pilot stage. This installment of the projects explores the implication of global trade in green iron & steel, climate clubs, and explicit policy packages to trigger the transition.

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Key messages

- **A global transition to net-zero CO_2 emissions steel by midcentury is possible through maximizing volume and quality of recycled steel from 25 to 50%+ of production, paired with several possible near zero emissions iron ore reduction technologies.**

- **Chinese capacity to make emission intense BF-BOF primary steel will soon exceed its demand. If Chinese firms can be persuaded to close the least efficient facilities with the worst air quality impacts this would leave more global market share for new clean iron ore reduction facilities, inside or outside of China.**

- **The next few years are critical to reorientate the global steel industry toward net zero emissions by mid-century.** It takes at least 5 years from project inception to production for new iron ore reduction facilities, usually much longer, and any new reduction facilities built in the 2030s will be operating in the 2050s.

- **Given most new demand for steel is outside developed countries, even a club of ambition that included the European Union, North America, South Korea, Japan, Australia and New Zealand (Narrow Club in this report), would not be large enough to transform the global steel industry by itself.** This is true even if the rest of the world adopted significant carbon pricing policies (e.g., rising to \$100/t CO_2e by 2050). A broader club including for example India is required.

- **Lead markets, especially for the first round of low GHG intensity iron ore reduction projects, are necessary to establish demand and investment certainty for clean iron ore reduction.** This can be established through government preferred and subsidized procurement (e.g, through contracts for difference), through production tax credits like the IRA, or perhaps through something like the tradable Zero Emissions Vehicle mechanism, e.g., a Zero Emission Iron instrument.

- **Reasonable cost finance is necessary to fund risky and expensive upfront investment, especially in developing countries.** For at least the first round of projects in developing countries some form of risk reduction or concessional finance mechanism is necessary.

- **Trade in low GHG intensity green hot briquetted iron (HBI) from multiple suppliers offers flexibility, security, and a means to transfer electricity and hydrogen consumption where it is cheapest and cleanest**, as well as adding value to scrap for mixed primary & secondary production. We found it could reach at least 10% of global production, limited only by available iron ore resources. To reach its potential, however, it requires clear trade rules and tariffing that accurately assesses GHG intensity for all traded steel and iron.

EXECUTIVE SUMMARY

Scenarios on the way to net-zero steel: "Baseline", "Narrow Club", "Broad Club", & "Broad Club Fossil Fuel Ban"

To meet the Paris Agreement goals to stabilize the global average temperature rise to "under 2°C and towards 1.5°C" global economy wide CO_2 emissions must reach net-zero by 2055-70. This requires all sectors, including iron and steel production, to reach zero or negative CO_2 emissions or be offset with permanent, verifiable and additive carbon dioxide removal (CDR). Net-zero CO_2 steel production by mid-century is possible but we must act very soon – national and international trade policy is required to end investment in unabated fossil fuel making as soon as possible, in as many countries as possible. This study explores the future energy and emissions profile of the global steel manufacturing sector using a geospatially explicit investment and stock turnover model. It encompasses critical uncertainties such as climate policy, international trade, and technological change, all in the context of the global overcapacity issue (i.e. the US 232 tariffs, GASSA alliance proposal, and the EU ETS CBAM) and the movement towards building climate alliances and border tariffs. We also explore the potential for trade in green iron and targeted subsidization of green iron production to help kick start the transition.

This project develops several spatially explicit, facility level pathways to net-zero global steel production by 2050. It builds on our previous NetZeroSteel study (Bataille et al., 2021a) and the data archive hosted at netzerosteel.org. It provides new analysis on the strength and breadth of policy needed to ensure all new steel plants are near zero emitting by the early 2030s, thus making global net zero emissions from the sector potentially feasible by 2055 without forced retirement of high emission "dirty" steel production. For the purposes of this analysis, we have assumed that CDR will be available in sufficient quantity and volume to offset the final 5-10% of emissions after 90-95% mitigation, but this an area of considerable debate.[1] We have gone beyond the solely political-economy driven investment decision framework used in our previous study to now also capture future decisions on technology investment using a cost-based model supported by a detailed global review of the economics of different steel production pathways. It includes the relative costs of capital, labour, fossil fuels, electricity, iron ore, and key infrastructure needs. Our analysis has also expanded to explore the potential role of international trade in reduced iron and steel within the context of several feasible geopolitical scenarios. These vary from the most unfettered trade conditions to highly regulated trade with GHG tariffs, including several scopes of preferential "climate clubs" focused on green steel and green iron. Our work provides new insights into the potential for climate action through trade to put the sector on a pathway to net zero, the

1 The difference between 5% and 10% residual emissions doubles the amount of CDR needed, but will also depend on the political willingness to specify 95% as "sufficiently abated" to meet Paris Agreement needs and the amount of permanent, additive and verifiable CDR available. Please see Bataille, Al Khourdajie, et al., (2023). Net-zero CO_2 within steel itself would require in-sector CDR using biomass, and there has long been considerable controversy surrounding the net-neutrality of biomass under anything less than very specific circumstances (Fuss et al., 2014; Hepburn et al., 2019a).

required size and strength of any potential "climate club", and the potential role of green iron trade from major iron ore producing nations to accelerate this transition. As with our previous report, results are supported by a granular and geospatially explicit approach that can show the impacts on individual facilities and countries, enabling inferences to be drawn about what local infrastructure and national policies might be necessary to achieve net-zero in the steel sector.

What would happen under business as usual?

We find that global steel output, including assumption of a significant improvement in material efficiency from today (~26%), is likely to grow to around 2.2 Gt per year by 2050 from today's 1.9-2.0 Gt per year in order to meet global development needs (our *Baseline* scenario). Combined with secondary recycled steel production using electric arc furnaces (EAFs) increasing from 25% today to 58% by 2050 based on scrap availability, this baseline scenario without significant new carbon policies will likely result in direct GHG emissions falling by 40% compared to 2022 levels. While a significant improvement, this is insufficient to meet the Paris climate targets – strong and broad climate policy action is needed in the iron and steel sector to achieve a 90-95% reduction to achieve Paris Agreement compliance as we have defined it.

What does policy strong enough to meet the Paris goals look like, and what are the trade implications?

With the baseline results in mind, we then explored the impact of various scopes of coverage and stringency of a "shadow"[2] carbon pricing equivalent on investment in all new and retrofit unabated[3] fossil fuel iron reduction and steel making facilities, and investigated the timing (start date and speed of stringency increase) and degree of country participation required to reach the Paris Agreement goals. More nuanced and realistic policy options to implement equivalent policy coverage and stringency are discussed later in the report. This exercise created a model ensemble of 30+ sets of results, from which we selected a small number of key scenarios to illustrate our main findings.

- *Baseline* – this scenario includes our technological, material efficiency, and recycling improvements but no climate policy drivers.
- *Narrow Club* – this scenario shows climate club performance with an exclusive club of high-income countries only: the EU/EEA, the USMCA trade zone, Japan, South Korea, Australia, New Zealand.
- *Broad Club* – this scenario shows a more inclusive club with a larger membership: the EU/EEA, the USMCA trade zone, Japan, South Korea, Australia, New Zealand, the ASEAN Free Trade Area (AFTA), and major iron producers: Brazil, South Africa, India, Guinea, Ukraine, Venezuela.
- *Broad Club Fossil Fuel Ban* – this scenario shows the same climate club from *Broad Club* but a ban on fossil fuel steel is implemented amongst its membership by 2025.

We assume that the climate clubs in the *Narrow Club*, *Broad Club*, and *Broad Club Fossil Fuel Ban* scenarios apply the same trade rules:

- The climate club pursues a trade protection policy that is expressed in terms of two tariff structures: a 30% tariff on imports from outside the club, and a GHG intensity-based tariff modelled on the EU carbon border adjustment mechanisms (CBAM) which effectively equalizes the carbon price for imports so that it matches the price inside the club.
- In addition, the climate club group provides subsidies for production of green iron ($100 USD 2020/tonne). The model does not explicitly capture policies or flows of investment capital between countries, but this subsidy could be imagined as a combination of both domestic policy support efforts from the governments of the major iron producing nations and foreign investment from the high-income members of the club to the iron producers.

Carbon pricing inside and outside the club is applied as follows:

- In the *Narrow Club* and *Broad Club* scenarios, the high-income regions in the club (GDP/capita above USD$20,000) have an internal carbon price or equivalent policies starting at 100 $/t$CO_2$e in 2022 imposed just on the iron and steel sector, rising over

2 Shadow carbon pricing is a modelling technique used to investigate the necessary stringency of policy to achieve climate policy goals. It can represent the stringency of various types of command-and-control style regulations, performances standards or actual pricing, which requires dynamic analysis of the use of any revenues.

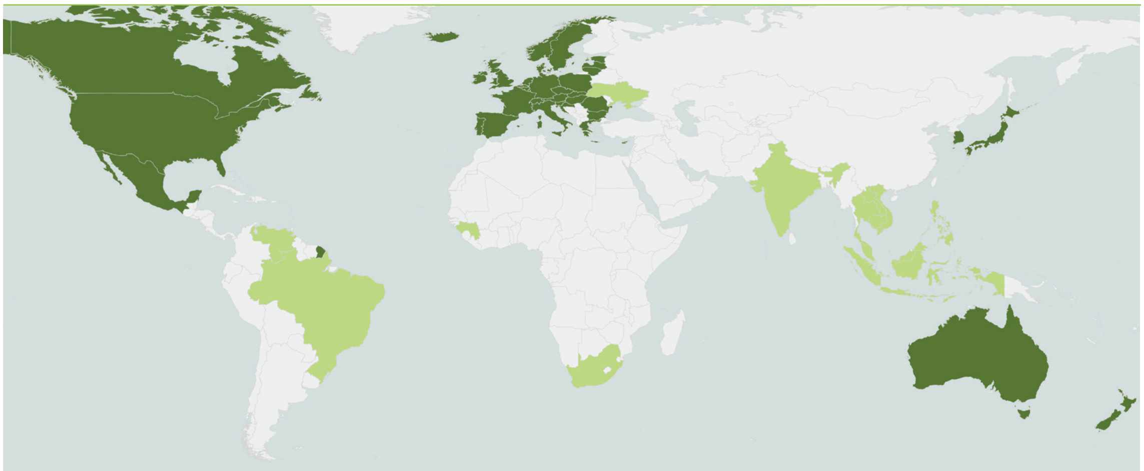
3 To be "abated" fossil fuel facilities are assumed to require 90% or better CO_2 capture rates.

time to 300 $/tCO$_2$e in 2050. These policies could include carbon pricing, CO_2 intensity standards, subsidies on clean production like the IRA production tax credits for iron, public and private green procurement, secondary content mandates, etc.

- In the *Narrow Club* and *Broad Club* scenarios, the low income regions in the club (GDP/capita below USD$20,000) apply carbon pricing equivalent to 30 $/tCO$_2$e in 2022, rising to 100 $/tCO$_2$e in 2050.
- In the *Broad Club Fossil Fuel Ban* scenario, all club members apply a $500 carbon price starting in 2025.
- In the *Narrow Club*, *Broad Club*, and *Broad Club Fossil Fuel Ban* scenarios, non-club members, i.e. the rest of the world. are assumed to pursue a significant but reduced push in terms of steel decarbonization policies, which we capture as a carbon price (or equivalent policies) of 30 $/tCO$_2$e in 2022, rising to 100 $/tCO$_2$e in 2050

Club membership, carbon pricing, trade tariffs and subsidies for each scenario are summarized below in **Table 1**. The climate club compositions for the *Narrow Club*, *Broad Club*, and *Broad Club Fossil Fuel Ban* scenarios are visualized in **Figure 1**.

Figure 1. Green Iron and Steel Climate Club Membership Under the three scenarios



● Narrow Club Scenario ● ● Broad Club and Broad Club Fossil Fuel Ban Scenarios

Table 1. Key Scenario Parameters

Scenario Component	Baseline	Narrow Club	Broad Club	Broad Club Fossil Fuel Ban
Climate Club Membership	No Climate Club	EU + EEA, USMCA, South Korea, Japan, Australia, New Zealand	EU + EEA, USMCA, South Korea, Japan, Australia, New Zealand + ASEAN Free Trade Area (AFTA) + Green Iron Majors (India, Brazil South Africa, Guinea, Ukraine, Venezuela)	
Carbon Price Schedule	No Carbon Price	Climate Club members, $100-300 Rest of World, $30-100	Climate Club members above $20k/capita, $100-300 Climate Club Members below $20k/capita, $30-100 Rest of World, $30-100	As Broad Club Scenario until 2024, then all Climate Club Members apply $500 in 2025 Rest of World, $30-100
Tariffs	No Trade Tariffs No Climate Tariffs	Climate Club Members: Carbon Border Adjustment Mechanism (CBAM) for All Countries 30% Border Tariff for Non-Club Members		
Subsidies	No Subsidies	Green Iron Technologies, $100 per tonne sponge or HBI		

In our 2021 NetZeroSteel study[4] we effectively imposed a global unabated fossil fuel ban based on the natural relining schedule for individual facility blast furnaces, but without dynamic trade and no consideration of excess unused capacity. To achieve the same stringency in our *Broad Club Fossil Fuel Ban* scenario, starting in 2025, we applied carbon pricing equivalent to $500/t tonne CO_2e inside the club applied through pricing or regulatory instruments, carbon border adjustments, and a $100 per tonne subsidy for green iron production. Meanwhile, countries outside the club also decarbonize but at a much slower pace: we use carbon pricing of $30/t rising to $100/t to represent background ambition and the Paris Agreement principle of "Common But Differentiated Responsibilities" (CBDR). Under these conditions, a global -92% reduction was achieved. Doing sensitivity analysis, abandoning CBDR, we also found that if *all* countries applied the equivalent of $30 per tonne CO_2 price rising to $300 linearly, or $100 today rising to $200, emissions would fall by -90% by 2047 and -95% by 2050. We tested a variation of the *Broad Club Fossil Fuel Ban* scenario that includes China inside the club: this brings the date for achieving -90% into the mid 2040s, indicating the extreme stringency of regulations that would be required. Unfortunately, there is currently no sustained global policy effort or consensus to implement a ban on fossil fuel steel. We also found that if the ban is not implemented by around 2030 it will likely be impossible to achieve net zero steel by 2050 even with every country in the world participating, unless relining cycles are sped up significantly. With this in mind, we explored alternative policy and coverage scenarios.

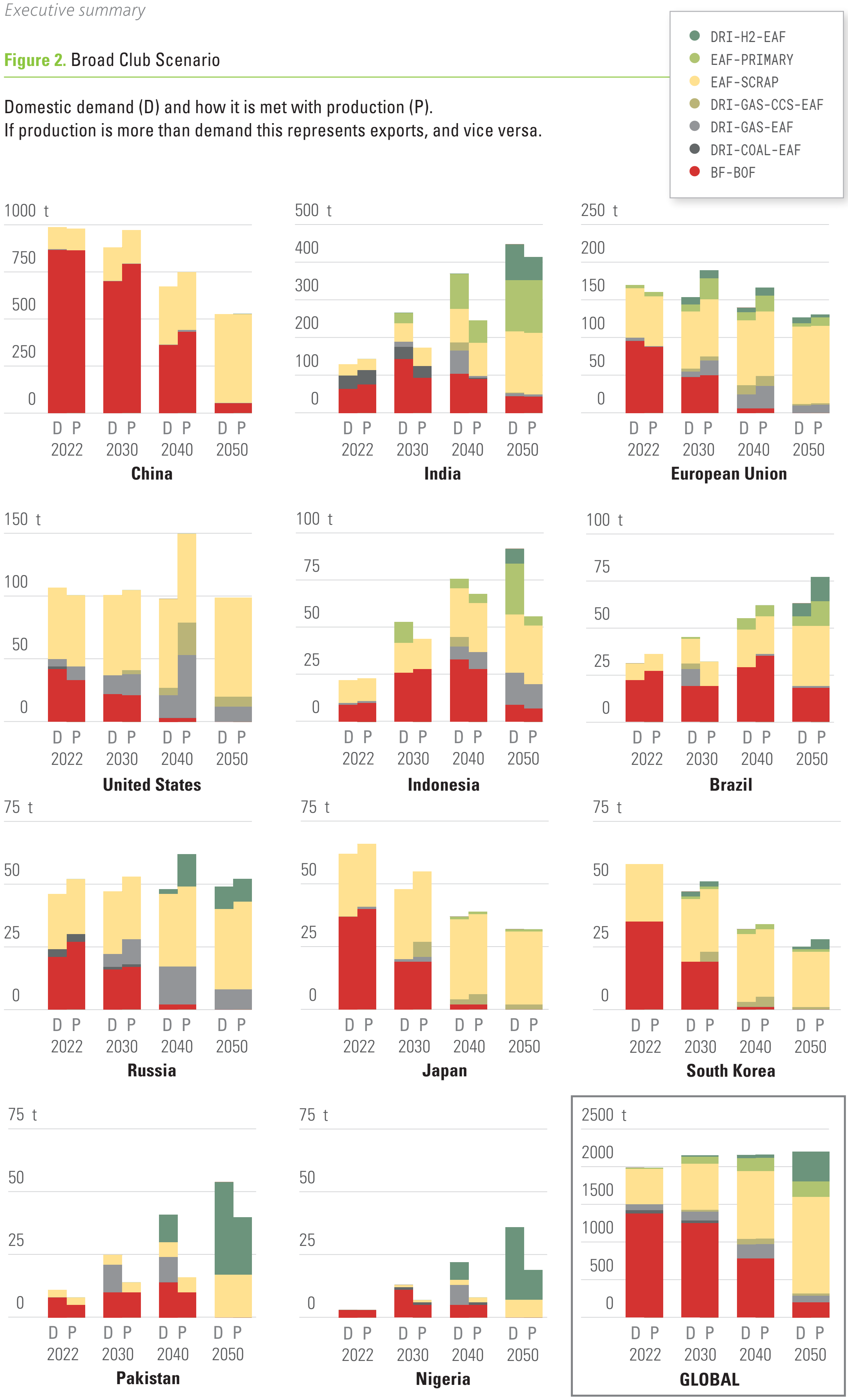
It is commonly suggested that an outgrowth of the EU/US GASSA negotiations might be able to shift the global steel industry towards a net zero transition. To simulate this, we created a scenario capturing action by a *Narrow Club* of (mostly) upper income countries: the European Union and the wider European Economic Area (EEA), the USMCA trade zone (formerly NAFTA), Japan, South Korea, Australia, and New Zealand. The *Narrow Club* applies stringent carbon pricing rising from $100 today to $300 in 2050, alongside carbon border tariffs, 30% import tariffs, and subsidies for green iron. Meanwhile, background ambition globally outside of the club is equivalent to a $30 carbon price today rising to $100 in 2050. Under this scenario, the world with the Narrow Club is able to bring down global emissions by only around 75% by 2050. This is simply because all indicators (demography, economic growth) appear to show that so much future steel demand will be outside the Global North, specifically in Asia, India and Africa. Even if rich industrial countries implement ambitious policies in their own club, and see their steel emissions trend close to zero, the residual emissions in the rest of the world remain high. We tested a variation of the *Narrow Club* scenario involving China inside the club: this has a large impact on cumulative emissions but does not significantly change the overall outcome for decarbonization by 2050.

Finally, we explored a wider climate club coalition involving all of countries from the *Narrow Club* scenario, adding the ASEAN Free Trade Area (AFTA) economies and also key green iron producers to the club (Brazil, South Africa, India, Guinea, Venezuela, Ukraine) and tuning the level of climate action in for each country to respect CBDR (our *Broad Club* scenario). The *Broad Club* scenario achieves an 85% reduction by 2050 and likely puts the world on track to achieve 95% or better by 2060, although our modelling in this study only extends to 2050. If blast furnaces are retired at 17-year intervals rather than 20-year intervals, we see the scenario achieving a slightly higher reduction of 87% by 2050. The high-income parts of this group (>$20,000 GDP/capita) would impose the equivalent of $100 through $300 per tonne CO_2 pricing through national policies (e.g., CO_2 intensity standards, carbon pricing like the EU ETS, subsidies on clean production like the US IRA production tax credits for energy but for iron, carbon pricing, maximization of secondary production, etc.), with a 30% external tariff, border carbon adjustment mechanisms (CBAM) and a $100/t green iron production subsidy. As with our *Narrow Club* scenario, our *Broad Club* scenario assumes that the rest of the world outside of the club operates with the equivalent of $30/t per tonne CO_2 rising to $100/t through 2050. Under these parameters we find that by 2050, residual blast furnace (BF-BOF) steelmaking has fallen to 202 Mt/a (9%), direct reduced iron (DRI) using integrated green & blue hydrogen has reached 393 Mt/a (18%), recycled steel evolves to 58% of global production (1283 Mt/a), and global green hot briquetted iron production for dedicated to exports for

4 Global facility level net-zero steel pathways: technical report on the first scenarios of the Net-zero Steel Project (Bataille et al., 2021a)

Figure 2. Broad Club Scenario

Domestic demand (D) and how it is met with production (P).
If production is more than demand this represents exports, and vice versa.



demand EAF steel making reach 207 Mt/a (10%). We tested a variation of our *Broad Club* scenario involving China inside the club: as before, we see in this case a lowering of cumulative emissions but not a large shift in decarbonization level achieved in 2050.

Several policy relevant results emerge from "*Broad Club*". First, key importers of green iron in our scenario are EU countries in the 2030s and 2040s and Indonesia and India in the 2040s and 2050s, ~140 Mt/a by 2050 to India alone (**Figure 2**). Second, there are strong tendencies to overbuild gas DRI in the intermediate years which then becomes stranded in 2050, e.g., in the US and Russia. Thirdly, the two speed policy environment (i.e. some members decarbonizing more rapidly than others, respecting CBDR) used leads to complicated intermediate results, e.g. the EU shipping BF-BOF steel from underused capacity outside the EU while building clean capacity within. Fourthly and possibly most importantly, we found that the *Broad Club* scenario, enjoying substantial benefits of induced innovation from advanced investment and the green iron subsidy, leads to the least global average cost per tonne, and almost the same cumulative emissions to 2050 as the outright global ban in the *Broad Club Fossil Fuel Ban* which comes at a much higher cost per tonne (**Figure 3**).

Figure 5 provides a visual overview of the *Broad Club* Scenario, including production by type and location in 2021 and 2050; red BF-BOFs are largely replaced by DRI-H_2 and EAF-Primary, where HBI (hot briquetted iron) is imported for making into steel in EAFs. The relative size of the circles indicates the production amount.

From this analysis, four major trends are evident:

- A marked shift in the balance of production away from the 2021 dominant concentration in Northeast Asia towards other global regions including Southeast Asia, India, Africa, North and South America
- A large-scale reduction in the dominance of Basic Oxygen Steelmaking from coal (BF-BOF pathway), shown in red
- A large increase in recycling (EAF-SCRAP pathway), shown in yellow
- A large increase in green steel manufacturing technologies, shown by the yellow-green (EAF-PRIMARY, imported green iron) and green (DRI-H_2-EAF, direct reduced iron with hydrogen) circles

The green iron subsidy triggers initial production leading to economies of scale and learning for the DRI

Figure 3. Global Cumulative Emissions and GHG Cost Reductions for four main scenarios (2024-2050)

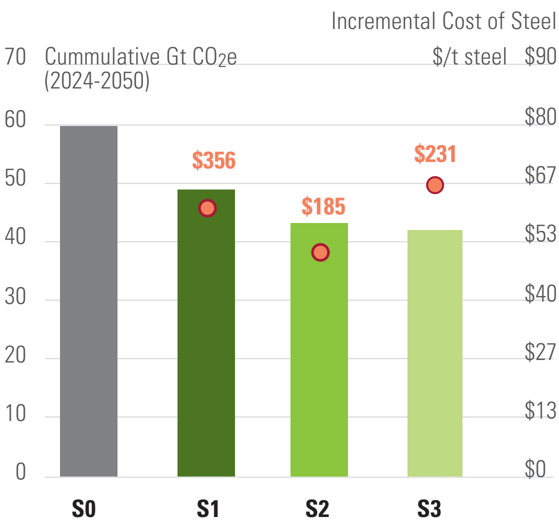
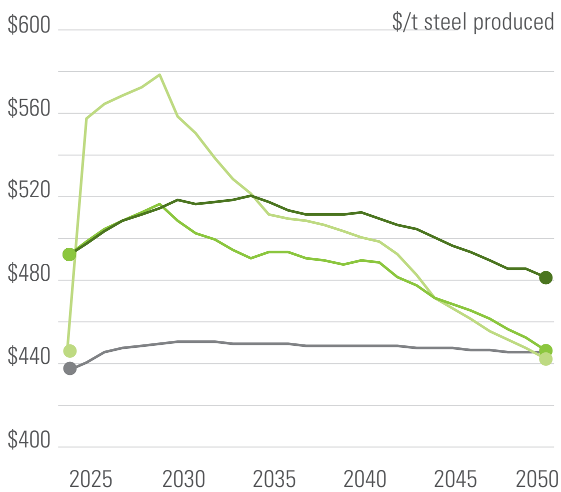


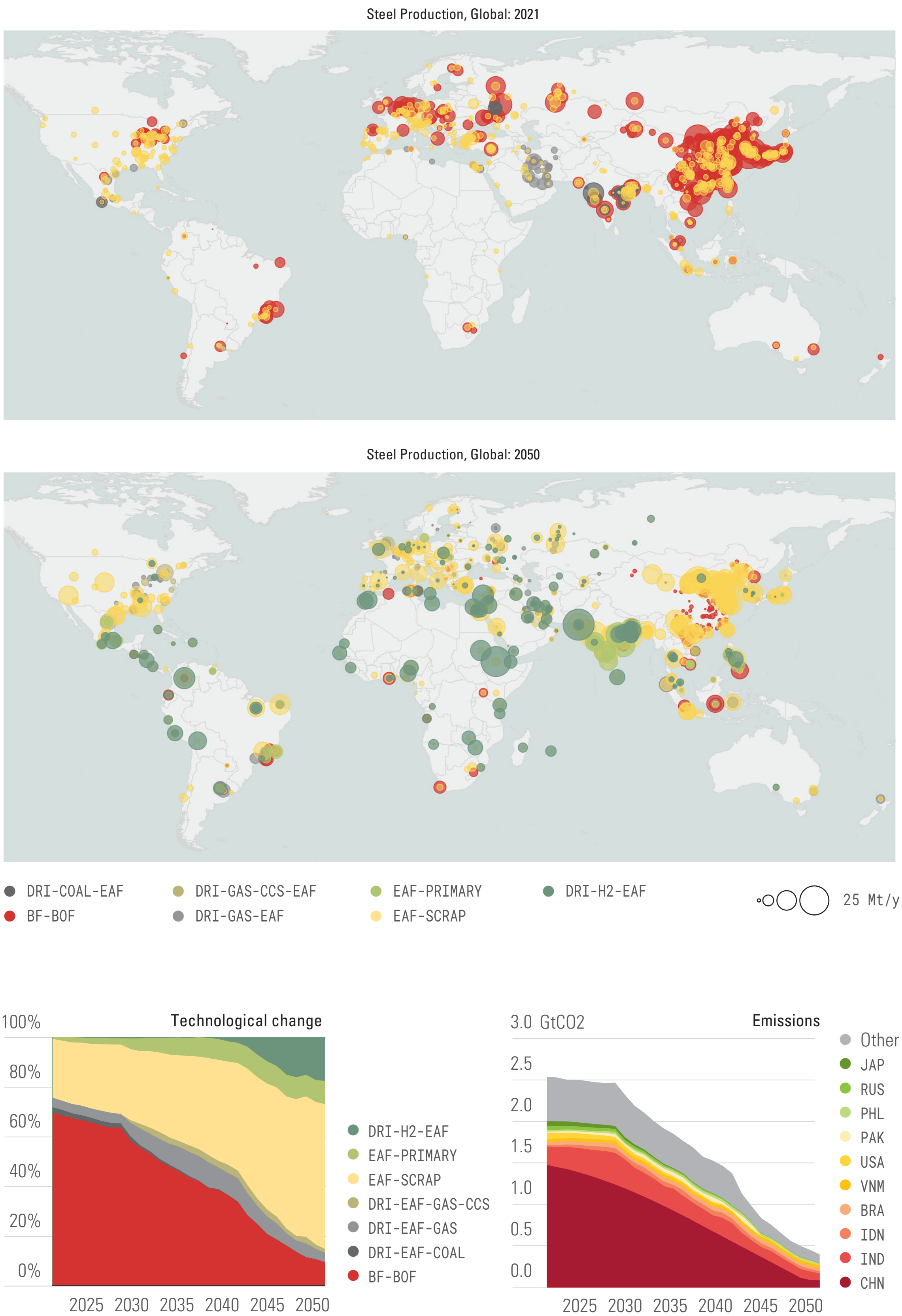
Figure 4. Global Evolution of Production and Transport Costs of Steel for Core Scenarios



S0 Baseline **S1** Narrow Club **S2** Broad Club **S3** Broad Club Fossil Fuel Ban

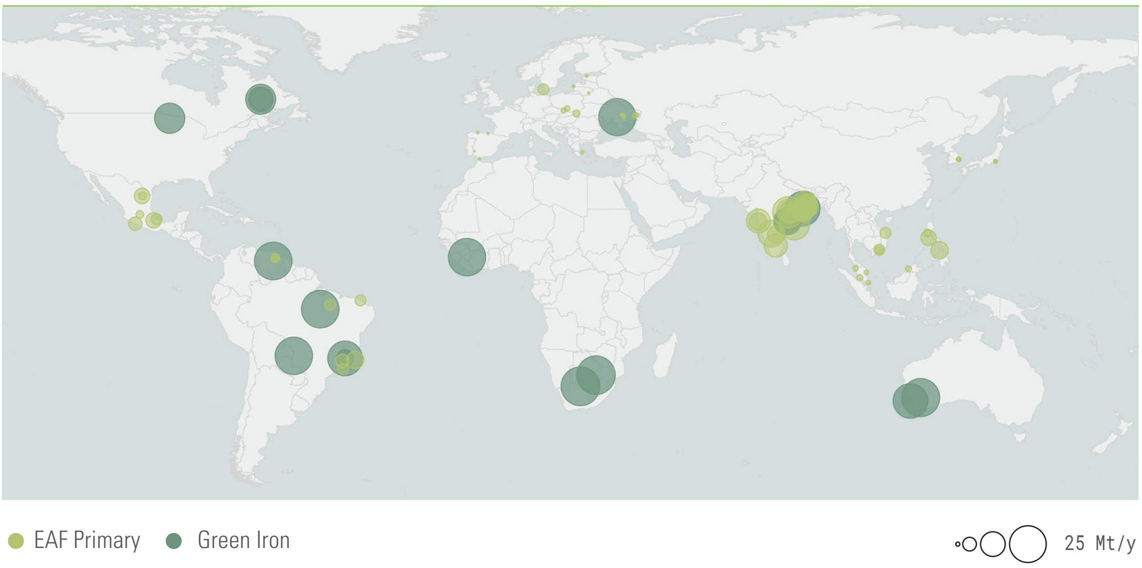
Cost per tons of steel reduced

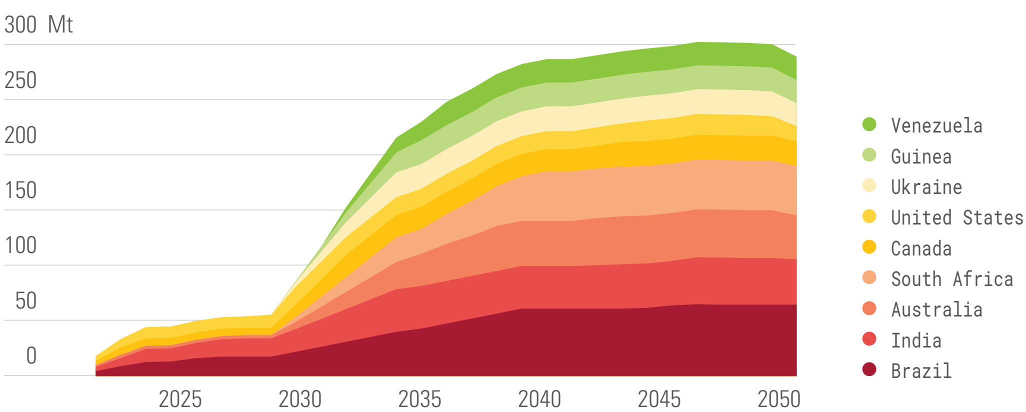
Figure 5. S2 Broad Club Scenario: Technological Change and emissions



technologies as well as providing club members with an alternative source of reduced iron from a diverse group of suppliers, while avoiding the political challenges of banning "unabated" fossil fuel iron ore reduction. Traded green iron is a significant component of the overall decarbonization story in our scenario, increasing from near zero in 2022 to 200-255 Mt annually by 2050, with Australia, Brazil, India, and South Africa as major producers. By 2050, steel made from green iron accounts for just under 10% of global demand, and is functionally only limited by the number of adequate quality mining sites and reserves added to the model. India, the member economies of ASEAN, the European Union, Mexico, and South Africa are notable consumers of green iron. Trade in green steel and green hot briquetted iron is likely essential to meeting any sort of deep reduction targets as it allows regions without adequate extra renewables, hydrogen or CCS geology to make use green steel in electric arc furnaces, either by itself or mixed with scrap. **Figure 6** shows the global distribution of green iron production (green circles) and where it is being smelted in electric arc furnaces (yellow-green circles) in 2050 in our Broad Club scenario. In this specific scenario, about 2/3 of global green iron production for 2050 is being exported to India, but it should be noted that under sensitivity testing we found many permutations and mixes of trade flows to be possible, and trade flows also vary through time (i.e. patterns shift over the model period 2022-2050). India has indicated a desire to make as much steel as possible domestically, but this could be done with imported reduced iron, and if not the iron would likely be exported instead to eastern Asia or Europe.

Figure 6. Production of Green Iron





An upshot of our analysis is that it will likely be cheaper to pay a market premium for green iron rather than to pay for carbon dioxide removal (CDR). While a market premium on top of the standard selling price of $100 per tonne green iron pulls as much as physically possible into the market for a subsidy of $56 per tonne CO_2 avoided[5], carbon dioxide removal will likely cost at least $100-300 per tonne CO_2, if it's available in sufficient quantity. This market premium will also likely have a strong effect on innovation, perhaps pulling the timeline for direct electrolysis-based steel production technologies forward to commercialization faster than anticipated.

5 In other work to be published later in 2024, we have found that the very "first-of-a-kind" FOAK reduced iron facilities require an additional $312 per tonne iron before other inducements, carbon pricing, or subsidies, with a range of $181-422 per tonne depending on variability in input costs, with the additional necessary premia falling rapidly with each additional plant due to learning effects.

If this were to happen before 2050 then emissions would fall faster than we have shown in all of our scenarios, cumulative emissions would be less, less CDR would be required, and the date for achieving net zero would occur earlier than our current model estimates. The results of this analysis are also very sensitive to short term policy influences on the Asian BF-BOF fleet as it comes up for relining in the decade following 2025. The ***Broad Club*** scenario, while achieving only -85% not -95% by 2050, also has the critical element of respecting common but differentiated responsibilities (CBDR) in the Paris Agreement, whereby richer members of the international community have agreed to shoulder more of the burden of reducing global emissions compared to countries that are still developing their industrial base to meet critical human development and wellbeing needs.

What's important about how we modelled the scenarios

Our pathways start with an updated database of existing steel facilities worldwide, defined by location, technology, capacity, production, energy consumption and GHG emissions in 2021. The Global Energy Monitor (GEM) database, which identifies 1055 unique facilities above 500kt per year capacity in 85 countries, capturing around 97% of global production, is the starting point for these definitions. We also employ the Global Infrastructure Emissions Database (GIEDS), Worldsteel Association production data, and the OECD national capacity database to cross reference facilities, build energy and emission profiles, and to identify the 3% of global production that is not identified in GEM. Missing global production is allocated to 33 retired or idled sites in the GEM database and to 15 additional sites in countries not included in the GEM database, bringing the total number of unique facilities to 1070 in 100 countries. Our scenario projections also seed future production in an additional 37 countries based on scrap availability and national steel demand and adds 15 green steel sites that are already under construction at the time of writing. Our boundary for emissions includes all direct energy and process emissions that occur at integrated iron and steel mills, differing from other boundaries (e.g., World Steel Association & the International Energy Agency) that include indirect off-site heat and electricity purchases and scope 3 intermediate input emissions. While a core assumption of our scenarios is that there is also policy to drive utility electricity emissions to near zero, the model is free to choose between utility and islanded electricity sources depending on local resources and prices, based on the projected utility prices in the IEA Net Zero Scenario (IEA, 2021, 2023b). Future steel demand is driven by a new purpose-built econometric analysis of the drivers of steel demand as a country's population grows, income per capita rises, and infrastructure needs grow.

To simulate steel production pathways the model tracks the age of all significant iron and steel making reduction facilities and progressively replaces key GHG intense processes, i.e., iron reduction and steel making, with the lowest cost options as they reach the end of their first operational life (we model an average of 20 years, with sensitivity testing to 17). The technology investment decision is based on economic costs (i.e. local capital, operating, labor, raw materials, and energy costs), available unused capacity, explicit and implicit infrastructure costs for new sites, geographic feasibility and national or regional climate policy or trade policy drivers (trade tariffs, subsidies, emission pricing). The pattern of future investment in steel production is therefore driven by scenario assumptions around the rate of technological change, the relative costs of steel production in different world regions (e.g. energy costs, labor costs), the strength of climate policy in different countries and trade zones, and explicit considerations around geopolitics and trade policy in relation to the iron and steel sector. At the time of writing in early 2024, only one 90% mitigation primary steel technology is currently commercially available (methane based direct reduction of iron (DRI) with carbon capture and storage), with one plant operating and several conversions and new builds underway, and intensive commercialization is only proceeding with 100% green hydrogen DRI-EAF or DRI-melter-BOF (11 EU investments planned at time of writing). Oxycombustion smelter-BOFs or BF-BOFs with CCS are technically feasible, but no known institution is investing the several years and ~USD$10+ billion likely needed to bring these technologies to full commercial fruition. Country level analysis identifies major shifts in capital investment from existing producers (e.g., China, South Korea) to new facilities in Africa and India.

Implications for global and national climate policy for steel use and demand

Chinese fleet and overcapacity

China's steel fleet capacity, currently producing 54% of global production, is projected to exceed domestic demand over the next decade, and what China decides to do with its excess BF-BOF capacity will have significant implications for the global steel market and the global clean steel transition. Will they retire the least efficient facilities? Or will they export or repurpose the steel for downstream exports like vehicles & structural steel, which would likely greatly reduce global steel prices and stress global steel companies? The Chinese government has a mandate in place to swap high efficiency new plants for older plants at a 1:1.25 ratio (1.5 in environmental sensitive regions, and 1:1 for clean secondary or primary production) (OECD, 2023a). Our modelling estimates that while Chinese secondary steel rises rapidly with available scrap, primary production falls off because of falling demand and rising relative cost of production, mainly labour costs, but slower than demand. In our Broad Club scenario Chinese exports temporarily rise to ~100 Mt per year through 2030, falling to ~50 Mt by 2040 and reaching negligible numbers by 2050 - other scenarios we explored saw exports as high as 200 Mt per year. China has shown a willingness to "swim upstream" against prevailing market forces to reset markets, however, and what it does with its excess BF-BOF steel capacity in the 2020s and 2030s matters. If Chinese firms can be persuaded to close the least efficient facilities with the worst air quality impacts this would leave more room globally for new clean iron ore reduction facilities.

Developing country demand

If development is successful in India and other lower income industrializing, emerging and least developed economies, their steel demand is set to surge - because of this, the climate club size is critical. Because most new demand is domestic demand in Asia, India and Africa, the club needs to encompass at least a portion of these regions to drive reductions towards net zero. In particular, demand in India may triple or more, and it may not be able to meet all its own demand, and especially if not using unabated coal BF-BOFs. Our modelling indicates it could be most economic to import the necessary iron for processing in electric arc furnaces. This requires, however, a clear signal to potential supply regions and firms that there will be sufficient demand to make these investments.

Any pathway to net zero steel requires all new iron ore reduction being near zero

A transition to net zero steel production is possible, and a natural movement to more secondary recycled production makes this easier, but requires that all new iron ore reduction is near zero emitting by the early 2030s. The key technology for making primary iron, coal-based BF-BOFs, must either change so that the emissions can be captured, or it must be a superseded with new near zero emissions iron reduction technologies (iron reduction produces 80%+ of steel emissions).

There is a significant potential for lock in of unabated gas based DRI capacity if global policy incentives are incremental as opposed to transformational. Unabated gas DRI roughly halves the GHG intensity of coal-based BF-BOFs, and its use is a natural response to gradually increasing climate policy. Unless these DRI facilities are designed to be easily retrofittable to 90%+ capture CCS or 100% electrolysis based hydrogen, they could end up as stranded capacity, emitting at one third to one half the rate of a BFBOF depending on electricity GHG intensity for the EAF. A key result is either policy must immediately move to sufficient stringency to trigger near zero emissions investment, or all investment must be retrofittable to near zero.

Our available recycled scrap forecast is +14%, 204 Mt/yr higher than in our previous study, Netzerosteel (2021), but requires building code, design & recyclability policies, as well as well functioning collection and sorting networks. Vehicles, buildings, & infrastructure need to be designed to be taken apart at end-of-life in a way that allows high quality, low contamination recycling, especially for copper.

Reaching net-zero requires crystal clear communication to steel makers that no more "unabated" BF-BOFs without 90%+ capture CCS can be built past 2025 in developed regions, and past 2030 in developing regions, and that they should be planning for near zero emissions alternatives. This is equivalent to running a carbon price schedule of $200 per tonne CO_2e starting today, effectively translating into a ban on unbated BF-BOFs, or $30 per tonne rising to $300. This requires a multi-level policy commitment to transition to net-zero GHG industry. This in turn requires a transition pathway planning process including all key stakeholders (e.g., steel firms, finance, unions, communities, governments) to assess strategic & tech options, competitive advantages, and uncertainties.

Starting the process of clean replacement of iron ore reduction plants for primary production in the late 2020s requires a fast and effective global innovation process to commercialize alternative primary iron reduction technologies. This is arguably happening fastest with green & blue hydrogen direct reduced iron (DRI) and possibly electrolysis. Green hydrogen DRI is underway in Europe and will likely meet the 2028 goal for several plants commencing operations. Several blue hydrogen DRI plants have been announced globally, while BF-BOF CCS is arguably going too slowly to meet the 2030 goal. This implies a requirement for accelerated R&D and especially commercialization to broaden the range of available technologies.

Lead markets can be created with partners to build economies of scale using several different policy options: public and private green procurement of green iron product that both prefers green iron and pays a premium, e.g., through limited but guaranteed pricing or output subsidies (e.g. through reverse auctioned contracts for difference). Our $100 per tonne subsidy for green HBI is a proxy for the range of policies that are possible - any technology that can provide near zero emissions reduced iron would be eligible for the subsidy, e.g., electrolysis or BF-BOF with 90%+ capture. There are many ways this subsidy could be actualized: as a straight dollar per tonne subsidy for production, as an IRA style production tax credit (which would have to be $312 per tonne (with a range of $181-422) in the US before all other inducements such as the IRA CCS, hydrogen, storage and electricity tax credits), as a contract for difference minimum price for steel, or as public or private agreement to buy at a minimum price, etc. How it would be funded is up for debate, but CBAM or intra-club national carbon pricing revenues provide one avenue.

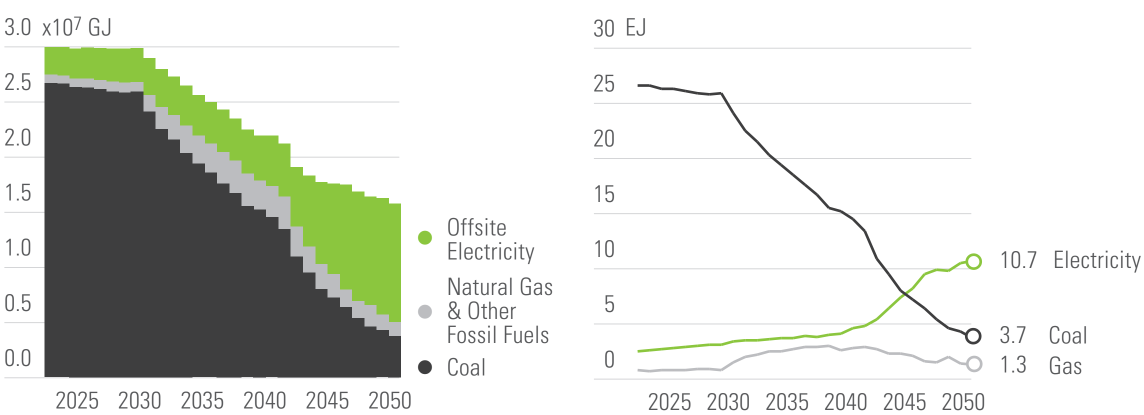
Public sources of funding will be limited beyond the first round of full scale plants, and some way must be found for industry to self-fund the transition and recover the costs from customers for steel. One possibility is to employ a Zero Emissions Iron (ZEI) tradable performance standard. Under such a policy, all iron sold within a region must come with a minimum tradable portion of near zero emissions iron, similar to the design of the California Zero Emissions Vehicles standard. Companies that overcomply could sell their excess permits to under complying companies. The standard could start as the equivalent of secondary content, but within 5 years transition to the equivalent of 1 zero emissions facility (i.e., 1 Mt/yr), then 2, 3, etc. In this way the industry would self-fund its own transformations on a pathway set by the most cost efficient clean firms. A ZEI standard could also replace the use of first of a kind subsidies if the necessary technology is ready enough, and just costs more.

Some sort of global finance mechanism is required to trigger investment in developing countries. Given much of the new demand for iron and steel will be in developing countries, and specifically on the journey from lower income ($1145 GNI/capita) through upper middle ($4465"), e.g., India at $2380 in 2022, to high-income ($13465") an international policy focus should be made on building near emissions facilities in these countries. This includes something like the Just Energy Transition Partnership (JETP), but for industry, e.g., a Just Industry Transition Partnership (JITP). The green iron subsidy in our study is one hypothetical means to operationalize an effective JITP. Another practical way might be for developed country steel companies to receive domestic compliance credits for building near zero emissions facilities in developing countries.

If it takes too long to commercialize low emissions technologies or to mandate their use, and high intensity facilities are built into the 2030s, early retirements may be necessary or the steel sector will not reach net-zero by 2050.

Clean electricity requirements increase 4.2 times in the *Broad Club* and *Broad Club Fossil Fuel Ban* scenarios, which may stress some countries' capacity to deliver. This can be reduced by importing reduced green iron from countries with iron ore and excess capacity for clean electricity (e.g., Australia, South Africa, Brazil). To alleviate overdependence on one supplier, purposeful cooperation to develop several supplying regions, to create a green HBI pool, can help alleviate this. This market can also help the incentivize the development of next-generation electrolysis technologies. We specifically found that HBI imports could help relieve electricity market pressures in key regions, e.g., the EU and India with its fast-growing demand, but our modelling indicates a cost premium is necessary to trigger uptake. A subsidy of $75-100 per tonne of green iron (eligible to all form of green iron production) is sufficient to trigger substantial investment in green iron production. While green HBI doesn't strictly initially compete against combined syngas based DRI with CCS or green hydrogen DRI

Figure 7. Broad Club scenario fuel use



because of its slightly higher costs, it instead provides a critical "2nd or 3rd best" strategy for moving gas with CCS or clean electricity consumption somewhere that can better accommodate it for geographic or geo-political reasons. It also drives global economies of scale cost reductions associated with DRI production, as seen in **Figure 4**.

Key final messages

- **A global transition to net-zero CO_2 emissions steel by midcentury is possible through maximizing volume and quality of recycled steel from 25 to 50%+ of production, paired with several possible near zero emissions iron ore reduction technologies**

- **Chinese capacity to make emission intense BF-BOF primary steel will soon exceed its demand. If Chinese firms can be persuaded to close the least efficient facilities with the worst air quality impacts this would leave more global market share for new clean iron ore reduction facilities, inside or outside of China.**

- **The next few years are critical to reorientate the global steel industry toward net zero emissions by mid-century.** It takes at least 5 years from project inception to production for new iron ore reduction facilities, usually much longer, and any new reduction facilities built in the 2030s will be operating in the 2050s.

- **Given most new demand for steel is outside developed countries, even a club of ambition that included the European Union, North America, South Korea, Japan, Australia and New Zealand (Narrow Club in this report), would not be large enough to transform the global steel industry by itself.** This is true even if the rest of the world adopted significant carbon pricing policies (e.g., rising to \$100/t CO_2e by 2050). A broader club including for example India is required.

- **Lead markets, especially for the first round of low GHG intensity iron ore reduction projects, are necessary to establish demand and investment certainty for clean iron ore reduction.** This can be established through government preferred and subsidized procurement (e.g, through contracts for difference), through production tax credits like the IRA, or perhaps through something like the tradable Zero Emissions Vehicle mechanism, e.g., a Zero Emission Iron instrument.

- **Reasonable cost finance is necessary to fund risky and expensive upfront investment, especially in developing countries.** For at least the first round of projects in developing countries some form of risk reduction or concessional finance mechanism is necessary.

- **Trade in low GHG intensity green hot briquetted iron (HBI) from multiple suppliers offers flexibility, security, and a means to transfer electricity and hydrogen consumption where it is cheapest and cleanest**, as well as adding value to scrap for mixed primary & secondary production. We found it could reach at least 10% of global production, limited only by available iron ore resources. To reach its potential, however, it requires clear trade rules and tariffing that accurately assesses GHG intensity for all traded steel and iron.

Country data and all other products available at netzerosteel.org, netzeroindustry.org

INTRODUCTION

Meeting the "under 2C and towards 1.5C" goals of the Paris Agreement (UNFCCC, 2015) requires global, economy-wide emissions to fall to net-zero by 2055 – 2070. Unfortunately, the history of treating steel as "hard to abate" or part of the "last 20% of emissions" has meant there has been a lack of ambitious global steel decarbonization roadmaps or scenarios, and more generally a vision of how the steel industry might become compatible with a world where temperatures are stabilized at 1.5-2°C above preindustrial levels. Many decarbonization planning exercises explicitly or implicitly assume that emissions from the steel industry will become net zero using carbon capture and storage on existing technologies or by or using carbon dioxide removal (CDR) technologies. Relying heavily on technological or natural CDR is a great risk because additive, verifiable, permanent and traceable offsets may not materialize in sufficient quantity at a reasonable cost to achieve net zero by mid-century. Maintenance of the current global steel production fleet using 70% BF-BOFs using 90% effective capture CCS would require roughly 300 Mt of offsets - $30-90 billion per year at $100-300 per tonne CO_2 for BECCS or DACCS (Keith et al., 2018). And these would have to be new purpose-built BF-BOFs designed specifically to integrate with CCS capture; the emissions sources from existing BF-BOFs, with 2-3 big point sources and several smaller dispersed ones, are relatively spread out across an integrated facility, making CCS retrofits difficult and only maximum 50% capture possible on existing facilities (Fan & Friedmann, 2021). At the time of writing, our estimate of the necessary investment (~USD $10-20 bn+) to successfully commercialize and deploy working BF-BOFs with CCS at scale, perhaps as "once through" smelter BOFs with oxycombustion to allow concentrated CO_2 that is easier to capture, is unfortunately nowhere to be seen and would be needed in just a few years from now to make a difference. Instead, the major players in steel manufacturing are overwhelmingly continuing to invest in dirty steel production from unabated BF-BOFs alongside a handful of upcoming facilities using methane with CCS or electrolysis based hydrogen to directly reduce iron (DRI).

Current global direct steel emissions are 2.6-3.7 $GtCO_2$ (6-10% of energy system CO_2), depending how they are measured (e.g., whether the GHG intensity of electricity or heat bought or sold is counted). Iron and steel plants can operate essentially indefinitely with refurbishments, and usually only end their lives when they become economically obsolescent. The most ambitious and widely known Paris Agreement compliant global scenario including iron & steel published to date is the IEA NZE scenario (IEA, 2021) and updated in (IEA, 2023b) & (IEA, 2023c). It employs ~26% material efficiency gains, more secondary recycling (33% of production rising to 48%) and transformative hydrogen, CCS and direct electrolysis-based production pathways to eliminate most emissions from the sector, leaving about 5% legacy unabated facilities (~112Mt) and ~222 Mt of residual post CCS emissions. The IEA NZE does not specify detailed technological results nor final 2050 emissions clearly, so these values are estimated based on common production GHG intensity (2.2 tonnes CO_2 per tonne BF-BOF) and capture values (90%).[6] While there is a clear vision in the NZE of how the global steel sector can transition to near net-zero, there is insufficient detail for national and firm actors to see how their industry and facilities may transition. Without this vision the likely default outcome will be vague promises from industry and government actors of an eventual transition to steel production with CCS, when what is needed is detailed investment and infrastructure planning to support the use of low emissions steel making technologies that are already on the verge of commercial viability (e.g., blue hydrogen with CCS or electrolytically based green hydrogen DRI steel making, followed by direct electrolysis once fully commercially developed) starting in the late 2020s, and no later than the early 2030s given the minimum 20 year life of the primary processes in steel plants. We need a detailed set of results to open imaginations and provoke debate, a necessary precursor for any change in policy, planning and investment.

6 The IEA NZE scenario identifies "CCUS-equipped", 37% in 2050, which could be BFBOF or syngas DRI, "electrolytic hydrogen based", 44% ", and "iron ore direct electrolysis", 14% ".

How iron and steel is made in a nutshell

Basic steel is a mixture of mostly elemental iron and 0.1-2.0% carbon for stiffness. To make stainless steel up to 20% chromium, nickel, manganese, and zinc are added. It is purified (contaminants are removed using oxygen lancing and slagging agents) and mixed in the correct portions for a given end-use in a ladle furnace that follows the basic oxygen furnace (BOF) or electric arc furnace (EAF) (**Figure 8**). Most primary steel today (~70%) is made using BOFs, while secondary recycled steel in made in EAFs. Both require iron inputs; the iron for BOFs comes from sintered iron ore, with the oxygen stripped from iron ore using carbon monoxide from coking coal as the reductant in blast furnaces (BFs), hence the common acronym, BF-BOF. In recycled steel, the iron comes in as scrap from vehicles, demolished buildings, etc.

Most of the emissions of CO_2 today from iron and steel production are from blast furnace iron ore reduction and basic oxygen furnace smelting (**Figure 9**). Please note that **Figure 9** includes indirect electricity emissions, and that 80% of steel finishing is electrified.

Figure 8. How we make iron and steel today, and the main options for decarbonizing it

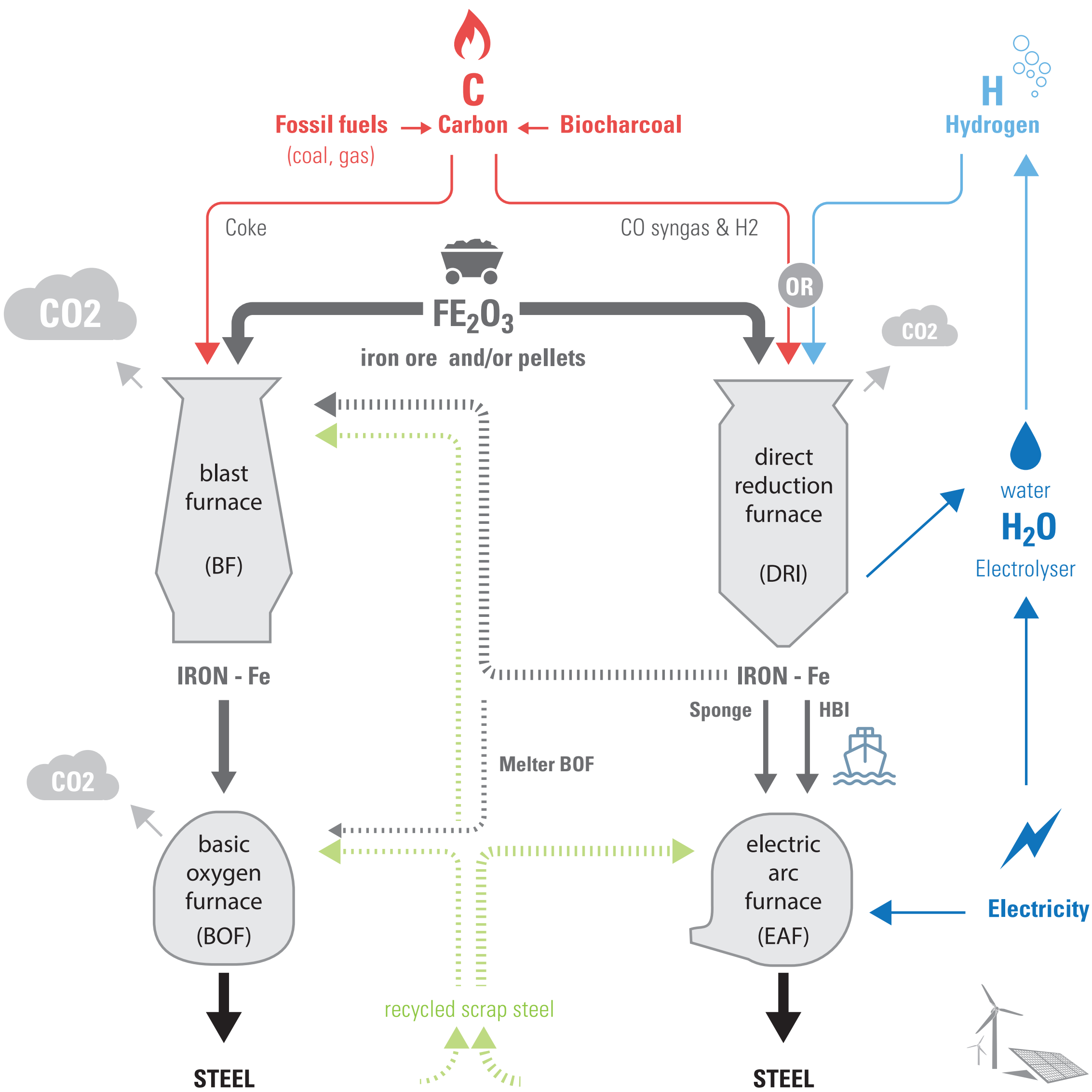
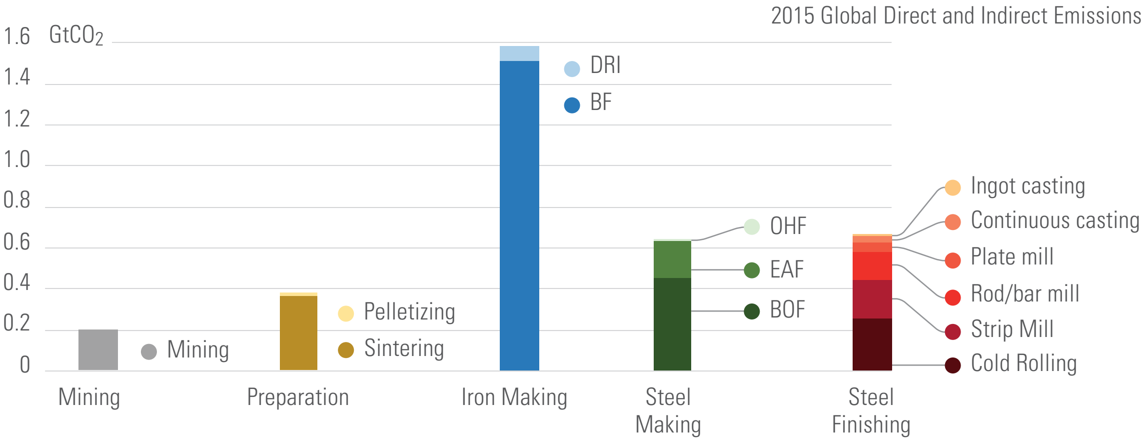


Figure 9. Emissions by process step (Wang et al., 2021)



The global steel fleet of today

The existing world steel production fleet is summarized in **Figure 10** and **Figure 11**. By far the largest portion of steel making is in east Asia, with 53% of global production in China. A very large portion of the BF-BOF fleet, responsible for most emissions, was built in 1990-2010, and it is and will continue to be coming up for furnace lining renewal in the 2020s.

Deep decarbonization options for iron and steel production

There is now a broad and deep decarbonization literature on steel.[7] At least nine main pathways to significant decarbonization have now been identified, summarized below along with Technology Readiness Levels (TRL), which were initially developed by NASA, have been provided[8]. TRL 9 represents a fully commercial technology ready for market uptake; TRL 4-6 represents the development stages (small to large prototypes), while TRL 7-9 are the deployment stages (pilot to full-scale demonstrators). The IEA uses an extended scale, where 10 is "Integration at scale needed", and 11 is for fully commercialized technologies described as "mature, proof of stability reached".

Material efficiency (e.g., more efficient use in vehicles and buildings) (TRL 10). The IEA, in a sequence of reports from 2019 through 2021, identified up to 40% material efficiency potential in steel use in the literature, and employed 29% in the ETP 2020 and NZE 2021 (IEA, 2019a, 2020b, 2021), and 26% in the latest version of the Net Zero scenario (IEA, 2023b).

Retrofit blast furnace basic oxygen furnace (BF-BOF) with up to 50% "end of pipe" carbon capture and storage (CCS) (TRL 5) (Fan & Friedmann,

7 The authors have used the following articles, but the steel decarbonization literature is expanding rapidly, so this list should be considered partial (Agora Energiewende - Industry et al., 2021; AGORA Industry, 2023; Devlin et al., 2023; Devlin & Yang, 2022; Fan & Friedmann, 2021; Fischedick et al., 2014; IEA, 2020e, 2022a; Lei et al., 2023; Lopez et al., 2023; Mission Possible, 2022; Sun et al., 2022; Tanzer et al., 2020; Toktarova et al., 2020, 2021, 2022; Trollip et al., 2022; Vogl et al., 2018; Vogl, Olsson, et al., 2021a; Wang et al., 2021; Yu et al., 2021).

8 See page 82 of the IEA 2020 Iron and Steel Roadmap (IEA, 2020e) for an extended discussion of TRLs, and how they are set by technology.

Figure 10. Where steel is produced in 2021

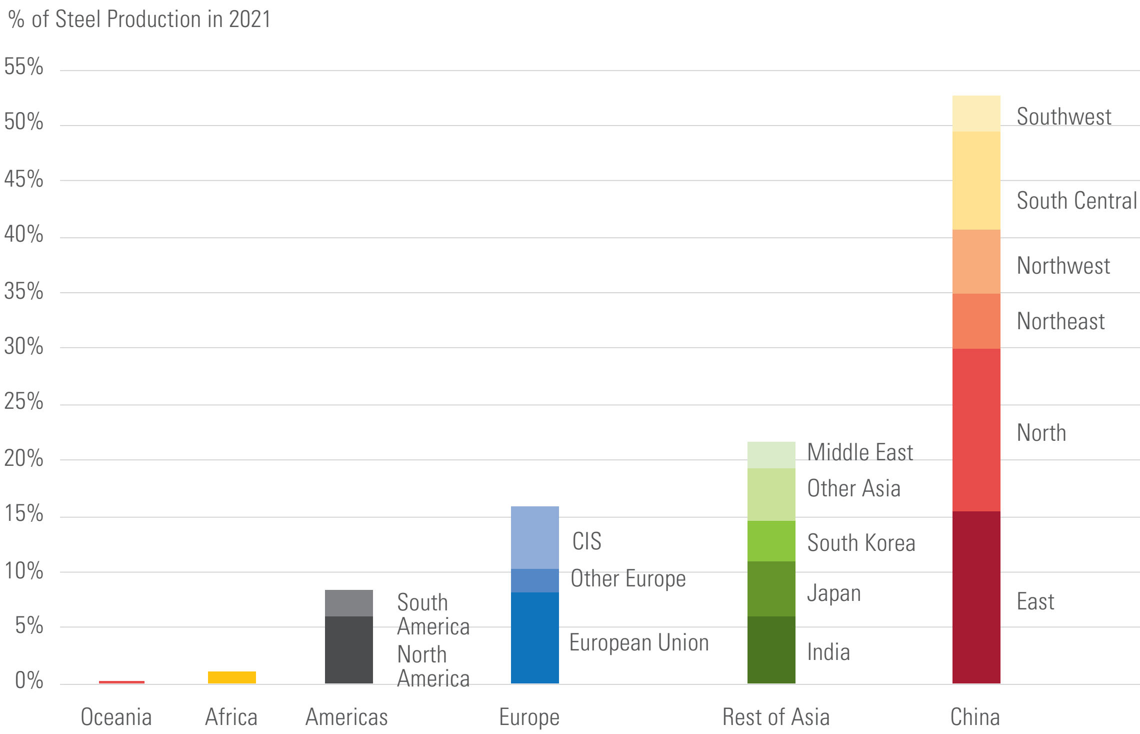
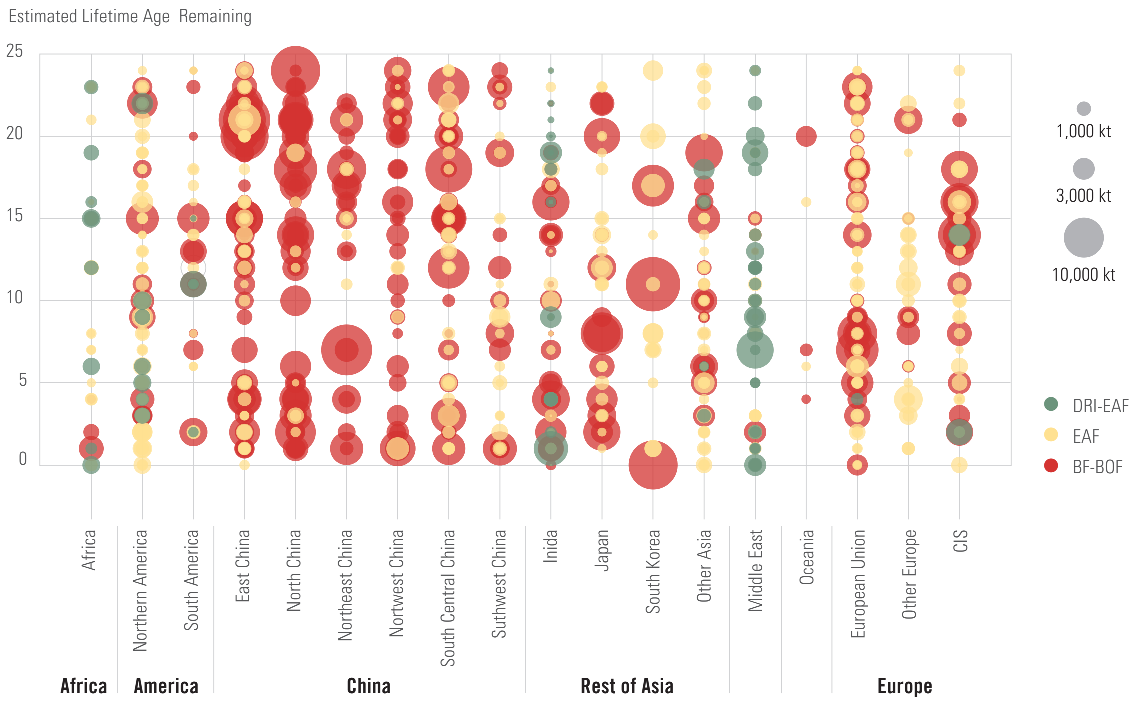


Figure 11. Global steel capacity by type and era of build in 2023



2021). Research indicates that existing modern BF-BOFs could be retrofit for up to 50% capture, but given only 25 years are available to 2050, this would lock in the remaining 50% of emissions, which is not Paris Agreement compatible without implausibly large amounts of CDR.

Hydrogen co-firing in BF-BOFs (TRL 5). Coal is the normal fuel and oxygen reductant (it removes the oxygen from iron ore) in BF-BOFs, but hydrogen can theoretically be co-fired up to 20-30% for heat and reduction needs. The upper limit is set by the need for coke, which provides structure to the functioning of the BF process, allowing gases to move upward and liquid iron to move downward. Again, this pathway is not compatible with net-zero emissions without excessive CDR.

New BF-BOFs can be built with up to 90%+ CCS, and can possibly use biomass as fuel and reductant (TRL 5) (Fan & Friedmann, 2021; IEA, 2020c; Tanzer et al., 2020). Theoretically, bioenergy with CCS can create negative emissions, but the net CO_2 emissions (to ground or atmosphere) associated with biomass depends on the biomass source stock and how it is gathered. Using new cut trees, especially old growth, would generally lead to net positive emissions, especially from the soil carbon disturbance, while switchgrass grown on degraded farm land would generally lead to negative emissions from both the switchgrass and the fixing of atmospheric carbon in the soil (Hepburn et al., 2019b) – there is a wide context dependent set of outcomes in between. As noted in the introduction, investment needed to take this technology pathway to full maturity on a timeline compatible with decarbonizing steel by mid-century appears not to be forthcoming from major steelmakers.

Syngas direct reduced iron (DRI) with CCS followed by an electric arc furnace EAF (TRL 9). A DRI steel making facility already operates in Abu Dhabi where methane is split into a syngas of hydrogen and carbon monoxide, and syngas is use as the reductant to strip oxygen from iron ore pellets (i.e., "directly reducing" the iron ore). Some of the post reduction reaction CO_2 is captured for use in enhanced oil recovery. If the well were sealed when extraction was complete or the CO_2 were put in a saline aquifer, the capture would be permanent. It should be noted that there are two commonly used reforming methods to make syngas from methane: standard steam methane reforming (SMR), from which about 60% of the CO_2 is concentrated and easily capturable, and autothermal reforming (ATR), where oxygen is injected and the heat to drive the reaction is made along with the syngas, allowing the exhaust to be almost pure CO_2. This allows much higher 95-99% capture rates. Current MIDREX facilities use SMR, and Tenova Energiron facilities use ATR, but MIDREX has discussed switching to ATR because of the ease of capture.

Green (electrolysis with clean electricity) hydrogen DRI followed by an EAF (TRL 7+). In this process, iron is directly reduced using the same principles as syngas DRI (described above), but instead of a syngas of hydrogen and carbon monoxide, pure hydrogen is used as the reductant instead. A heat source is needed to drive the 900°C reaction, unlike in syngas DRIs where carbon monoxide oxidizing provides the heat. The reduced iron is then sent to an electric arc furnace for melting and smelting into steel, where a small amount of carbon (0.1-2%) must be present for making steel. One full scale version of these plants is being built in Sweden for first of a kind operation, and eleven are now announced to be built across Europe for operation commencing 2025-2030 (Vogl, Sanchez, et al., 2021). The IEA previously provided a TRL of 5 in their 2020 roadmap (IEA (2020)), but as progress is now moving very quickly in this area, we assign 7+ in our own assessment.

DRI-melter-BOF. A modification of the hydrogen DRI process was announced in 2022 by ThyssenKrupp (ThyssenKrupp, 2022), whereby they reduce their iron ore using DRI, then melt it in an electric smelter, strip the slag, and then process the iron in their legacy BOF. This allows roughly an 80% reduction and the use of slightly poorer quality pellets (62-66% instead of 66%+) (BHP, 2023). They also said they intended to move to EAF in the 2040s when more high-quality pellets are available and their BOF is due for replacement.

Aqueous/Molten oxide electrolysis (TRL 4-5) reduction, followed by an EAF. Finally, a very promising but lower TRL family of technologies are aqueous or molten oxide electrolysis (Junjie, 2018; Müller et al., 2021). Electricity is directly used as the reductant and melting heat source High temperature (1600°C) electrolysis involves the use of the melted slag as an electrode, while in lower temperature aqueous electrolysis (60°C to a couple of a hundred °C) the iron ore is put in an acid bath and electricity is run through the bath as the direct reductant. In both cases the direct reduced iron would be sent on to an EAF for making into steel.

A summary of conceptual developments in recent studies

There have been several key conceptual developments and continuation of outstanding questions in the steel decarbonization literature since the fall of 2021:

- **Based on available technologies, global net zero steel pathways are possible.** If the Paris goals are to be met the 2020s will be crucial. Supply chains for key process components, like DRI furnaces and blue or green hydrogen making equipment, will need to be built out. DRI furnace making in particular will have to be increased by 5-7 times (AGORA Industry, 2023). These investments will require certainty the demand will materialize to be met. Production will cost more per tonne, which mean large finance requirements. There will also almost certainly be residual emissions unless CDR is employed (Agora Energiewende - Industry et al., 2021; Bataille et al., 2021b; Mission Possible, 2022; Yu et al., 2021). On the hopeful side, at least one study (AGORA Industry, 2023) has argued we can get to net zero by 2045 if we can go as fast as furnace relining, using an average blast furnacing lining life of 17 years based on Vogl et al. (2021a).

- **Maximizing material** efficiency in steel use is widely recognized as a primary strategy for reducing iron and steel emissions, with reductions up to 25% being conservatively possible, but has not yet been widely acted upon (AGORA Industry, 2023; Bataille et al., 2021a; IEA, 2019a, 2021, 2023b).

- **Maximizing secondary production using scrap in electric arc furnaces has been confirmed as the first best option for decarbonizing steel production** (IEA, 2020d, 2023b), and is growing more rapidly than expected in China. This is subject to contamination levels for some key end uses (Daehn et al., 2017; Panasiuk et al., 2022). Many regions are providing supports to switch to secondary production where possible, e.g. the US and Canada. Mixed primary and secondary production, where up to 50% new iron is added to scrap to make it more useable across a range of end-uses, is becoming more and more standard in North America for solely economic reasons.

- **Several primary production technologies are available to decarbonize the global steel sector** (Bataille et al., 2021b; Fan & Friedmann, 2021; IEA, 2020d; Mission Possible, 2022; Wang et al., 2021).

- **At least two geospatial analyses of global low emissions pathways have been completed** (Bataille et al., 2021b; Lei et al., 2023). Both studies employed maximum secondary steel making, but Lei et al (2023) generally assumed a preponderance of CCS for remaining primary steel making, while Bataille et al (2021) employed a regionally appropriate mix of investments, including BF-BOFs or smelter BOFs with CCUS when the scenario allowed, DRI with syngas and CCUS followed by an EAF, and DRI with green hydrogen. Neither study explored the impact of trade, a key focus of this study.

- **Several studies using inter-regional case studies have shown the potential for green HBI trade to shift the cost of electrolysis based hydrogen to regions with lower clean electricity prices** (Devlin et al., 2023; Devlin & Yang, 2022; Gielen et al., 2020; Trollip et al., 2022).

- **Some form of offsetting CDR is likely to be necessary for residual emissions.** Given the remaining residual emissions attached to most low-carbon technologies, biomass CDR steel production has been explored in at least two studies (AGORA Industry, 2023; Fan & Friedmann, 2021). There is, however, considerable controversy surrounding the net-neutrality of biomass under anything less than very specific species, soil carbon and harvesting circumstances (Hepburn et al., 2019a).

- **The jury is still out what will happen in developing country markets, where most new steel demand will be.** While the question of what happens with Chinese steel production is ever present, especially what China does with its BF-BOF capacity in excess of demand as domestic needs for infrastructure and building fall, the speed with which secondary production is advancing is mitigating this somewhat. The big question is now what happens as India's and then Africa's need for infrastructure and buildings accelerates (Bataille, Stiebert, et al., 2023a). In the first Net zero Steel project (Bataille et al., 2021b) we estimated demand would rise 3 to 10 times over current levels in the largest developing countries (e.g., India, Pakistan, Nigeria, & Indonesia). There are several hypotheses: that their development will somehow be less steel intensive; that they could import LNG for use in DRI facilities; that BF-BOF CCS will be mastered; that they will import steel, etc. In the first Net-zero report we projected that domestic scrap production would be maximized, but typically only cover 25-33% of demand, and that the remainder, depending on the country, would need to be domestic or imported hydrogen based DRI, BF-BOF with CCS in a couple of specific cases (e.g., Indonesia). One India-specific steel decarbonization study estimated that demand would be best met without about 25% secondary scrap, 20% BF-BOF CCC, 18% electrolysis, and about 50% "blue then green" hydrogen DRI (TERI & ETC, 2022).

- **What happened to HISARNA**, the oxycombustion based upgrade to BF-BOF steel making that eliminated coking and allowed capture of concentrated CO_2? HISARNA was developed to the TRL 7 level for the EU ULCOS project in the early 2010s, but the company developing it was subsequently purchased by Tata Steel, and nothing public is currently known about any ongoing developments. It is unclear at the time of writing whether the development of this technology has reached a commercial or technological dead end.

- **Finally, will there be a breakthrough in electrolysis-based iron making?** Several different companies are working on different versions of direct electrolysis of iron ore to iron, e.g., Boston Metals is working on hot, 1600°C electrolysis, and Elektra and ArcelorMittal on 60-80°C aqueous electrolysis. Direct electrolysis has the promise of high energy efficiency, modularity, no direct CO_2 emissions and in some case the ability to use poorer quality ores and even mine tailings, unlike DRI. If a commercialization breakthrough were made this could overturn steel's reputation as a "hard to abate/decarbonize" sector. But no technology has yet been demonstrated at the commercial megatonne per year scale, the crucial test for broad acceptance.

Building on these studies, the objective of this project, using the base methodology of the Net zero steel (2021a) report, is to produce transparent facility level scenarios (i.e., geographically explicit and based on real world steel production plants) of a global primary and secondary steel industry that goes to near zero emissions by 2050. It is meant to be highly transparent, so stakeholders (national & local governments, firms, unions, communities) can see where their facilities stand today and at necessary 2030, 2040, and 2050 benchmarks, and thereby provoke debate. Evolving from our 2021 report, the process allocation mechanism now includes a cost and explicitly modelled trade component, based on regional capital, labour, energy and intermediate input costs and varying capacity as well as geographic endowments and political preferences. Ideally this scenario report will help provide support for challenging the still prevalent idea that that the steel transition must necessarily be slow or supported by extensive offsets. This will shift the conversation to the much more real and challenging effort that needs to be made in the areas of lead market policies (e.g., public and private preferential green procurement with a premia to cover the extra cost), infrastructure for CO_2 disposal and/or hydrogen production, carbon pricing and competitiveness protections, the timeline of the transition, how to approach stranded assets, and how firm, workforce and community dislocation can be minimized.

Ultimately the report and facility level 1.5°C to 2°C compliant pathways, with associated 2030, 2040 and 2050 GHG intensity benchmarks, are meant to represent a globally integrated framework for stakeholders to work towards net-zero targets, helping identify capital investments and retirements and policies that can minimize social costs and overcome market and non-market barriers. For steel producers the results can represent a global benchmark to evaluate, measure and create their own plans. For national and regional policymakers, the results will be a blueprint for planning and designing new policies and targets. It is not expected that the results of this project will be accepted as is by nations or steel makers – its purpose is instead to provoke more ambition in their own proposals.

Research Questions

Given the needs for net-zero emissions economy wide by 2050, there are a limited number of production pathways that can replace current high emission intensity production. In our previous 2021 report we explored what that transition might mean for global facilities given information on developing technologies, including relative energy costs and access to CCS geology, but unhindered by political realities and the effects of trade.

In this report we further explore how country and plant level transitions to net-zero steel technologies may be impacted by: geopolitical restrictions; differential climate policy; differential costs across capital, labour, and all forms energy; varying capacity utilization; and trade in iron and steel.

1. What is the potential role of differential regional climate policy through trade to bring about the transition towards a net zero global steel fleet on a Paris Agreement compatible timeline, and at what cost? Are there regions and countries that have inherent geographic benefits and supply chains that lower the cost of production for new near-zero production technologies that may be able to export to other countries?
2. What is the minimum required size and composition of a "Climate Club" (Nordhaus, 2015) coalition of countries focused on green iron and steel trade needed to achieve net zero steel by 2050? How do potential trade tariffs between countries or potential production subsidies for green steel impact the evolution of net-zero steel production?
3. What is the role of the green iron trade from major iron producing nations in accelerating this transition? Under what conditions do iron ore producers produce and export green iron?

METHOD

Model Baseline

Location and Condition of Steel Production Facilities

The purpose of our method is to simulate the sequential, geospatial evolution of the global steel production fleet from its current composition to one capable of meeting future demand from low carbon steel production pathways. For this we need an as accurate as possible picture of the 2021 fleet – our original analysis was based on the 2019 fleet. We explored two databases, one from the Global Energy Monitor (GEM) project with all the facilities they could find with production capacities of more than or equal to 0.5 Mt per year[9], and one from the Global Infrastructure Emissions Database (GIEDS) project.[10] We found the former clearer, more detailed, and more useful for our purpose, and GEM kindly provided us with a copy of their updated 2021 database (all errors of analysis remain ours). The following critical data was used from the GEM database: facility capacity, type (BF-BOF, EAF, DRI-EAF, induction, OHF, etc.), estimated age and thereby duration until a retrofit, and the location by latitude and longitude, which determines access to clean hydrogen from clean electricity or to CCS for methane based DRI production.

We found 2.3 Gt of operating crude steel capacity in 2021 in the GEM database, in 85 countries at 1,055 unique facilities. From this we estimated of 1.9 Gt of 2021 production, or 97% of the global total. We cross referenced with the GIEDS database, country level production identified by the Worldsteel Association, and the OECD national capacity database to identify the remaining 3% of global production. In doing so we thereby found 15 additional countries (100 total) with reported production and/or capacity. We then estimated 46 additional producing facilities (mostly smaller EAFs) based on average regional operating characteristics of facilities and spatially allocated them in near existing production or in major country industry centres. An additional 37 countries were are also seeded in the model for future production based on scrap availability and national demand for steel. We then added 16 announced and under construction sites for DRI-H_2-EAF and DRI-GAS-EAF-CCS projects that had capacity information and availability dates before 2027 from the green steel tracker dataset[11].

Three other key databases were employed. The Oil & Gas Climate Initiative (OGCI & GCCSI, 2021), was used to locate estimates of the locations of usable geological reservoirs (the centroids of suitable geological formations were compared to the longitudes and latitudes of existing steel facilities). We also used the Global Solar Atlas (Solargis & World Bank, 2023) and the Global Wind Atlas (Davis et al., 2023; DTU & World Bank, 2023) to ascertain local renewable energy potential, as the basis for electricity costs for technologies like direct reduced iron using green hydrogen (DOE, 2015; Ramasamy et al., 2022; Stehly et al., 2020; Trollip et al., 2022).

Deriving Facility Level Energy, Emissions and Production

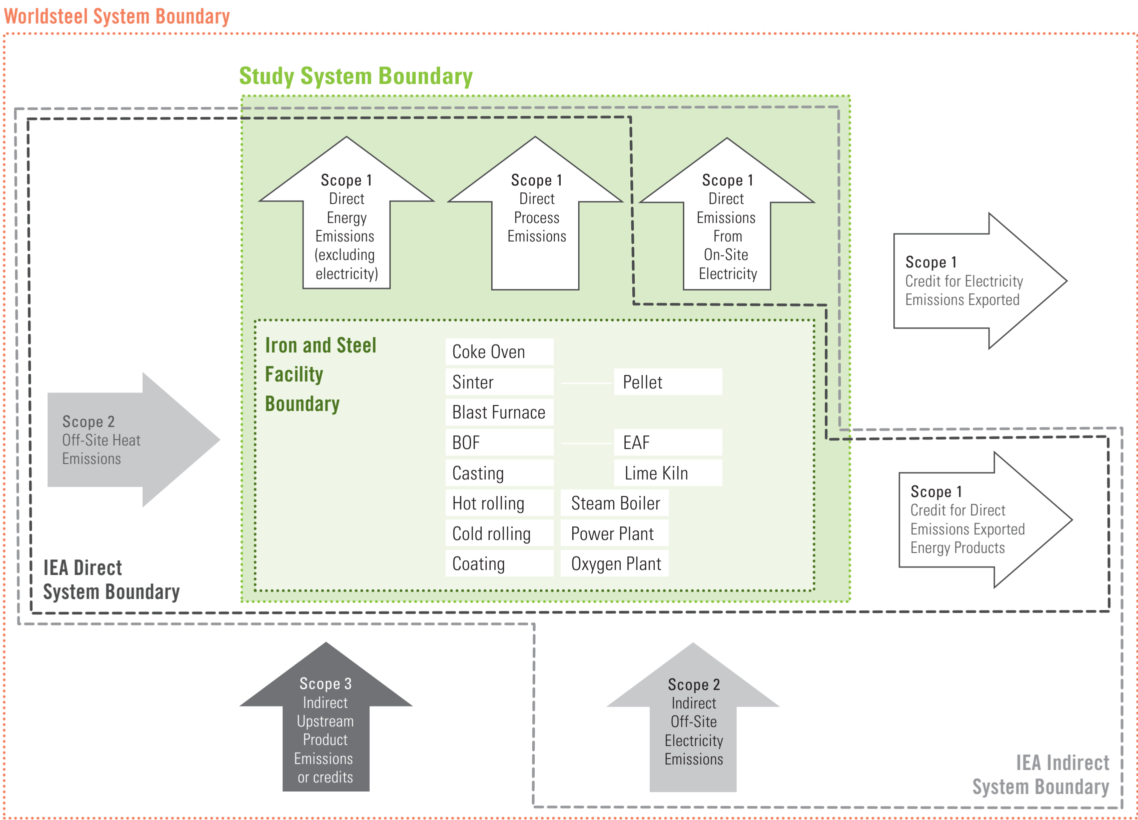
Due to mismatches in primary data, we were unable to use the GIDS facility emissions data, and had to consider a combination of other sources. The most complete and up to date global picture of direct sectoral emissions available are from the IEA Iron and Steel Technology Roadmap (IEA, 2020e) and the IEA/OECD Greenhouse Gas Emissions from Energy Database (IEA, 2023a). The published emissions and emission factors were also reviewed by the World Steel Association, which arguably has the best perspective on global world steel production and facility level information. The IEA Iron and Steel Roadmap reports that global direct emissions from iron and steel facilities in 2019 was 2.6 $GtCO_2e$. This also corresponds to the over-

9 https://globalenergymonitor.org/projects/global-steel-plant-tracker/tracker-map/; https://www.gem.wiki/Category:Steel_plants

10 http://gidmodel.org/?page_id=41

11 https://www.industrytransition.org/green-steel-tracker/

Figure 12. Different System Boundaries for Emissions from Iron and Steel Facilities



all emissions from the GIDS database that reports 2.6 $GtCO_2e$ for 1,417 facilities in their database (i.e., this does not include 529 facilities in the database that do not have an associated iron and steel production capacity – presumably indicating that they are either iron ore mining facilities or secondary production facilities). Global Efficiency Intelligence[12] also reported global direct emissions of 2.6 $GtCO_2e$. We use these studies collectively to build emissions benchmarks combined with updated production from the Global Energy Monitor and Worldsteel to create a detailed picture of present and possible future sectoral emissions.

This study uses a boundary for direct emissions that includes all direct energy and process emissions that typically occur at integrated iron and steel mills (**Figure 9**). These include emissions associated with: iron ore sintering, coke ovens, blast furnaces and basic oxygen furnaces; on-site heat and electricity production; iron ore pelletization; direct reduction; ladle furnaces; casting and hot and cold rolling processes. Upstream emissions are not included from mining or deep beneficiation[13] of iron ore, processing of scrap steel off-site, and embodied emissions associated with the purchase of alloy metals, oxygen, lime, electricity and heat inputs. No credits for energy-product sales are included. Downstream secondary manufacturing from the flat and long steel products that are the final outputs of steel mills are also excluded.

The boundary of direct emissions in the IEA report closely overlaps but does not exactly match with the study boundary (**Figure 12**). Whereas in our study boundary we include all emissions that are energy-related emissions and process emissions that occur on-site, the IEA report diverges and considers on-site electricity generation as indirect emissions. Both we and the IEA consider off-site electricity generation as indirect emissions. **Figure 12** compares different CO_2 emissions system boundaries adopted by Worldsteel,

12 Hasanbeigi, A. (2021). Global Steel Industry's GHG Emissions — Global Efficiency Intelligence

13 For example, the use of electricity to concentrate 33% magnetite to 66%+ DRI grade ore for DRI pellets.

the IEA iron and steel roadmap and for the purposes of our study (direct emissions with no crediting).

Residual emissions from EAFs that are a result of coal and coke being added as carbon sources to carburize the melt and contribute to slag foaming, as well as graphite electrode consumption, have not been included in the analysis. Most of these emissions, 50-60 kgCO_2e/tonne of steel produced, are associated with the added carbon sources and we assume that steel makers will pursue alternative carbon sources such as renewable biomass to eliminate these emissions (Echterhof, 2021). The remaining emissions from graphite electrode consumption, 5-7 kgCO_2e/tonne of steel, will be more difficult to reduce, but even where all future production in 2050 is from EAFs the total contribution of graphite electrode consumption emissions is estimated at 0.01 GtCO_2e or approximately 0.4% of current 2022 emissions of 2.6 GtCO_2e.

The reason that the IEA considers on-site electricity generation to be a source of indirect emissions is that they are working within a context of global energy modelling where they model all grid connected electricity generation together, regardless of whether the electricity is ultimately used on or off-site for industrial facilities. The boundary used in this study instead allocates all on-site electricity generation emissions to the steel produced, even if the facility is exporting electricity and it is being used by another sector. This may seem like we are unnecessarily penalizing the emission intensity of crude steel production. However, in a net-zero modelling context we must acknowledge that these on-site electricity emissions are inherent to the BF-BOF process – the gases that emerge from blast furnaces and coke ovens are a widely varying mixture of hydrogen, carbon monoxide, carbon dioxide, volatile organic compounds and often particulate matter. They cannot safely be released to atmosphere as is and must either be sold for combustion or be combusted or oxidized on site. It can be used as a fuel in blast furnaces through top gas recycling, but more normally it is used to make electricity, often more than the facility needs. If the BF-BOFs are replaced with DRI or molten oxide electrolysis units, however, there will be no off-gases available for electricity generation, and also no need to dispose of them otherwise.

Table 2. IEA Energy / Emissions Balance 2019, Based on Iron and Steel Roadmap

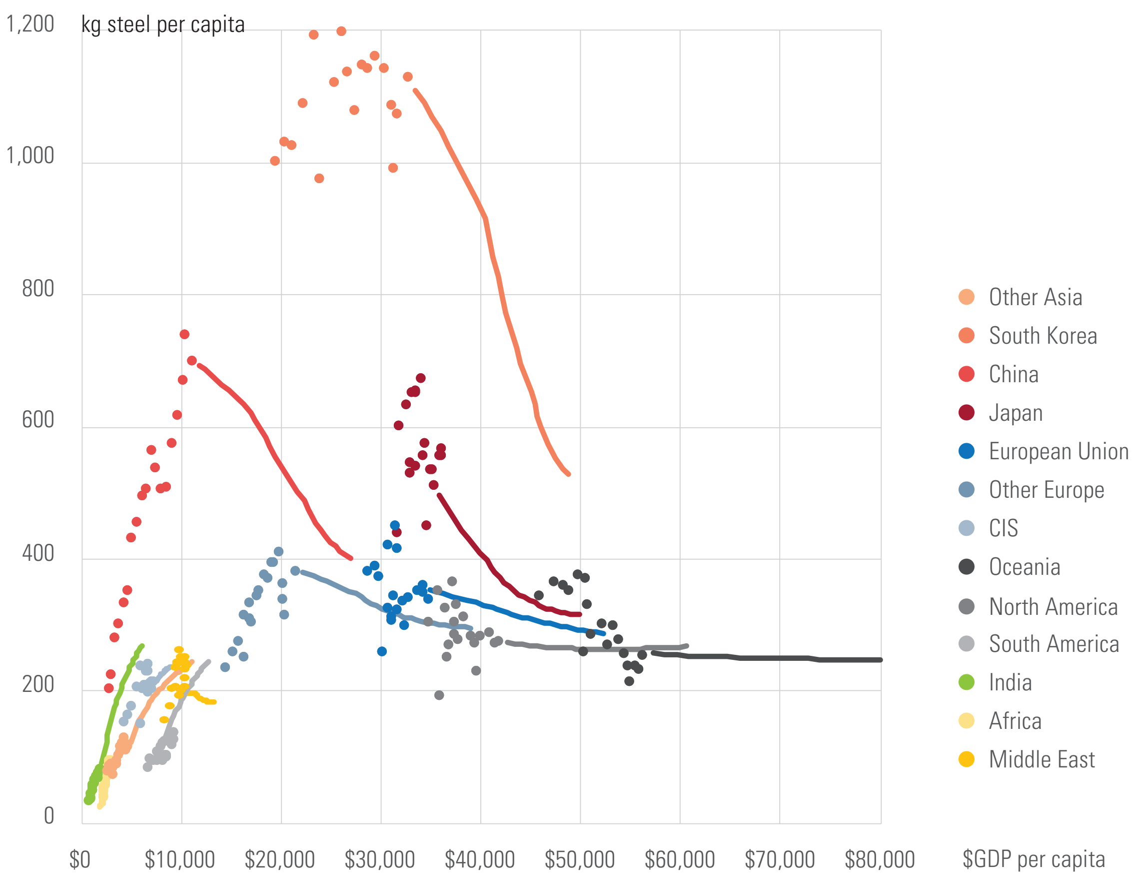
Fuel Type	Estimate of Net Mtoe Consumption	Estimate of Actual Consumption (Mtoe)	Estimate of Actual Consumption (EJ)	Estimate of Emission Factor (GtCO_2e/EJ)	Emissions (GtCO_2e)	Production 2019 (Gt crude steel)	Emission Factor tCO_2e/t crude steel	Energy Use (GJ/t crude steel)	Notes
Direct Energy Use									
Coal	627	730	30.54	0.093	2.84				
Oil	9	11	0.45	0.0741	0.03				
Natural Gas	79	92	3.84	0.056	0.22				
Bioenergy	8	9	0.38	0	0.00				
Exported Energy	-	118	4.94	0.093	0.46				
IEA Direct Sub-Total	**723**	**723**	**30.28**		**2.63**	1.88	1.40	16.11	<= looking for 2.6 GtCO_2e, &1.4 tCO_2e/t
Our Direct Inc. Net Exported		**827**	**34.62**		**3.03**	1.88	1.61	18.42	<= 19 GJ/t
Indirect Energy Use									
Imported	14	14	0.61	0.093	0.06				
Electricity	107	107	4.50	0.139	0.62	1.88	0.33		<= use global avg. electricity factor
Indirect Total	**122**	**122**	**5.10**		**0.68**	1.88	0.36	2.72	
Direct + Indirect									
TOTAL	**845**	**948.7**	**39.72**		**3.71**	1.88	1.98	21.14	<= looking for 845 Mtoe, 3.7 GtCO_2e, 2.0 tCO_2/t
On-site Elec Gen, & off-site Elec Gen & Heat Exports									
		225	9.44		1.08				<= 1.1 GtCO_2e
Worldsteel Comparison									
IEA Direct					2.63		1.40		
Indirect Elec					0.62		0.33		
Indirect Scope 3					0.19		0.10		<= Scope 3 Back-calculated
Total					**3.44**	**1.88**	**1.83**		<= Worldsteel Sustainability Indicator for 2019

Model Key Drivers

Projecting Demand for Steel

We investigated several different demand assessments from the established literature, including the IEA's 2020 Energy Technology Perspectives (ETP), 2020 World Energy Outlook (WEO) Sustainable Development Scenario (SDS), the IEA's Net Zero Emissions (NZE) scenarios (IEA, 2020a, 2020f), as well as the findings of the 2019 IEA's Material Efficiency report (IEA, 2019b). Demand for steel products is a summed demand from end-use demand for vehicles, buildings, machinery and energy, transport, sanitary and water supply infrastructure, and evolves through time with a country's stage of development. Data availability for these demands on a per country basis is sparse and uncertain. Instead of attempting to aggregate individual sub-sectoral estimates of steel demand for each country in a highly uncertain bottom-up fashion, we have instead approached the problem from the top-down perspective of a long-term relationship between $GDP/capita and historical kg/steel demand. The typical relationship between steel demand and rising $GDP per capita in time is for countries with a low $GDP per capita (less than $20,000/capita), to have rapidly rising steel demand to fulfill infrastructure and development needs. These needs are usually met in the decades of industrial development between $20,000/capita and $40,000/capita, after which with most infrastructure built, demand starts to plateau and then fall with increasing $GDP. **Figure 13** demonstrates for a number of countries the historic relationship between $GDP/capita and steel demand and fits the country data to a World Bank projection of $GDP until 2050.

Figure 13. Historical and forecast of demand based on $GDP/capita and kg steel/capita relationship



Total steel demand by region based on each country's long-term Worldbank GDP forecast to 2050 is summarized in **Figure 14**.

After demand is established, we then need to see how much recyclable scrap is available to meet demand before making new iron products.

Projecting Scrap Steel Availability

Scrap steel or recovered steel available for recycling is classified into three main categories: home scrap, prompt scrap and end-of-life scrap. Home scrap (about 20% of current scrap) is material in the form of trimmings or rejects from within the steel mill site itself – it is usually reprocessed immediately on-site.

Figure 14. History and Forecast of Demand by Major Region (2004-2050)

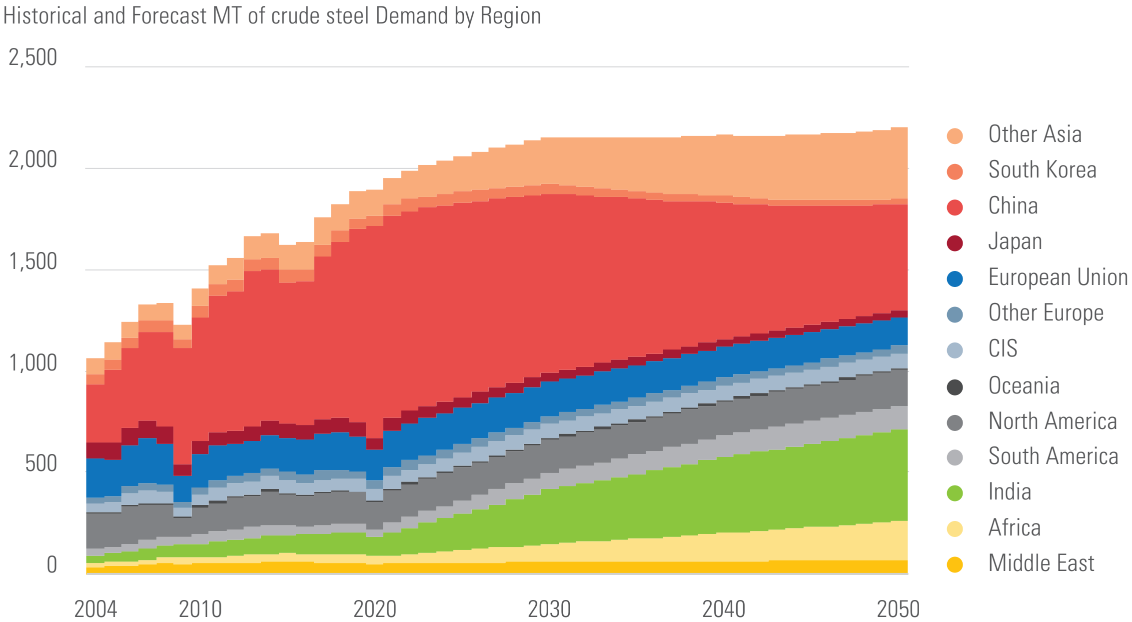
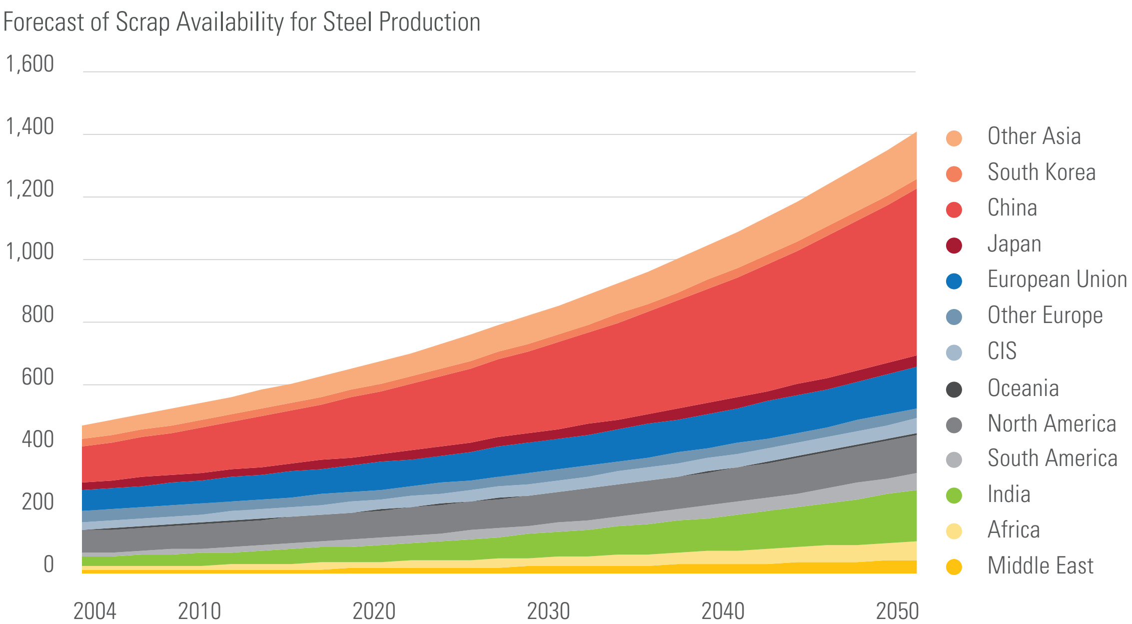


Figure 15. Estimate of Scrap Steel Availability for Steel Production (2022-2050)



Because home scrap is on-site recycling it is essentially netted out by using net crude vs. gross crude steel production. Prompt scrap is industrial scrap or manufacturing scrap, generated by first-tier customers and is usually recycled within a year. This is currently about ~13% of total finished steel production (240 Mt in 2021) but is expected to fall as more efficient secondary manufacturing techniques are put in place to reduce prompt scrap.

To determine the level of recycled scrap steel available for remelting in electric arc furnaces (EAFs) we track prompt and end-of-life scrap (685 Mt). Note, however, not all scrap ends up being used for EAF crude steel production. Some is used in iron foundries for example. These other uses are roughly 70 Mt, so that about 615 Mt or 33% of crude steel production is estimated to be used in steel production. This value is very close to the equivalent estimate of 33% that IEA NZE scenario uses for steel mill EAFs in 2020. Some of the scrap steel is used to charge BF-BOFs and the rest (450 MT steel) are used in steel mill EAFs.

Global recycling rates are quite high, with approximately 85% of end-of-life steel estimated to be collected for recycling, yet variable by type (high for appliances, vehicles, structural steel) and lower for packaging, reinforcement bar and oil and gas sector equipment. Arcelor Mittal projects that even in the BAU case end-of-life (EOL) scrap increases from roughly 445 Mt today to 1200 Mt by 2050 (ArcelorMittal, 2019).

For a country level perspective of recycled steel, the Bureau of International Recycling publishes some detailed national level statistics for selected economies e.g. (BIR, 2022, 2023). Regional forecasts are also available from Xylia et al. (2018) and Wang et al., (2021). In the end we used an availability of 1.4 Gt by 2050, at 86% utilization (1.2 Gt), allocated as per our sources and based on historic and forecast demand to estimate stocks of scrap steel in each country.

Table 3 Comparison of different Prompt and End-of-Life Scrap Steel Forecasts – forecasts may have different levels of production in 2050

Scenario	Prompt and EOL Scrap Recycled in Steel Production	2015	2020	2050
IEA Net Zero (2023)	Mt (Prompt and EOL)	-	620	941
	% of Crude Steel Production	-	33%	48%
Arcelor Mittal	Mt (EOL)	-	440	1200
	% of Crude Steel Production	-	23%	55%
Wang et al.	Mt (Prompt and EOL)	400	-	1,574
	% of Crude Steel Production	25%	-	63%
Xylia et al.	Mt (Home)	113	-	188
	Mt (Prompt)	238	-	906
	Mt (EOL)	259	-	426
	MT (Prompt + EOL)	497	-	1,332
	% of Crude Steel Production	31%	-	49%
Net Zero Steel (2024)	Mt (Prompt + EOL to EAFs)		450	1,290 (Baseline)
	% of Crude Steel Production		23%	59% (2,200 kt production)

Technology Availability and Costs

Technology Availability

Deep decarbonisation options for iron and steel manufacturing and their technology readiness have been discussed earlier in Section 3.3. Our scenarios in this study feature 9 main technologies. For more data on technology information such as overnight capital costs, energy and raw material consumption, please see the Appendix. Observers may note we have not included BF-BOF with CCS, nor smelter BF-BOFs (SR-BOF-CCS), i.e., HISARNA, in our modelling runs. While some progress was being made with SR-BOF-CCS during the European ULCOS project (Quader et al., 2016), and it potentially reached a TRL of 7, progress seemed to cease in the mid 2010s when the key technology was purchased by Tata Steel. There has been no evidence of progress since, nor for BF-BOF-CCS beyond the COURSE 30 and COURSE 50 projects in Japan (COURSE50, 2021), which from all evidence seems to be at the small mass partial pilot TRL 5 level.

Perhaps more controversially, we have also not included either form of direct iron ore electrolysis (molten or aqueous) simply because these technologies, while well-funded and making rapid progress, are at such an early level of development (TRL 2-3) and their commercialization dates are highly uncertain. It can be expected some of the market share going to DRI primary technologies will likely go to electrolysis – the updated IEA Net zero scenario (IEA, 2023b) assigns 14% of primary to electrolysis by 2050. Future work may include induced innovation scenarios with these technologies, and SR-BOF-CCS if there is evidence of progress.

Technology Costs

Decisions about where to build new steel production and what technologies to deploy are mainly driven by estimates of the economic costs of different steel production pathways in different locations. Fischedick et al (2014), Mayer et al. (2019) and Vogl et al. (2018) provide a detailed analysis of near zero emission iron and steel technologies, particularly the direct reduction of iron with hydrogen (DRI-H_2) route that is prominent in our model. Production costs of the main existing technologies, i.e., blast furnace to basic oxygen furnace (BF-BOF), electric arc furnaces (EAF) and direct reduction of iron with natural gas (DRI-GAS) are summarized by Medarac et al. (2020) for large producing countries and on a global scale by the IEA in their Iron and Steel Roadmap (IEA, 2020e). A state-of-the-art literature review was conducted to understand costs across 11 categories, including: capital, maintenance, labour, energy, raw materials, support infrastructure, carbon capture and storage, carbon pricing, subsidies, transport, and trade tariffs. The cost data and their supporting information are elaborated on in much greater detail in the Appendix. Readers should understand that the model does not feature a single "representative cost" for each technology category (i.e. a simplistic "technology X costs $Y/tonne" system), but rather contains dynamic cost elements that vary in space and time at every individual location. For example, energy costs are distinct across geographies to reflect differing availability of renewable energy and fossil energy resources; labour costs vary between countries and also change across the model time horizon from 2022 to 2050 in line with changes in country GDP; capital costs for facilities using otherwise identical technologies might change between two locations because of differences in the cost of capital available; trade barriers and subsidies might make importing steel from one country to another economic or uneconomic; subsidies and carbon tax policies for a given location might make certain technologies economically attractive in model year 2030 but not in model year 2029 etc.

As an example, **Figure 16** compares and contrasts two illustrative situations where the levelized cost of steel manufacturing differ. The left-hand panel illustrates how the model thinks about near future costs (2030) for a manufacturing site in central China. In this example, the lowest cost technology out of all the options being assessed is a BF-BOF, owing to its low capital, operating, raw materials and energy costs, and the fact that carbon pricing is low (the social cost of GHG pollution is not factored in). In the China 2030 case the difference between carbon intensive steelmaking pathways and low carbon alternatives is large, in the order of hundreds of USD$. The second panel illustrates modelled costs for a manufacturing site in Mexico in 2050. In this example, the cost differential between the high carbon (BF-BOF, DRI-GAS) technologies and the net zero compatible technologies (DRI-

GAS-CCS, DRI-H_2) is much narrower, only $70-100, a divide that is much easier to bridge with supportive climate policies. The difference is the most stark for DRI-H_2, where energy costs in at the Mexican example site shown here are significantly lower than those at the example site in China, and the capital and maintenance costs have fallen significantly in the period between 2030 and 2050. One reviewer noted that electrolyzers may be much cheaper in China than we have estimated, on the order of $200-400/kw instead of $1000-1200, but we were unable to find direct evidence of these costs, and the durability of the units.

Figure 16. Illustrative Levelized Cost of Steel and Variation in Space and Time

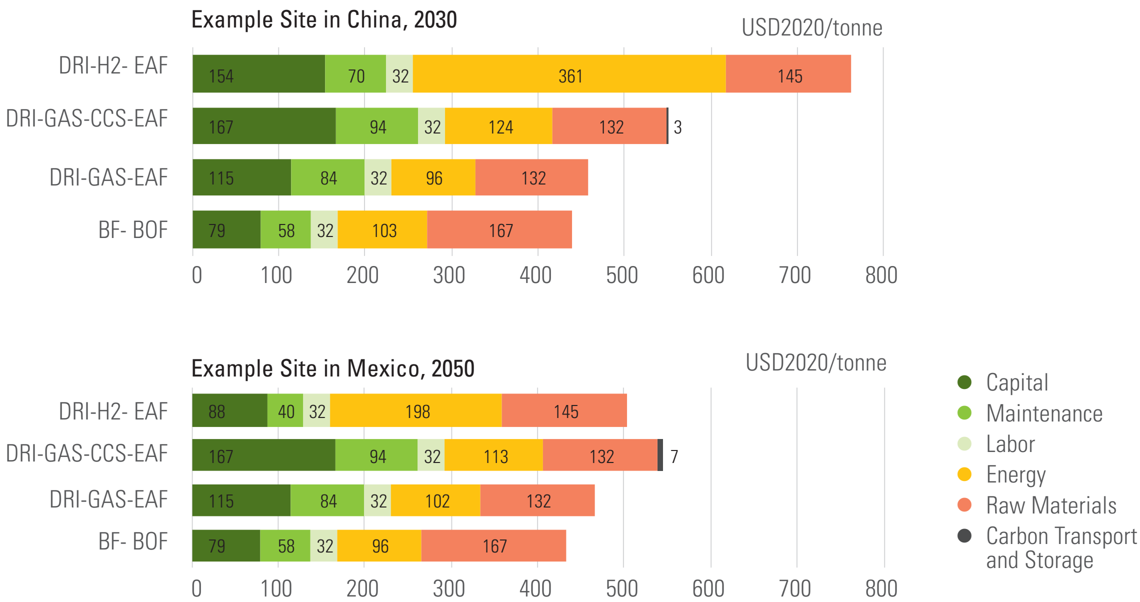


Table 4

Production Output	Model Short Name	Technology Pathway	Start Year Availability in Model
		Emission Intensive Primary Production	
Steel	BF-BOF	Blast Furnace with Basic Oxygen Furnace	2022
Steel	DRI-GAS-EAF	Direct Reduced Iron with Natural Gas, followed by Electric Arc Furnace	2022
Steel	DRI-COAL-EAF	Direct Reduction of Iron with Coal, followed by Electric Arc Furnace	2022
		Near-Zero Primary Production	
Steel	EAF-SCRAP	Electric Arc Furnace used with Scrap	2022
Steel	EAF-PRIMARY	Electric Arc Furnace used with Green Iron / Hot Briquetted Iron	2022
Steel	DRI-GAS--CCS-EAF	Direct Reduced Iron with Natural Gas, followed by Electric Arc Furnace, 90% of CO_2 is Captured and Stored	2022
Steel	DRI-H_2-EAF	Direct Reduced Iron with Green Hydrogen, followed by Electric Arc Furnace	2028
Green Iron / Hot Briquetted Iron	DRI-GAS-CCS	Direct Reduced Iron with Natural Gas, CO_2 Captured and Stored	2022
Green Iron / Hot Briquetted Iron	DRI-H_2	Direct Reduced Iron with Green Hydrogen	2028

Production Projections

A brief summary of our projection methodology is presented here, while the full step-by-step methodology is detailed in our Appendix.

The study commences with a thorough examination of the global steel production landscape in 2021, encompassing 1114 facilities across 137 countries. Key aspects such as nominal capacity of existing facilities, their output, their age, local energy resources, and proximity to potential carbon capture sites are analyzed. In exploring various scenarios, the model next considers the impact of differing domestic climate policies in each global region, technology subsidies, trade alliances, and financial conditions across countries. These factors include the stringency of climate policies, reflected in the pricing of greenhouse gas (GHG) emissions per tonne, and the implementation of any subsidies for different steel production pathways. The study also examines the effect of trade alliances and tariffs, including carbon border adjustment mechanisms, on steel imports. The cost of capital in different countries is factored in, influencing investment decisions in new plants and equipment.

The model projects through time in one-year increments from 2022 to 2050, estimating total steel demand and ferrous scrap availability for each country based on population and GDP growth. This single-demand scenario anticipates a global steel demand reaching 2.2 Gt by 2050 (see Section 4.2.1, page 37). Countries are analyzed yearly in descending order of their GDP, allowing larger economies to exert a greater influence on the global steel market.

For each year, the model assesses each country's steel production facilities. Plants reaching a 20-year economic lifespan are retired (we also tested 17 years), and those operating below capacity are first optimized to meet domestic demand. Scrap steel remelting, specifically through electric arc furnaces, is the next avenue for meeting demand, constrained by domestic scrap availability and overall limits on solely secondary steel use (to reflect that recycled steel may not always be suitable for certain applications such as automotive or aerospace manufacturing and that some exceptional purity primary steel may always be required). If these domestic measures fall short of meeting total demand, the model seeks to import steel from locations with available spare capacity (if any), prioritizing lower-cost steel first and considering factors like transport costs and trade tariffs. Imports (if available) are only used up to a threshold where their costs begin to substantially exceed the costs of simply building new production. We define this as the lowest cost of new production plus a 20% margin, based on the differential between existing foreign facilities only needing to meet operating cost plus transport & applicable tariffs, and new investment requiring anticipation of full capital amortization.

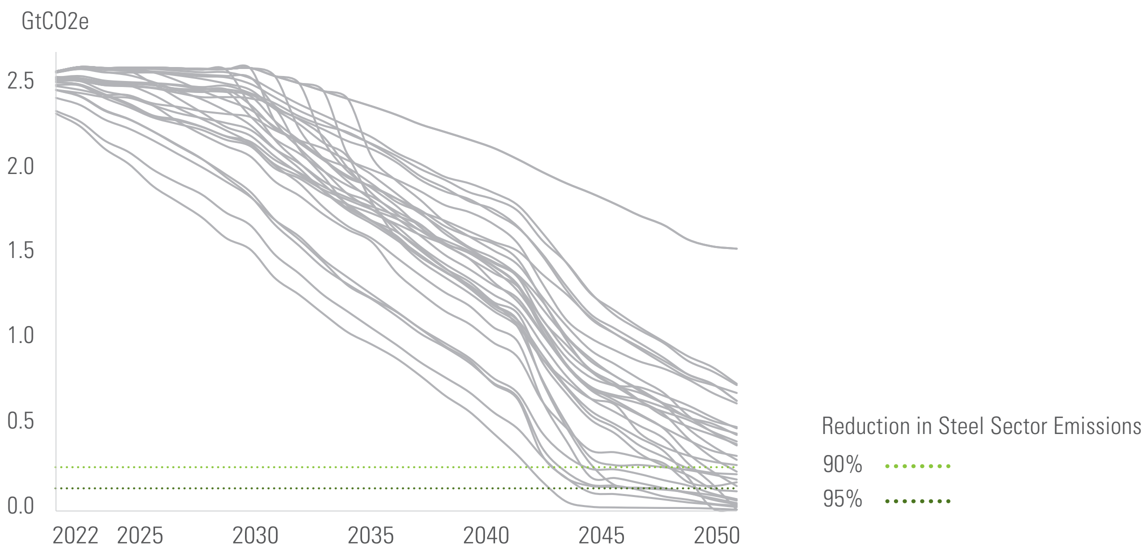
Only after all other means of meeting demand are exhausted as options for meeting demand does the model move to consider construction of new steel production facilities. At this point the model performs a cost assessment of all the available sites where new steel facilities might be constructed, factoring in a myriad of economic costs and constraints. These include capital, labor, energy, and raw material costs, alongside technology costs varying over time and by production pathway. Noteworthy constraints include the maximum capacity of existing sites, the pace of new construction, and national limits on fleet expansion, reflecting real-world logistical and regulatory challenges. Although we assume a uniform set of nameplate equipment capital costs for all technologies globally (with changes in time due to incremental technological improvements, as described in the methodological appendices), the relative costs of different technologies in different regions will differ due to differentiated financing costs (e.g., the cost of borrowing capital to purchase equipment), local labor costs, energy costs, infrastructure availability, and emission pricing. New capacity is deployed in incremental units until the model is able to close the production gap left by the retirement of production facilities that are at the end of their economic life.

STRENGTH AND TIMING OF CLIMATE ACTION

To set the scene for answering our main research questions (see Section 3.5) we explored the level of climate policy ambition and global coordination that might be needed to achieve a transition to net zero steel by 2050. As we concluded in our 2021 report (Bataille et al., 2021a), a net zero steel transition requires a policy landscape that supports investment into clean steel production, either through an actual levy on GHG pollution (such as practiced in the European Union through the EU Emissions Trading System (European Parliament, 2003)) or through equivalent subsidies (such as those for net zero compatible technologies in the US Inflation Reduction Act (IEA, 2023)). We capture the level of climate policy ambition in each country by setting a carbon price (Hallegatte et al., 2013). The effect of a sufficiently high carbon price in the model is to raise the perceived cost of GHG-intensive steel production pathways so that they are brought into competition with net zero steel production technologies. Prices that are sufficiently high to completely deter fossil fuel steel production are analogous to policies that ban fossil fuel steel manufacturing, i.e. something approximating a moratorium on new blast furnaces and their rapid phase-out (Vogl et al., 2021b).

We ran a large ensemble of model runs with different carbon price trajectories to represent varying levels of climate policy ambition (**Figure 17**) We varied both the level of near-term ambition (i.e., the starting price in 2025), with groups starting at CO_2 prices of $30/tonne, $100/tonne, and $200/tonne and also the long term ambition (i.e. the price level reached in the final model year of 2050). We also explored scenarios where a moratorium is placed on new fossil fuel steel manufacturing, represented using a CO_2 price of $500/tonne. These scenarios reveal useful information about not only the total effort required but also the window of opportunity for action and the importance of near-term policy activity. Our findings are detailed below.

Figure 17. Scenario Ensemble



Global Ambition for Achieving Net Zero by 2050

Defining what level of emissions can be considered "net zero" for an individual segment of the economy such as the steel industry is a complex task (Bataille, Stiebert, et al., 2023b), because of uncertainties around how natural carbon cycles will change in future, and how quickly other industrial sectors might decarbonize. Most research exploring transition pathways towards net zero emissions includes some way of capturing carbon from the atmosphere and sequestering it permanently, usually referred to as carbon dioxide removal (CDR). A common trend seen in IPCC scenarios that focus on keeping global warming within 1.5 – 2°C (IPCC, 2022) is to assume that by the middle of this century, CDR technologies will be able to offset the last 5-10% of remaining emissions. The difference between 5% and 10% residual emissions doubles the amount of CDR needed, but will also depend on the political willingness to specify 95% as "sufficiently abated" to meet Paris Agreement needs and the amount of permanent, additive and verifiable CDR available - please see (Bataille, Al Khourdajie, et al., 2023) for a longer discussion. Net-zero CO_2 within steel itself would require in-sector CDR using biomass, and there is considerable controversy surrounding the net-neutrality of biomass under anything less than very specific circumstances. **Figure 18** highlights the model runs from our ensemble that reduce emissions by 90% and 95% compared to the 2022 baseline. We found that rising carbon price trajectories with end-of-horizon prices of 300 $/tonne or higher by 2050 are required for a 95% reduction, whereas trajectories of $200 by 2050 (or higher) can achieve a 90% reduction provided that the starting year price is $100.

Importance of Near-Term Climate Action

Figure 19 compares and contrasts the model runs from the ensemble with weaker near-term action (trajectories starting at 30 $/tonne) against those which have an emphasis on bringing emissions down more quickly (trajectories starting at 100 $/tonne). Cumulative emissions are significantly lower in those simulations with stronger near-term action. A central reason for this is that a large part of the Chinese BF-BOF steel fleet is coming up for relining in the late 2020s.

Timing for a Global Fossil Fuel Steel Phase-Out

Figure 20 highlights the model runs that apply a $500 carbon price to simulate a rapid phase out of global fossil fuel steel manufacturing, with the introduction date of the policy as the main variable of interest. Our modelling shows that an immediate phase out policy would lead to a 95% reduction in CO_2 emissions by the early 2040s, and that the last possible date for achieving a 95% reduction through a global moratorium on fossil fuel steel production is 2031. This date is obviously sensitive to the assumed lifespan of furnaces between relining; (Vogl, Olsson, et al., 2021a) indicate that the global average length of blast furnace campaigns depending on overall age of the furnace – they estimate the typical first relining is after 19 years, the second 15 and the third 13, for an overall average of 17. Most of the Chinese fleet is on its first relining.

In summary, our global 2023 analysis aligns strongly with the findings of our 2021 work (Bataille et al., 2021a). Key differences include the underlying model inputs being updated to a 2021 data foundation while our first model run year is 2022, incorporating the latest data on the conditon of the global steel production fleet, and our model now features explicit trade between model regions, regionally differentiated costs for steel production, and the ability to simulate elements of real world trade policy such as alliances between regions, trade tarrifs, subsidies etc. None of our main conclusions from 2021 have changed. Net zero steel production by 2050 is still possible, but this requries urgent action from policymakers, as every passing year without action increases the cumulative emissions released to atmosphere. Reaching net-zero requires crystal clear communication to steelmakers that unabated fossil fuel steel production, especially using blast furnaces, cannot continue past the early 2030s and that they shuld be planning now to introduce near zero emission alternatives.

Figure 18. Model Simulations Achieving >95% and >90% Emissions Reduction by 2050

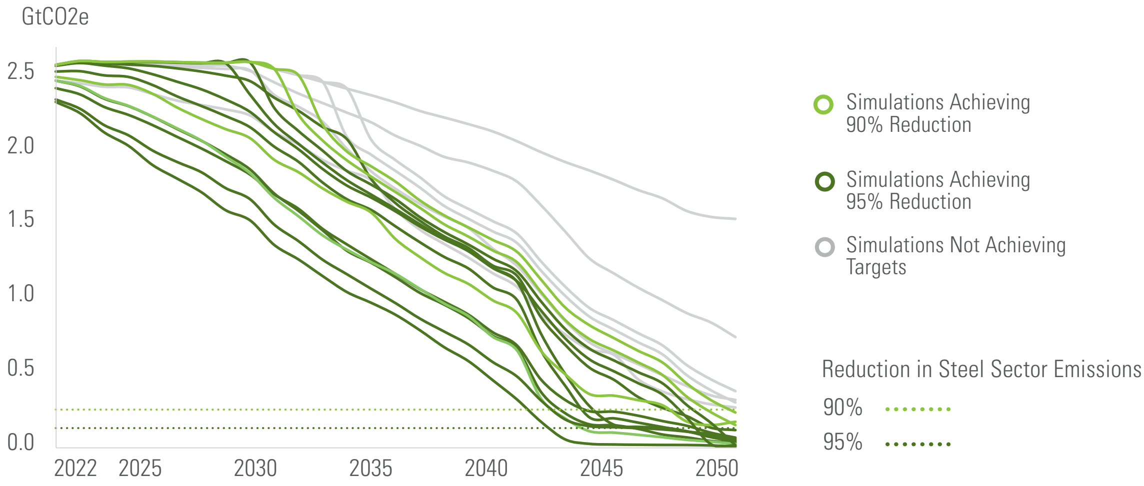


Figure 19. Cumulative Emissions Under Different Global CO2 Price Trajectories

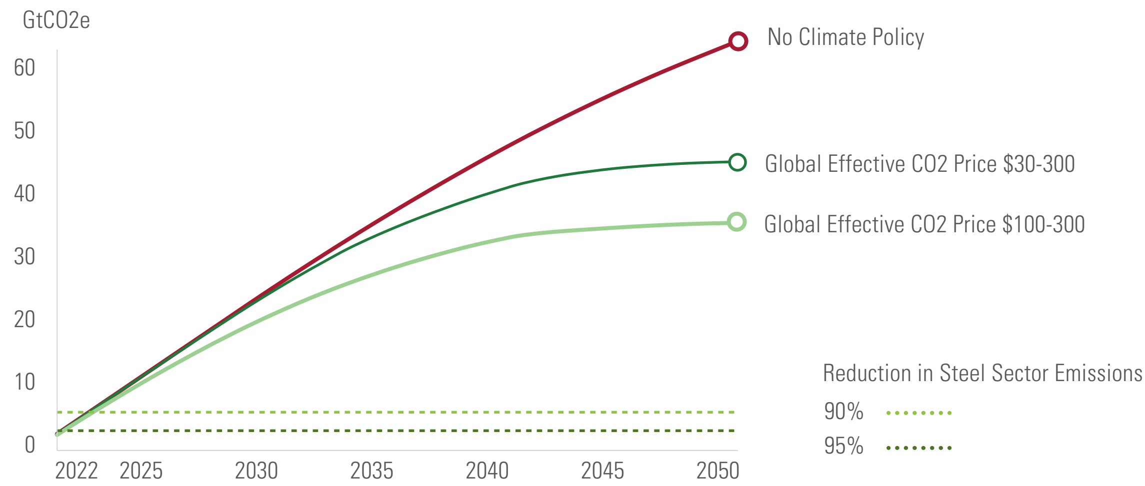
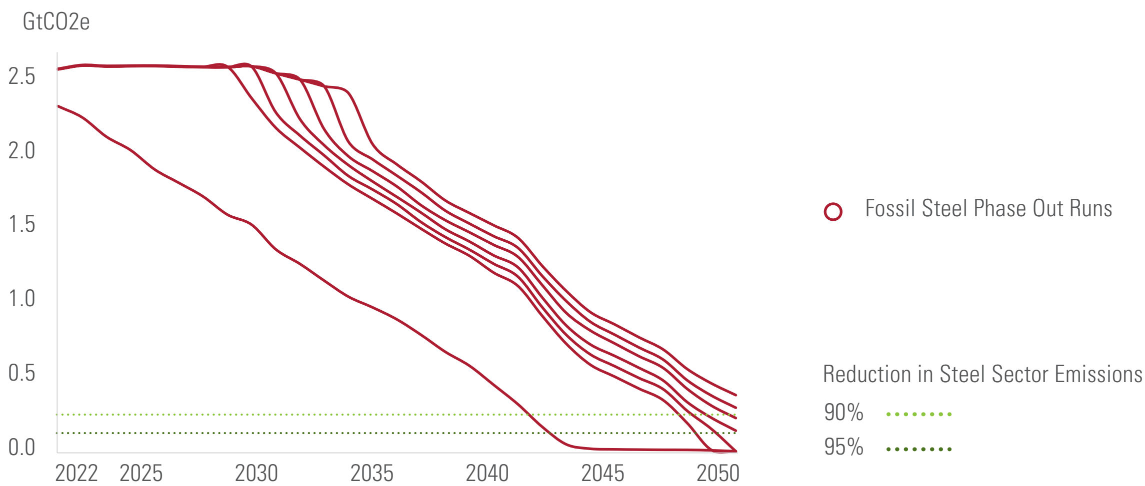


Figure 20. Model Simulations Exploring Rapid Fossil Steel Phase Out



EXPLORING TRADE COALITION FORMATION AND ACTION

Challenges for Unified Global Action

Our previous work explored the concept of unified global action on emissions from steel manufacturing. As shown in Section 5, achieving a 95% reduction in steel sector emissions requires carbon pricing or equivalent subsidies from all countries to be on rising trajectories towards 300 $/tonne by 2050, or imposing a near term global ban on fossil steel no later than 2030-2031.

However, the history of international climate negotiations shows that unified global action on emissions is a challenging prospect:

- **Diverse Economic Interests:** Different countries have varying levels of dependence on the steel industry for their economic growth. Developing nations may prioritize industrial growth over emissions reductions, while developed nations might push for stricter environmental standards.
- **Technological and Financial Barriers:** Transitioning to low-emission technologies in steel production is expensive and technologically challenging. Not all countries have the financial resources or technical expertise to make this transition solely with their own resources.
- **Global Policy Coordination:** Achieving a consensus on emission reduction targets and methods requires complex international negotiations. Different countries have different priorities and capabilities, making it hard to agree on a unified approach.
- **Competition and Market Dynamics:** The global steel market is highly competitive. Companies and countries might be reluctant to be first movers in net zero steel if it puts them at a competitive disadvantage, especially if there is a risk that others might not follow suit.
- **Implementation and Enforcement:** Even if agreements are reached, implementing them consistently across different countries and monitoring compliance poses significant challenges.
- **Supply Chain Complexity:** The steel industry's supply chain is global and complex. Coordinating emissions reductions across the entire supply chain, including raw material extraction, transportation, and manufacturing, is a daunting task.

At the time of writing, carbon pricing is fragmented into multiple geographic markets and there is no single scheme or treaty with global coverage. The Paris Agreement (UNFCCC, 2015) also enshrines the concept of "common but differentiated responsibilities" (CBDR), i.e., that while all countries are collectively responsible for addressing climate change, not all countries are expected to decarbonize at the same pace, with richer highly industrialized nations expected to lead the way. As a result, obtaining buy-in to the idea of "green steel" from all countries that participate in the global trade system may well not materialize this decade, leaving large potential markets for high carbon "dirty" steel, dragging the pace of the transition backwards through inertia. As not all future actors in the global steel system are likely to be willing and/or able to participate to the same degree, there is significant value in exploring alternative approaches to the idea of unified global action.

Analysis of the Role of Climate Clubs for Green Steel Trade

A key research question is the size and extent of any global collaboration on trade necessary to create a shift towards net zero steel. In this section of the report we explore the concept of "climate clubs" (Nordhaus, 2015) for steel and green iron trade. Climate club members would apply broadly aligned energy and climate policies within the club, trade preferentially with one another, and impose tariffs on imports of "dirty" high GHG steel from outside of the club. To understand the potential composition of any climate club, we conducted an assessment of key existing regional economic integration groups (i.e. trade blocs), which is expanded on in more detail in the methodological appendices. We reviewed the status of (the):

- European Union (EU) / European Economic Area (EEA)
- North American Free Trade Agreement (NAFTA) / United States-Mexico-Canada Agreement (USMCA)
- ASEAN (Association of Southeast Asian Nations) / ASEAN Free Trade Area (AFTA)
- Regional Comprehensive Economic Partnership (RCEP)
- MERCOSUR (Mercado Común del Sur, Southern Common Market)
- Gulf Cooperation Council (GCC)
- Eurasian Economic Union (EAEU)
- Southern African Development Community (SADC)
- Economic Community of West African States (ECOWAS)
- African Continental Free Trade Area (AfCTFA)
- Caribbean Community (CARICOM / Caribbean Single Market and Economy (CSME))

Our qualitative assessment concluded that the European Union, USMCA (formerly NAFTA), and the ASEAN Free Trade Area are the strongest and best developed trade blocs at the time of writing, and the EU is already exploring negotiations with the United States (the key economic anchor for USMCA) to potentially establish preferential trade arrangements for green steel and green iron (Executive Office of the President of the United States, 2021). In a second category we would group MERCOSUR and the GCC, both of which have significantly reduced trade barriers amongst members but face ongoing challenges to full integration. In a third category we would group the EAEU, SADC, ECOWAS, and the CSME, all of which have only made minor steps towards trade integration. Finally, we note that RCEP and AfCTFA could represent transformative, globally dominant trade blocs in future (regionally centered on Asia Pacific and Africa respectively), but as both have only been established relatively recently it appears too early in their history to comment on their success or failure in achieving their goals.

As a final grouping we have considered those countries that could be important actors in the future of steel manufacturing because of their large iron deposits. The largest and highest grade iron ore formations in the world are found at 14 locations in just 9 countries: Australia, Brazil, South Africa, India, Ukraine, Guinea, Venezuela, the United States, and Canada (Hagemann et al., 2016; Krishnamurthy, 2022). Collectively we term these countries the "Green Iron Majors" and explore their inclusion/exclusion from trade bloc formations in our scenario analysis.

We ran a large ensemble of model runs with different memberships to explore different combinations of trade blocs for green iron and green steel, to understand which groupings would result in emission reductions by 2050 that would be in line with the aspirations of the Paris Agreement.

For analytical purposes, we assume:

- The high-income regions in the club (defined as GDP/capita above USD$20,000) have an internal carbon price or equivalent policies starting at 100 $/tCO_2e$ in 2022, rising over time to 300 $/tCO_2e$ in 2050.
- The low-income regions in the club (defined as GDP/capita below USD$20,000), when included, have an internal carbon price starting at 30 $/tCO_2e$ in 2022, rising over time to 100 $/tCO_2e$ in 2050.
- The rest of the world (i.e. outside the club entirely) are assumed to pursue a significant but reduced push in terms of steel decarbonization policies, which we capture as a carbon price (or equivalent policies) of 30 $/tCO_2e$ in 2022, rising to 100 $/tCO_2e$ in 2050, i.e. roughly 3x less than the top rate applied in the "climate club" group.

- The participants in the climate club pursue a trade protection policy that is expressed in terms of two tariff structures: a 30% tariff on imports from outside the club, and a GHG intensity-based tariff modelled on the EU carbon border adjustment mechanisms (CBAM) which effectively equalizes the carbon price for imports so that it matches the price inside the club.
- In addition, the climate club group provides subsidies for production of green iron ($100 USD 2020/tonne).
- All countries engage in high levels of steel recycling, making optimal use of their available ferrous scrap deposits.

Our findings are detailed below.

A Narrow Climate Club of High-income Countries Cannot Achieve Net Zero Steel

Figure 21 highlights climate club groupings that feature only high-income economies and regions. The top line in **Figure 21** represents Baseline, "No Climate Policy" emissions. The climate club operates at an equivalent carbon price of $100 today rising to $300 in 2050 while the rest of the world, outside of the club, decarbonises but at a much slower pace, equivalent to $30 today rising to $100 in 2050. The in-club membership explored in the highlighted model runs includes various combinations of the EU, USMCA, Japan, South Korea, Australia and New Zealand. While these regions are powerful economies, they are collectively too small in terms of their future demand for steel to drive the global transition to net zero using trade alliance mechanisms. Simulations using these groupings can achieve deep decarbonisation of steel production but the total emission reductions by 2050 are only of order of 70-75%. This falls short of most definitions of net zero by a significant margin because the associated level of carbon dioxide removal (CDR) required would have to be extremely high - as well as being expensive it might run up against technical or physical limits. Climate clubs likely need to expand beyond rich, industrialized economies in order to be successful in delivering a transition to net zero.

Expanding the Climate Club to be more Inclusive

Once we ascertained that our exclusive trade groups involving only high-income countries proved insufficiently large to decarbonize global steel production by 2050, we explored the performance of additional trade coalitions. For example, we investigated adding the ASEAN Free Trade Area (AFTA) and other key global south economies that are also major iron producers: Brazil, India, South Africa, Venezuela, Guinea, and Ukraine (**Figure 22**). To incentivize participation, we added a collectively paid subsidy for $100 per tonne green iron, while being pragmatic about CBDR – this grouping benefits from significant economies of scale and learning with the hydrogen DRI technology, on the order of 200-250 Mt/yr. This scenario allows for clean iron production where it is cheapest, and for steel production to carrying on in historic OECD locations, alleviating concerns about employment and steel security.

The Role of a Fossil Fuel Steel Phase-Out

As can be seen in **Figure 21** and **Figure 22**, even our most successful climate club coalitions using the simulation inputs defined in Sections 6.2.1 & 6.2.2 struggle to get global steel sector emissions below 0.4 $GtCO_2e$ by 2050, which means policy efforts are falling short of our 90% or 95% reduction targets. This implies that unless more countries can be added to the climate club and enact more stringent climate policies, net zero steel cannot be achieved by 2050, all other simulation variables being equal. With this in mind, we explored the role of a near complete moratorium on fossil fuel steel production inside the climate club coalition. We implemented a representative CO_2 price of $500 starting in 2025 and found that the 90% reduction by 2050 threshold can be reached using this approach if a sufficiently large enough climate club is involved.

Figure 21. Exploring Trade Coalitions: Groups of High-Income Economies Only

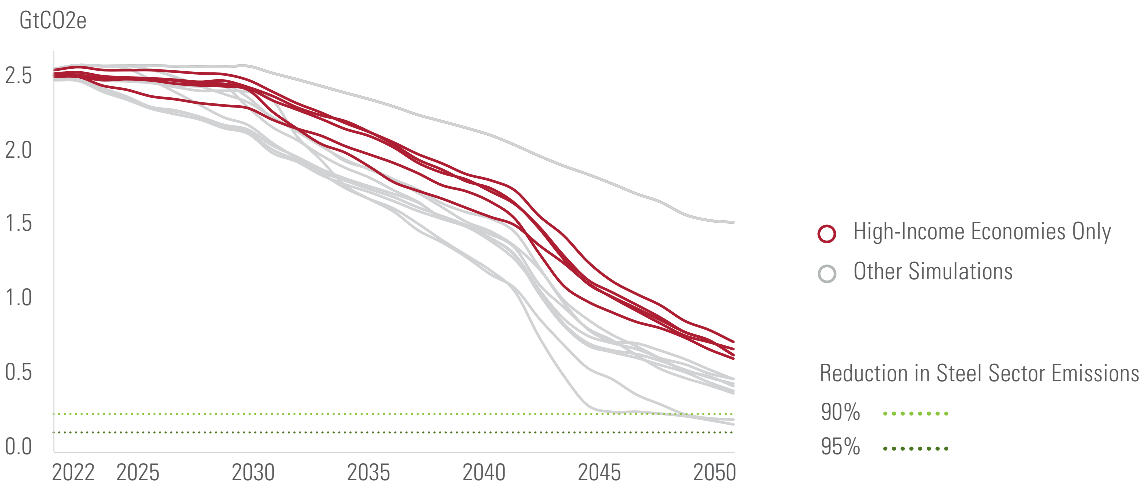


Figure 22. Exploring Trade Coalitions: Groups of High-Income Economies with Key Global South Partners

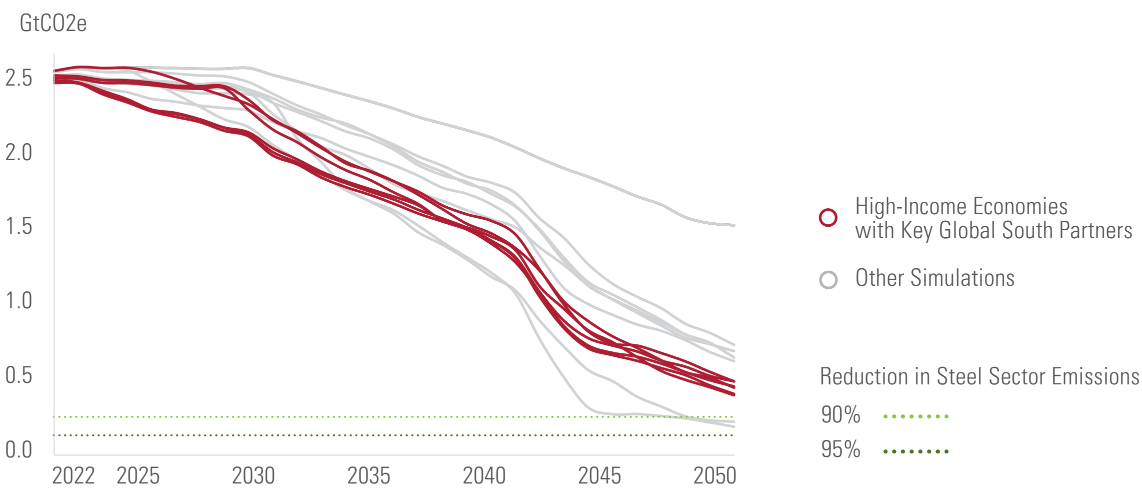
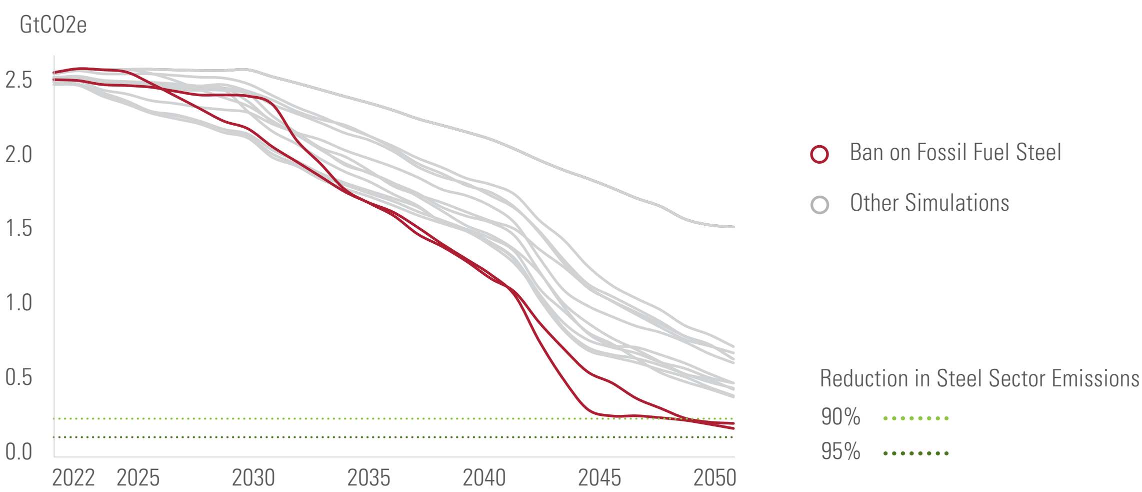


Figure 23. Exploring Trade Coalitions: Broad Climate Clubs with a Ban on Fossil Fuel Steel



CORE SCENARIO RESULTS

We present four main scenarios drawn from our model ensemble (see above Section 5 and 6)

- *Baseline* – this scenario includes our technological and recycling improvements but no climate policy drivers
- *Narrow Club* – this scenario shows climate club performance with an exclusive club of high-income countries only: the EU/EEA, the USMCA trade zone, Japan, South Korea, Australia, New Zealand
- *Broad Club* – this scenario shows a more inclusive club with a larger membership: the EU/EEA, the USMCA trade zone, Japan, South Korea, Australia, New Zealand, the ASEAN Free Trade Area (AFTA), and major iron producers: Brazil, South Africa, India, Guinea, Ukraine, Venezuela
- *Broad Club Fossil Fuel Ban* – this scenario shows the same climate club from *Broad Club* but a ban on fossil fuel steel is implemented amongst its membership by 2025

We assume that the climate clubs in the *Narrow Club*, *Broad Club*, and *Broad Club Fossil Fuel Ban* scenarios apply the same trade rules:

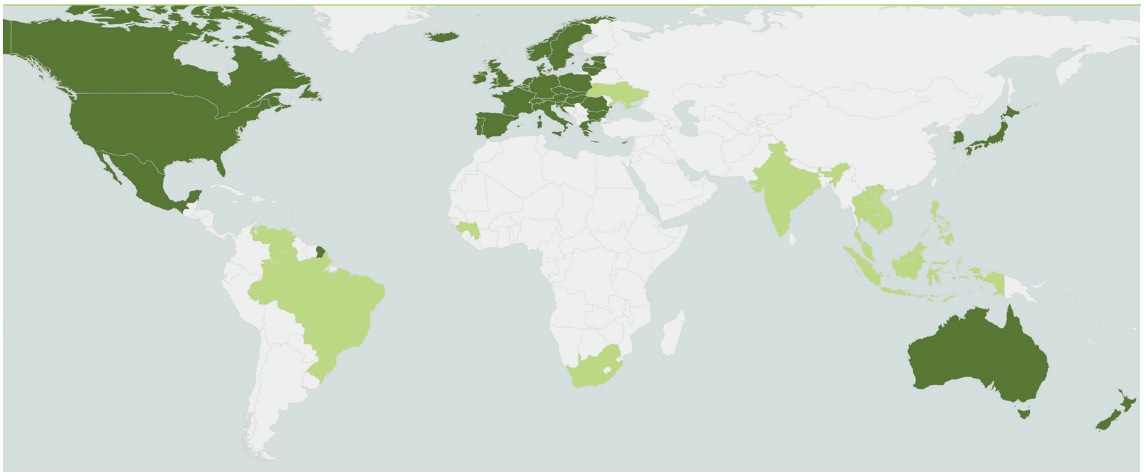
- The climate club pursues a trade protection policy that is expressed in terms of two tariff structures: a 30% tariff on imports from outside the club, and a GHG intensity-based tariff modelled on the EU carbon border adjustment mechanisms (CBAM) which effectively equalizes the carbon price for imports so that it matches the price inside the club.
- In addition, the climate club group provides subsidies for production of green iron ($100 USD 2020/tonne). The model does not explicitly capture policies or flows of investment capital between countries, but this subsidy could be imagined as a combination of both domestic policy support efforts from the governments of the major iron producing nations and foreign investment from the high-income members of the club to the iron producers.

Carbon pricing inside and outside the club is applied as follows:

- In the *Narrow Club* and *Broad Club* scenarios, the high-income regions in the club (GDP/capita above USD$20,000) have an internal carbon price or equivalent policies starting at 100 $/t$CO_2$e in 2022, rising over time to 300 $/t$CO_2$e in 2050. These policies could include carbon pricing, CO_2 intensity standards, subsidies on clean production like the IRA production tax credits for iron, secondary content mandates, etc.
- In the *Narrow Club* and *Broad Club* scenarios, the low income regions in the club (GDP/capita below USD$20,000) apply carbon pricing equivalent to 30 $/t$CO_2$e in 2022, rising to 100 $/t$CO_2$e in 2050.
- In the *Broad Club Fossil Fuel Ban* scenario, all club members apply a $500 carbon price starting in 2025.
- In the *Narrow Club*, *Broad Club*, and *Broad Club Fossil Fuel Ban* scenarios, non-club members i.e. the rest of the world are assumed to pursue a significant but reduced push in terms of steel decarbonization policies, which we capture as a carbon price (or equivalent policies) of 30 $/t$CO_2$e in 2022, rising to 100 $/t$CO_2$e in 2050

Each scenario builds on a previous scenario such that the individual components are additive as shown in **Table 4**, with their key parameters in **Table 5**.

Figure 23. Green Iron and Steel Climate Club Membership Under the three scenarios



● Narrow Club Scenario ● ● Broad Club and Broad Club Fossil Fuel Ban Scenarios

Table 4. Scenario Components

Scenario Component	Baseline	Narrow Club	Broad Club	Broad Club Fossil Fuel Ban
Advanced Steel Recycling	✓	✓	✓	✓
Climate Club Includes High-Income Countries Only	-	✓	✓	✓
Climate Club Includes High-Income Economies with Key Global South Partrners	-	-	✓	✓
"Ban" on Fossil Fuel Steel Production Starting in 2025	-	-	-	✓

Table 5. Key Scenario Parameters

Scenario Component	Baseline	Narrow Club	Broad Club	Broad Club Fossil Fuel Ban
Climate Club Membership	No Climate Club	EU + EEA, USMCA, South Korea, Japan, Australia, New Zealand	EU + EEA, USMCA, South Korea, Japan, Australia, New Zealand + ASEAN Free Trade Area (AFTA) + Green Iron Majors (India, Brazil South Africa, Guinea, Ukraine, Venezuela)	
Carbon Price Schedule	No Carbon Price	Climate Club members, $100-300 Rest of World, $30-100	Climate Club members above $20k/capita, $100-300 Climate Club Members below $20k/capita, $30-100 Rest of World, $30-100	As Broad Club Scenario until 2024, then all Climate Club Members apply $500 in 2025 Rest of World, $30-100
Tariffs	No Trade Tariffs No Climate Tariffs	Climate Club Members: Carbon Border Adjustment Mechanism (CBAM) for All Countries 30% Border Tariff for Non-Club Members		
Subsidies	No Subsidies	Green Iron Technologies, $100		

Global Distribution of Steel Production

Figure 24 compares and contrasts the status quo in 2021 (top panel) with the projections for 2050 (bottom panel) under our *Baseline* scenario. The different colors indicate different steel production technologies, while the relative size of the circles indicates the production amount. Two main trends are evident from this figure.

- Global production of steel diversifies away from Northeast Asia by 2050, with substantial growth in Southeast Asia, South Asia (especially India), the Middle East, Africa, and South America
- Europe, China and the United States see most (but not all) of their domestic facilities switching to steel recycling (electric arc furnaces, in yellow)

Figure 25 compares the results from the 2050 model year for our 3 climate policy scenarios, *Narrow Club*, *Broad Club*, and *Broad Club Fossil Fuel Ban* against one another. Four major trends are evident under all three scenarios:

- Primary steel production diversifying to a broader range of global regions including Southeast Asia, South Asia (especially India), Africa, North and South America
- A large-scale reduction in the dominance of Basic Oxygen Steelmaking from coal (BF-BOF pathway), shown in red
- A large increase in recycling (EAF-SCRAP pathway), shown in yellow
- A large increase in green steel manufacturing technologies, shown by the yellow-green (EAF-PRIMARY, imported green iron) and green (DRI-H_2-EAF, direct reduced iron with hydrogen) circles.

Figure 24. Comparing Global Distribution of Steel Production, 2021 vs 2050, Baseline Scenario

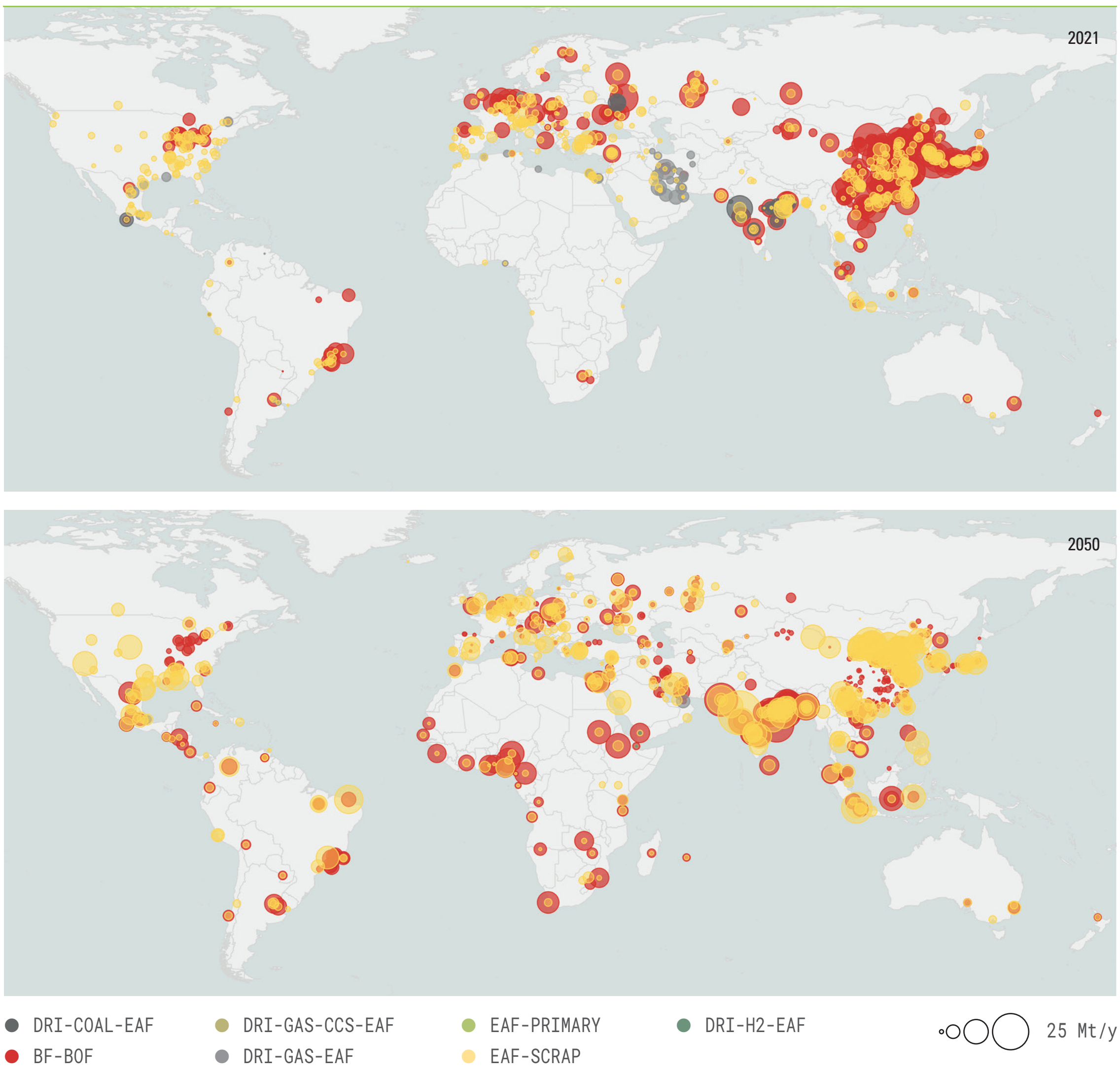
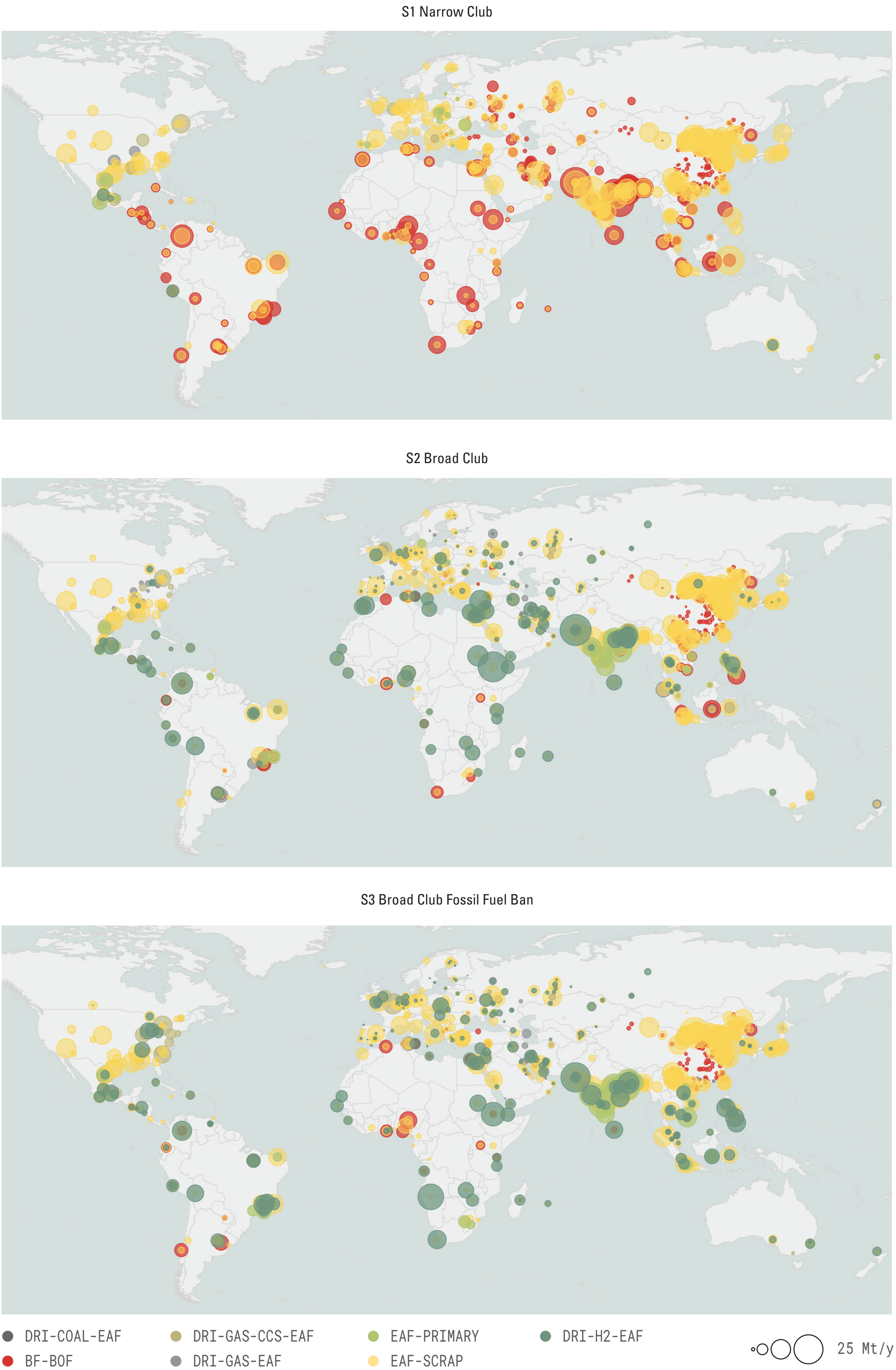


Figure 25. Comparing Global Distribution of Steel Production in 2050 Under the Narrow Club, Broad Club, and Broad Club Fossil Fuel Ban Scenarios



Global Green Iron Trade

Figure 26 below compares the spatial distribution of green iron sources (green circles) with consumers (yellow-green circles) in our *Narrow Club*, *Broad Club* and *Broad Club Fossil Fuel Ban* scenarios. Green iron trade does not occur in our *Baseline* scenario and so is not depicted.

- In *Narrow Club* (where the climate club is limited to a relatively small number of high-income countries) green iron trade increases to around 36 Mt annually by 2050. Green iron is mostly traded inside of the climate club, with the most significant flows being Australia, Canada and the United States supplying Europe. There are limited out-of-club flows, for example Brazil develops an independent green iron industry which mostly supplies domestic demand with some exports.
- In *Broad Club* and *Broad Club Fossil Fuel Ban* (which share the same climate club membership) green iron trade increases to between 200-250 Mt annually by 2050. In both scenarios the United States, Canada, and Australia are joined by Brazil, South Africa, India, Ukraine, Venezuela and Guinea and India as major producers. In *Broad Club*, steel made from green iron accounts for just under 10% of global demand by 2050, whereas for *Broad Club Fossil Fuel Ban* the equivalent figure is greater at almost 12%. This value would be higher if a wider range of beneficiable iron ore resources were included. India, the member economies of ASEAN, Mexico, and Brazil are the most notable consumers of green iron in both scenarios.

Figure 27. S2: Broad Club: Total Green Iron Production

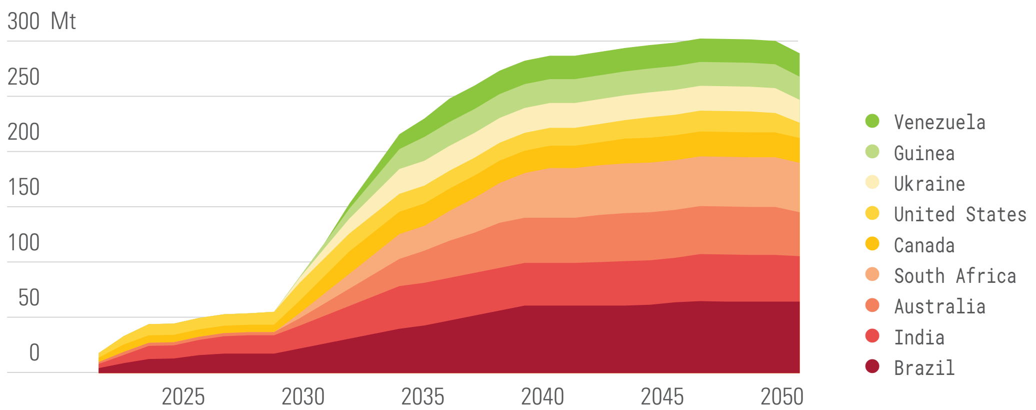
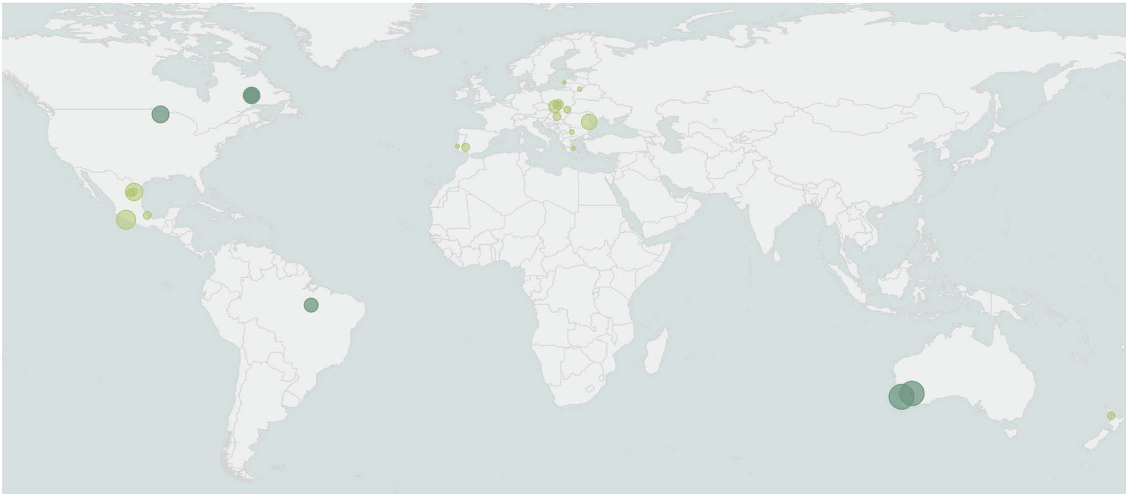
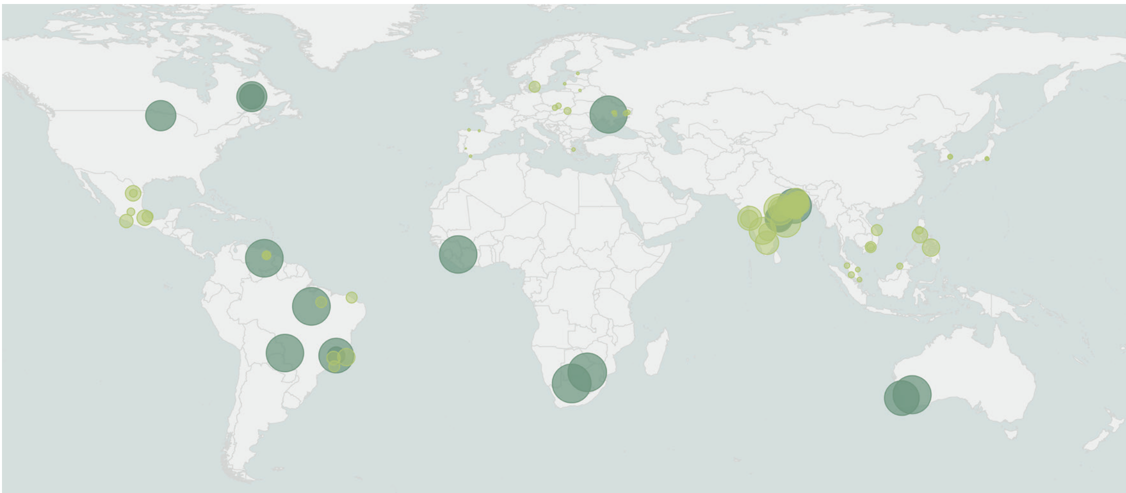


Figure 26. Comparing Global Green Iron Trade
Under the Narrow Club, Broad Club, and Broad Club Fossil Fuel Ban Scenarios

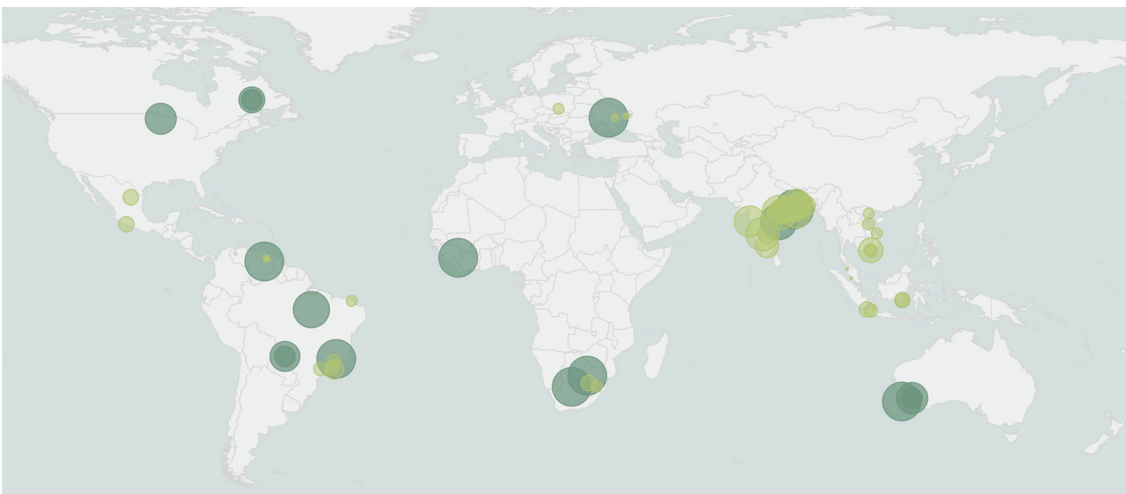
S1 Narrow Club - Steel Production 2050



S2 Broad Club - Steel Production 2050



S3 Broad Club Fossil Fuel Ban - Steel Production 2050

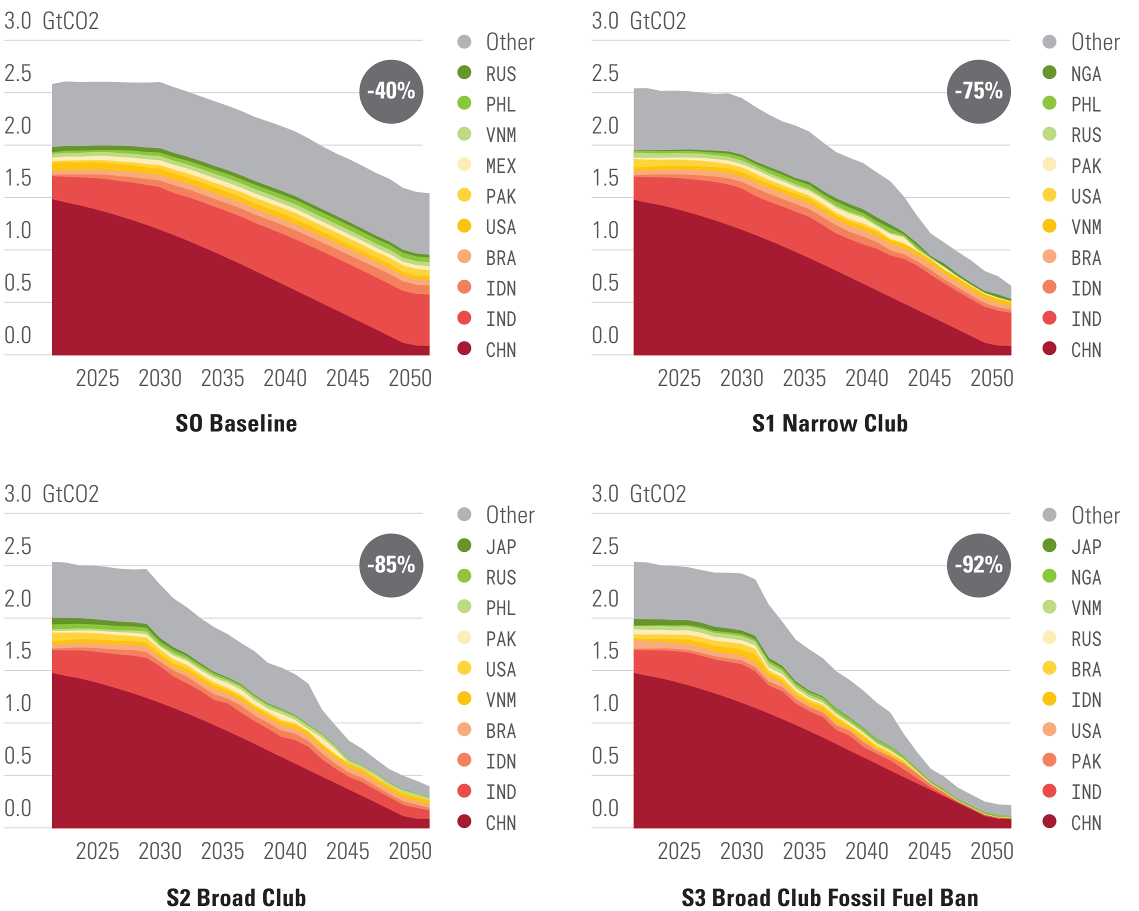


Net Zero Emissions By 2050

Figure 28 below compares and contrasts total emissions over time from 2022 to 2050 for all four scenarios, alongside the emission reductions achieved vs a 2022 baseline. First off, the ***Baseline*** scenario (upper left panel) achieves a 40% reduction in emissions by 2050. The *Narrow Club* scenario (upper right panel), featuring a climate club comprised of high-income countries, achieves a 75% reduction by 2050. The *Broad Club* scenario (lower left panel), which has a 2-speed climate club involving a mix of Global North and Global South members on different decarbonization trajectories and trading amongst themselves, achieves an 85% reduction by 2050. Finally, the deepest emissions reductions are achieved by *Broad Club Fossil Fuel Ban* (lower right panel) at 92%, the result of a near total ban on fossil fuel produced steel inside of the same large climate club from *Broad Club* (54 countries) starting in 2025.

Overall, our evaluation is that neither ***Baseline*** nor *Narrow Club* would be compatible with Paris Agreement aspirations for net zero emissions by 2050 - 2070. The *Broad Club* scenario does not achieve net zero emissions by 2050 but appears in a good position to achieve this target during the 2050s. We conducted a sensitivity test using a 17-year furnace relining cycle with our *Broad Club* scenario, and reductions moved from -85% to -87%. *Broad Club Fossil Fuel Ban* is the only scenario that can be argued to be unequivocally net zero compatible by 2050.

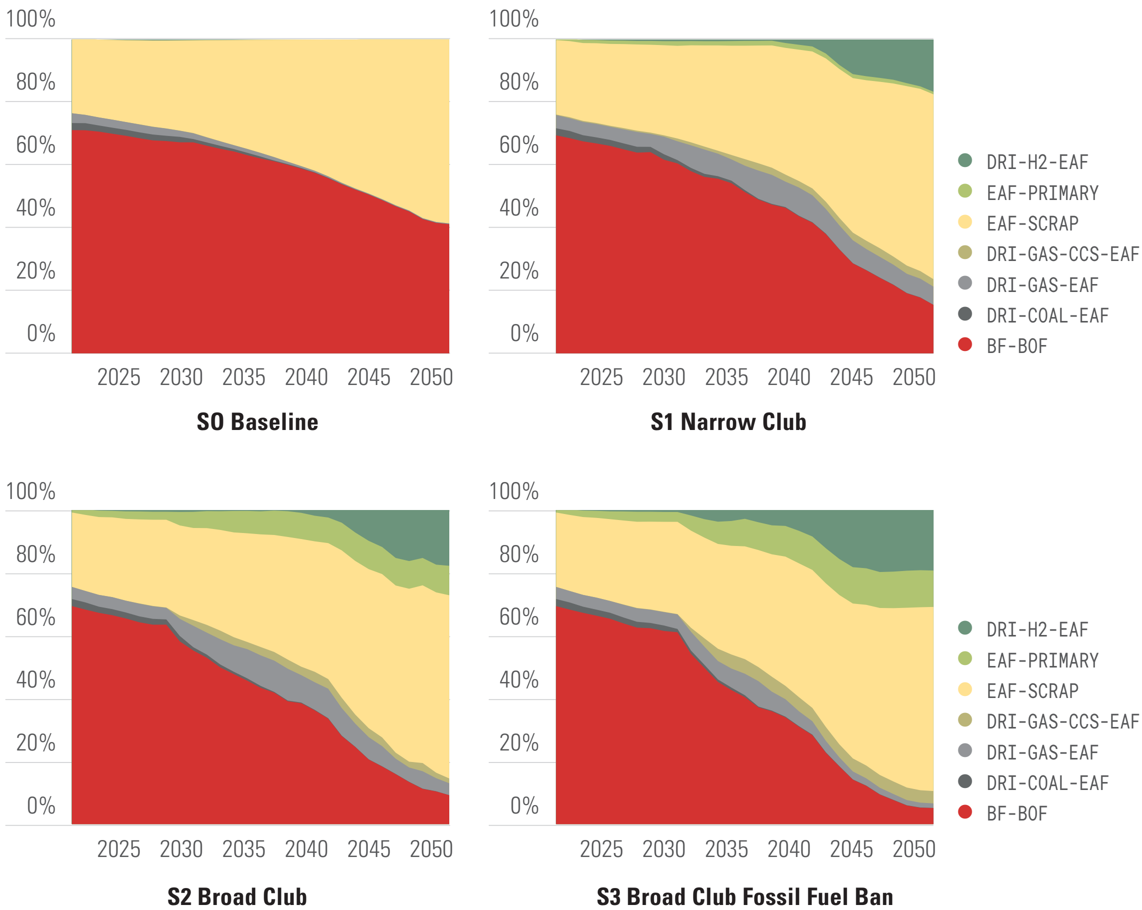
Figure 28. Comparing Emissions Over Time Horizon (2022-2050) Amongst Core Scenarios



Technological Change

Figure 29 below compares and contrasts technological change over time under our four core scenarios. Clean electrification combined with large scale increases in steel recycling (yellow) is the most significant single driver of steel sector decarbonization across all four scenarios, with recycling supplying 58-59% of demand across all four scenarios. The *Baseline* scenario (upper left panel) sees the blast-furnace basic-oxygen furnace (BF-BOF) pathway supply the lion's share of the remaining primary steel by 2050. In contrast *Narrow Club* (upper right panel), *Broad Club* (lower left panel), and *Broad Club Fossil Fuel Ban* (lower right panel) all see a shift away from steel production with BF-BOFs (in red), with this falling to 5-15% of production by 2050. Steel made using unabated natural gas (DRI-GAS, in grey) is between 1.5-6% of total production, depending on the scenario, while the same process using carbon capture and storage (DRI-GAS-CCS, in dark yellow) ranges between 1.5-4%. The largest single source of primary steel in those scenarios that offer significant decarbonization of the steel sector is steel made using direct reduced iron with hydrogen (DRI-H_2-EAF, in green), ranging from 17-19% of total production by 2050. Finally, steel made from green iron (EAF-PRIMARY, yellow-green) comprises a further 1.75-11.5% of production. *Narrow Club* has the lowest amount of green iron (1.75%), followed by *Broad Club* (9.5%), with *Broad Club Fossil Fuel Ban* having the most (11.5%). Again, green iron seems only to be limited by available beneficiable reserves.

Figure 29. Comparing Technological Change Over Time Horizon (2022-2050) Amongst Core Scenarios



The Impact of Including China in a Climate Club for Green Steel

Our Core Scenarios *Narrow Club*, *Broad Club*, and *Broad Club Fossil Fuel Ban* notably do not include China in their various climate club groups, although we have explored scenarios with China included as part of a green steel climate club in our broader model ensemble approach highlighted in Section 5. The role of China is of great interest to the future direction of the international steel manufacturing sector, as the world's second largest economy and the single largest producer of steel. We highlight below in **Figure 30** and **Figure 31** how including China inside of a green steel climate club coalition has large and significant effects on our core scenarios:

- Chinese participation affects cumulative emissions but not overall 2050 reductions for *Broad Club*. It simply brings forward in time mitigation that would have occurred later.
- Chinese participation would bring decarbonisation targets forward to the mid 2040s under *Broad Club Fossil Fuel Ban,* similar to the results from (AGORA Industry, 2023).

Figure 30. Impact of Including China in Broad Club Scenario with Potential to Achieve Net Zero Steel

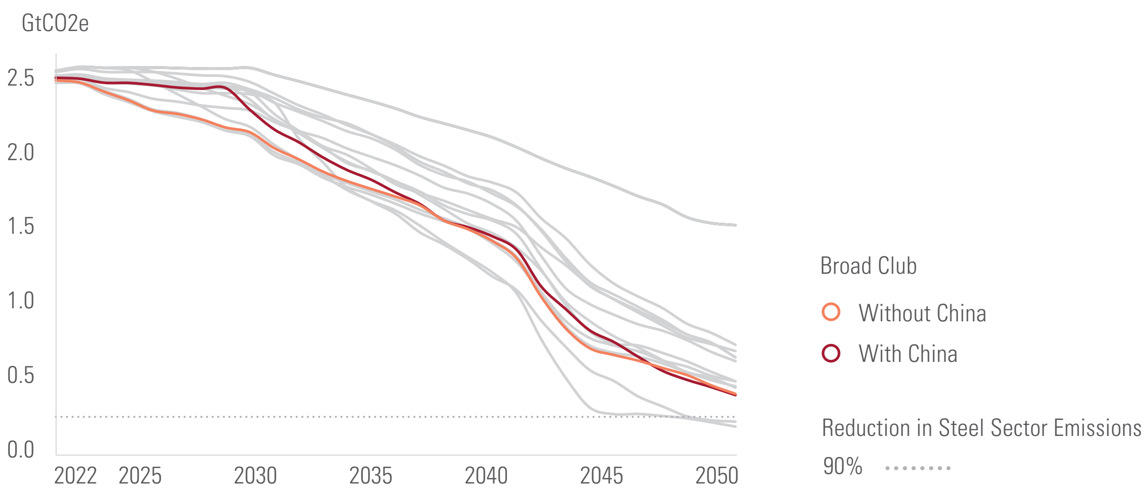
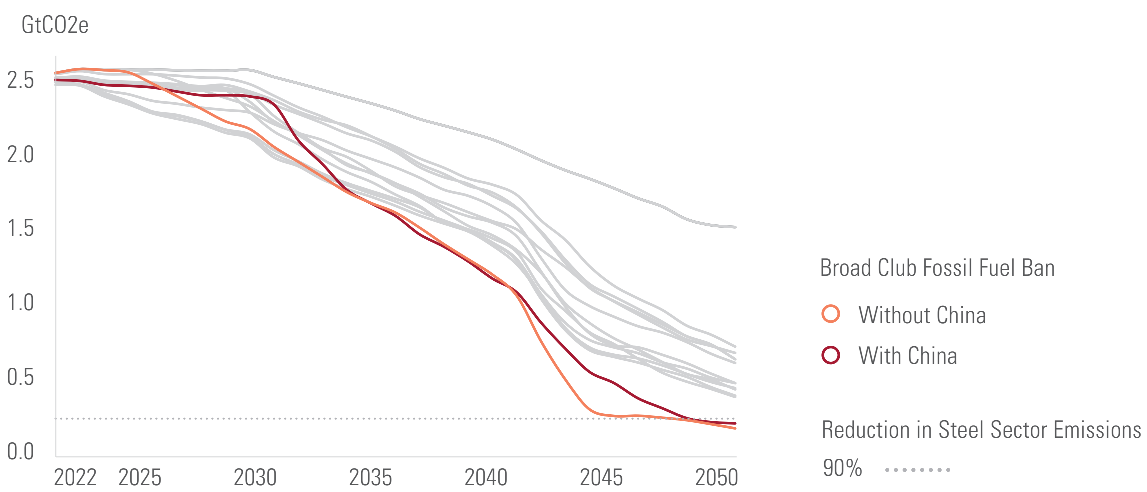


Figure 31. Impact of Including China in Broad Club Fossil Fuel Ban Scenario with Potential to Achieve Net Zero Steel



The Impact of Accelerated Retirements

To investigate the impact of accelerated retirements on the BF-BOF fleet, we carried out an exploratory simulation with stock turnover rates in the model reduced from 20 to 17 years. The 17 year interval matches the global average length of all blast furnace campaigns observed in (Vogl, Olsson, et al., 2021a). They estimate the typical first relining is after 19 years, the second 15 and the third 13. Most of the Chinese fleet is on its first relining, which partly why we have chosen to maintain 20, with the understanding switching major process will likely take more time.

The overall effect in our analysis is a slight uptick in the overall rate of decarbonisation across the globe as carbon intensive steel production with BF-BOFs turns over more quickly. This would take the 2050 conditions for *Broad Club* from an 85% reduction on 2022 levels to an 87% reduction.

Scenario Cost Comparison

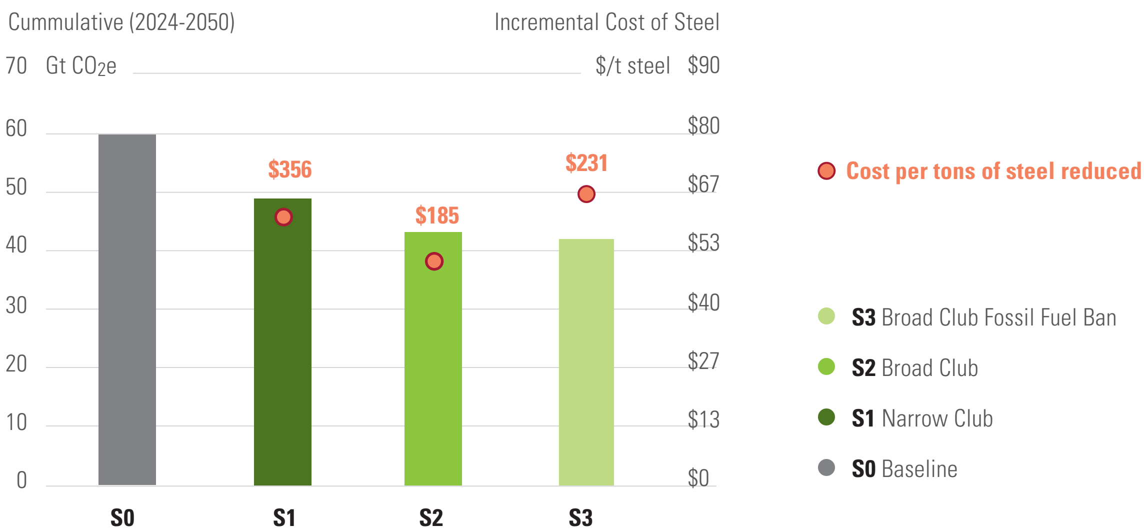
Figure 32 identifies the cumulative emissions between 2024-2050 for each of the four scenarios as we the relative cost of emission reductions. Cumulative emissions in the baseline are 60 gigatonnes ($GtCO_2e$) and between 49 and 42 $GtCO_2e$ in the various low carbon scenarios. Costs of emission reductions are actually lower for the two more ambitious low carbon scenarios, *Broad Club* and *Broad Club Fossil Fuel Ban*, than the *Narrow Club* scenario. We can hypothesize that the larger climate club reduces abatement costs overall as there are more options for low carbon production from members.

Importantly, we also find that the *Broad Club* scenario enjoys substantial benefits of induced innovation from advanced investment and the green iron subsidy. This leads to the least global average cost per tonne ($185/t CO_2e) , and almost the same cumulative emissions to 2050 as the outright global ban of the *Broad Club Fossil Fuel Ban* scenario, which comes at a much higher cost per tonne ($231/t CO_2e reduced).

Costs are presented both in terms of the incremental cost from the baseline of emission reductions per tonne of CO_2e reduced from the baseline, as well as the incremental cost per tonne of all steel produced in the scenario.

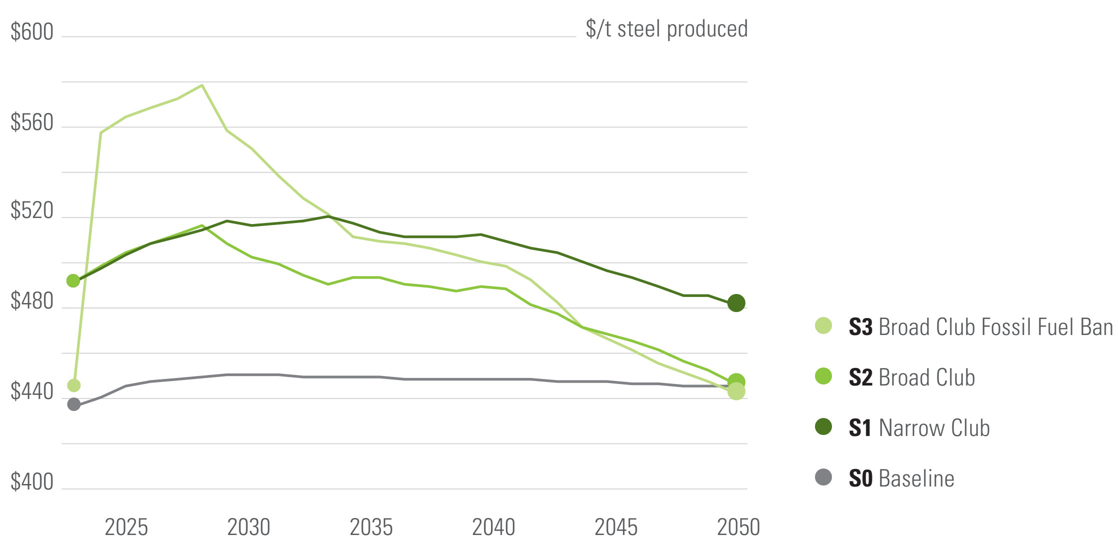
The average global costs of steel production including their transport costs in each modelled year between the scenarios is presented in **Figure 32**. These global

Figure 32. Global Cumulative Emissions and GHG Cost Reductions for four main scenarios (2024-2050)



costs would be lower than average market costs as they do not include other marketing costs and profit margins nor do they include additional costs such as trade tariffs, CBAM and carbon pricing. Baseline costs without significant carbon policy rise modestly from today to about $450/ tonne of crude steel production and remain relatively flat to 2050. In comparison, the *Broad Club* and *Narrow Club* scenarios have costs that are initially $55-$65 more expensive until 2029 at which point costs of the *Broad Club* scenario decline over time to be nearly the same as the baseline scenario by 2050. Costs for the *Narrow Club* scenario increase until 2034 and then decrease but are still $35 more expensive than the baseline in 2050. In comparison, costs for the *Broad Club Fossil Fuel Ban* scenario are very high, reaching $129 more expensive in 2029 before rapidly declining costs over time to be nearly the same as the baseline scenario by 2050.

Figure 33 Global Evolution of Production and Transport Costs of Steel for Core Scenarios



POLICY IMPLICATIONS

How China responds to falling internal building and infrastructure demand for steel will be critical. China does not operate a strictly market-based allocation system for incentivizing steel production. Province by province state operated and guided enterprise steel production targets are set in accordance with the goals of long term 5-year plans, with regional managers' reward systems often based on whether they meet and beat targets. China has been structurally producing about 5-6% more steel than it needs for decades, and this steel ends up on the open global market – this is commonly referred to as the "overcapacity" problem. Given China produces more than half the world's steel, this reduces prices from what they might have been. The US Section 232 tariffs and the EU's equivalent are designed to meet this structural overbuild.

China's steel fleet capacity, currently producing 54% of global production, is projected to exceed domestic demand over the next decade, and what China decides to do with its excess BF-BOF capacity will have significant implications for the global steel market and the global clean steel transition. Will they retire the least efficient facilities? Or will they export or repurpose the steel for downstream exports like vehicles & structural steel, which will continue to reduce global steel prices and stress global steel companies? The Chinese government has a mandate in place to swap high efficiency new plants for older plants at a 1:1.25 ratio (1.5 in environmental sensitive regions, and 1:1 for clean secondary or primary production) (OECD, 2023a), but has 147 Mt per year of high efficiency unabated blast furnaces under development, according to the Global Energy Monitor (Swalec & Grigsby-Schulte, 2023). Evidence points so far to China channeling its excess steel into increased vehicle and structural steel exports. Our modelling estimates that while Chinese secondary steel will rise rapidly with available scrap, primary falls off because of falling demand and rising relative cost of production, mainly labour. China has shown a willingness to "swim upstream" against prevailing market forces to reset markets, however, and what it does with its excess BF-BOF steel in the 2020s matters. If Chinese firms can be persuaded to close the least efficient facilities with the worst air quality impacts this would leave more global room for new clean iron ore reduction facilities.

Developing country demand means climate clubs need to be broad in order to be effective. Demand for steel in developing countries, if development is successful in India and other lower income industrializing, emerging and least developed economies, is set to surge - because of this, the climate club size is critical. Our analysis has shown that because most new demand is domestic demand in Asia, India and Africa, the club needs to encompass at least a portion of these regions. In particular, demand in India may triple or more, and it may not be able to meet all its own demand, even using all available secondary scrap based production and unabated coal based BF-BOFs – the Global Energy Monitor indicates 153 Mt of unabated blast furnaced are under development in India (Swalec & Grigsby-Schulte, 2023). Our modelling indicates it may be most economic to import the necessary iron and steel. Ideally this could be low carbon HBI for combination with local scrap for processing in electric arc furnaces into structural steel. This requires, however, a clear signal to potential supply regions and firms that there will be sufficient demand.

Maximization of high-quality, well sorted secondary production globally is key. Our available recycled scrap forecast is +14%, 204 Mt/yr higher than in Netzerosteel (2021), but requires material efficiency building code, design & recyclability policies, as well as well-established collection and sorting networks. Vehicles, buildings, & infrastructure need to be designed to be taken apart at end-of-life in a way that allows high quality, low contamination recycling, especially for copper. In our modelling, where minimum efficient scale is met, we have allocated all new domestically generated scrap to domestic secondary production. In this way, the basic needs for rebar and lower quality structural steel can then be met at least partially domestically in developing countries as they head into their high demand periods for basic water, sanitary, energy and transport infrastructure. This requires however the establishment of scrap gathering networks, and that a market signal is present to incentivize its use (Bataille, Stiebert, et al., 2023a). This may be a simple as government preferment for local reinforcement bar and basic structural steel, but a trigger may be required.

Any pathway to net zero steel requires all new iron ore reduction being near zero as soon as possible. A transition to net zero steel production is possible but requires that all new iron ore reduction is near zero emitting by the early 2030s. However, the key technology for making primary iron, coal-based BF-BOFs, must either change so that the emissions can be captured, or it must be a replaced with new near zero emissions iron reduction technologies. Reaching net-zero requires crystal clear communication to steel makers that no more "unabated" BF-BOFs without 90%+ capture CCS can be built past 2025 in the Global North, and in 2030 in the Global South, and that all countries and firms should be planning for near zero emissions alternatives. This is equivalent to running a carbon price schedule of $200 per tonne CO_2e starting today, effectively translating into a ban on unbated BF-BOFs, or $30 per tonne rising to $300. This requires a multi-level policy commitment to transition to net-zero GHG industry. This in turn requires a transition pathway planning process including all key stakeholders (e.g., steel firms, finance, unions, communities, governments) to assess strategic & tech options, competitive advantages, and uncertainties.

Starting the process of clean replacement of iron ore reduction plants for primary production in the late 2020s requires a fast and effective global innovation process to commercialize alternative primary iron reduction technologies. This is arguably happening fastest with green & blue hydrogen direct reduced iron (DRI) and possibly electrolysis. Green hydrogen DRI is underway in Europe and will likely meet the 2028 goal for several plants being operating. Several blue hydrogen DRI plants have been announced globally, while BF-BOF CCS is arguably going too slowly to meet the 2030 goal. This implies accelerated R&D and especially commercialization to broaden the range of available technologies.

Lead markets can be created with partners to build economies of scale using several different policy options: public and private green procurement of green iron product that both prefers green iron and pays a premium, e.g., through limited but guaranteed pricing or output subsidies (e.g. through reverse auctioned contracts for difference), or a tradable Zero Emissions Iron instrument (based on the California ZEV) that requires a certain portion of production or consumption in a region by near zero emission. Our $100 per tonne subsidy for green HBI is a proxy for the range of policies that are possible - any technology that can provide near zero emissions reduced iron would be eligible for the subsidy, e.g., electrolysis or BF-BOF with 90%+ capture. One way to carry out this study would be as a US IRA style production tax credit. We calculate the basic level of premia needed for the very first plant, given the absence of a carbon price, would be $312 per tonne minus any other existing inducements, e.g. the 45Q production tax credits for CCS, 45V PTC for hydrogen, any other inducements and regional carbon pricing.

Our modelling indicates that if lead market policies are put in place, significant induced economies of scale and learning are likely, and historic experience has shown these can be stronger than anticipated. Our scenarios with the $100 per tonne green iron subsidy all show strong induced economies of scale and learning effects, and if these policies are agnostic to technology and source these can be expected to exert a strong pull on the expected eventual emergence of electrolysis technologies.

Some sort of global finance mechanism is required to trigger investment in developing countries. Given much of the new demand for iron and steel will be in developing countries, and specifically on the journey from lower income ($1145 GNI/capita) through upper middle ($4465"), e.g., India at $2380 in 2022, to high-income ($13465") an international policy focus should be made on building near emissions facilities in these countries. This includes something like the Just Energy Transition Partnership (JETP), but for industry, e.g., a Just Industry Transition Partnership (JITP). The green iron subsidy in our study is one hypothetical means to operationalize an effective JITP.

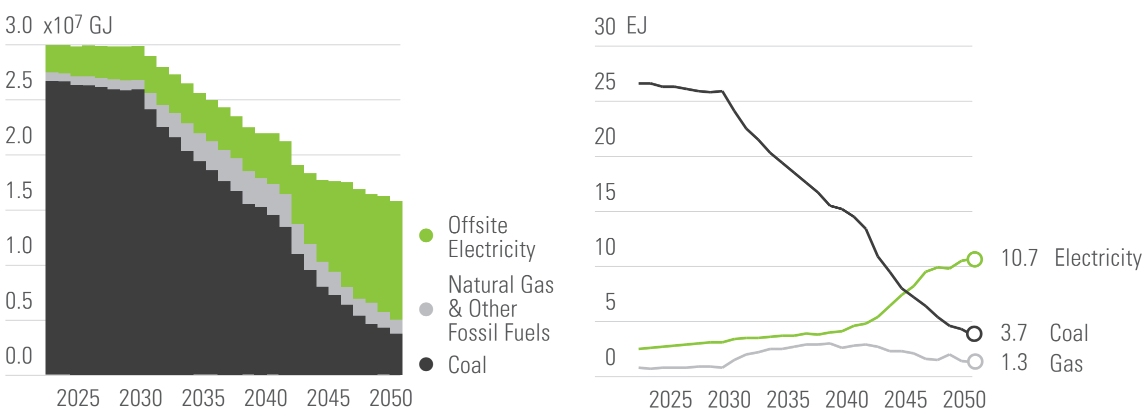
If it takes too long to commercialize low emissions technologies or to mandate their use, and high intensity facilities are built into the 2030s, early retirements may be necessary or the steel sector will not reach net-zero.

Global clean electricity requirements increase by 4.2+ times by 2050 in the *Broad Club* **and** *Broad Club Fossil Fuel Ban* **scenarios, which may stress some countries' capacity to deliver the necessary electricity for reducing iron using hydrogen or direct electrolysis.** This can be reduced by importing reduced green iron from countries with iron ore and excess capacity for clean electricity (e.g., Australia, South Africa, Brazil). To alleviate overdependence on one supplier, purposeful cooperation to develop several supplying regions, to create a green HBI pool, can help alleviate this. This market can also help incentivize the development of next-generation electrolysis technologies. We specifically found that HBI imports could help relieve electricity market pressures in key regions, e.g., the EU and India with its fast-growing demand, but our modelling indicates a cost premium is necessary to trigger uptake. A subsidy of $75-100 per tonne of green iron (eligible to all form of green iron production) is sufficient to trigger substantial investment in green iron production. While green HBI doesn't strictly initially compete against combined syngas based DRI with CCS or green hydrogen DRI because of its slightly higher costs, it instead provides a critical "2nd or 3rd best" strategy for moving gas with CCS or clean electricity consumption somewhere that can better accommodate it for geographic or geopolitical reasons. It also drives global economies of scale costs reductions associated with DRI production.

Key final messages

- **Chinese capacity to make BF-BOF primary steel will likely soon exceed its demand. If Chinese firms can be persuaded to close the least efficient facilities with the worst air quality impacts, and they can enforce it adequately, this would leave more global market share for new clean iron ore reduction facilities, inside or outside of China.**
- **The new few years are critical to reorientate the global steel industry toward net zero emissions by mid-century.** It takes at least 5 years from project inception to production for new iron ore reduction facilities, usually much longer, and any new reduction facilities built in the 2030s will be operating in the 2050s.
- **Lead markets, especially for the first round of low GHG intensity iron ore reduction projects, are necessary to establish demand and investment certainty for clean iron ore reduction.** This can be established through government preferred and subsidized procurement (e.g., through reverse auctioned contracts for difference), through production tax credits like the IRA, or perhaps through something like a tradable performance standard like the California Zero Emissions Vehicle mechanism. If a global financial incentive for green iron could be established, significant economies of scale and learning are likely, while increasing security of supply for steel makers with tight electricity markets.
- **Reasonable cost finance is necessary to fund risky and expensive upfront investment, especially in developing countries.** For at least the first round of projects in developing countries some form of risk reduction or concessional finance mechanism is necessary. A direct per tonne subsidy for low carbon iron reduction could accomplish this objective.

Figure 34. Broad Club scenario fuel use



- **Trade in low GHG intensity green HBI from multiple suppliers offers flexibility, security, a means to transfer electricity and hydrogen consumption where it is cheapest and cleanest**, as well as adding value to scrap for mixed primary & secondary production. To reach its potential, however, it requires clear trade rules and tariffing that accurately assesses GHG intensity for all traded steel and iron.

Limitations to this analysis and future research

Characterization of upfront capital costs

While capital, labour and energy costs are adjusted by region and through time, there is an upfront labour component in capital costs that we did not have the data to represent dynamically across regions, i.e. the general construction component of building a DRI plant in the US versus India. If data were available, especially for building brand new plants in key markets like India, this could be readily incorporated in the analysis. It likely would not change the overall messaging, because labour costs would apply equally across production types, but change some of the cumulative emissions and absolute values.

Induced innovation

A key outcome of this research was the large reduction in the direct capital and energy supply costs for hydrogen Direct Reduced Iron (DRI) production, triggered by the $100 production subsidy combined with stringent climate policy. Without intensive research it is unclear what portion of this is from the induced innovation mechanisms in the model, or from global economies of scale. Investigating this phenomenon, and how to optimize it, is critical.

As part of a deeper induced innovation study, we suggest a detailed assessment of possible breakthrough technologies, focussing on the range of at least 5 different electrolysis technologies that have been announced. A key analytical need is to assess how they differ in inputs, but also what marketable and non-marketable co-benefits exist. For example, the Electra technology (low temperature electrolysis) is reputed to able to use mine tailings and extract other metals at the same time. The same consideration would be given to standard ores – LKAB's mine tailings in Sweden are reputed to have large amounts of available rare earths.

Iron ore supplies for DRI based production

Our analysis incorporated known assessed high quality, DRI appropriate iron ore resources booked as reserves. Several researchers and commentators have focussed on the global supply of iron ore, and especially high-quality iron ore, as a rate limiter for DRI growth. While resource assessments show there is more than sufficient high-grade ore still available to serve at least a first generation of DRI plants until electrolysis is commercialized, the focus in the past has been mainly on developing the cheapest and highest volume sources suitable for immediate delivery to BF-BOFs. How fast new beneficiable iron ore reserves appropriate for DRI, e.g., Australian or Canadian magnetite and titanomagnetite, could be developed is a key question. Future work could incorporate a deeper and more dynamic assessment of key supply regions, the total resources and what it would cost to transform them to usable reserves, and a deeper assessment of beneficiation needed within future modelling scenarios.

Trade in scrap, and competition between primary and secondary production

In our analysis all available scrap was held domestically where minimum efficiency scale allowed, given its priority as a decarbonization strategy. Allowing trade in scrap, and competing secondary and primary for a range of end uses, may change the results.

Extension of the study time horizon to 2070

Given China's current commitment to net zero by 2060, and India's by 2070, we would like to extend the range of the model time horizon to 2070. This would also allow us to consider whether a "Global North" climate club would need to hit net zero earlier in consideration of CBDR.

APPENDIX

APPENDIX: ASSESSMENT OF REGIONAL "TRADE BLOCS"

Table 6 provides an overview of various key regional economic integration groups, their membership, and the extent to which economic integration has been successful as of the time of writing, early 2024.

Table 6. An Overview of the Status of Key Regional Economic Integration Groups, "Trade Blocs"

Regional Economic Integration Group	Members	Status in 2023
European Union (EU) / European Economic Area (EEA)	EU: Germany, France, Italy, Spain, Netherlands, Poland, Sweden, Belgium, Austria, Ireland, Denmark, Finland, Portugal, Czech Republic, Greece, Romania, Hungary, Slovakia, Bulgaria, Croatia, Slovenia, Lithuania, Latvia, Estonia, Cyprus, Luxembourg, Malta EEA: Iceland, Liechtenstein, and Norway	Comprehensive economic integration with a single market and a common currency (the Euro) used by most member states Harmonization of laws and regulations across a wide range of policy areas Free movement of goods, services, capital, and people Well-developed institutions to support and govern the integration process
North American Free Trade Agreement (NAFTA) / United States-Mexico-Canada Agreement (USMCA)	United States, Canada, Mexico	Significant reduction of trade barriers among the three member countries Established clear rules and dispute resolution mechanisms for trade and investment Facilitated increased economic integration and cooperation among the member states
ASEAN (Association of Southeast Asian Nations) / ASEAN Free Trade Area (AFTA)	Indonesia, Thailand, Malaysia, Philippines, Singapore, Vietnam, Myanmar, Cambodia, Laos, Brunei	Facilitates free trade among the member states of ASEAN Has already successfully reduced tariffs and trade barriers among its member states Represents an important step towards the broader goal of ASEAN economic integration
Regional Comprehensive Economic Partnership (RCEP)	All of ASEAN (see above), plus China, Japan, South Korea, Australia, New Zealand	Comprises ASEAN plus most of the largest economies in the Asia-Pacific region, covering a significant portion of the world's population and GDP Aims to lower trade barriers and harmonize trade rules among its member states May represent a significant step towards greater economic integration in the region
MERCOSUR (Mercado Común del Sur, Southern Common Market)	Full members: Brazil, Argentina, Uruguay, Paraguay, Venezuela Associate members: Bolivia, Chile, Colombia, Ecuador, Guyana, Peru, Suriname	Aims to promote free trade and the fluid movement of goods, people, and currency among its member states Has successfully reduced trade barriers among its full members Faces challenges in fully implementing its objectives, including remaining trade barriers among member states
Gulf Cooperation Council (GCC)	Saudi Arabia, United Arab Emirates, Qatar, Kuwait, Oman, Bahrain	Aims to establish a common market and a customs union among its member states Has implemented measures to facilitate the free movement of goods, services, capital, and people among its member states Still faces challenges and obstacles to full economic integration
Eurasian Economic Union (EAEU)	Russia, Kazakhstan, Belarus, Armenia, Kyrgyzstan	Aims to promote economic integration among its member states, including the free movement of goods, services, capital, and labor Has successfully implemented some measures to facilitate integration Faces challenges in fully achieving its goals, including remaining trade barriers among member states
Southern African Development Community (SADC)	South Africa, Angola, Tanzania, Mozambique, Zambia, Zimbabwe, Democratic Republic of the Congo, Botswana, Namibia, Malawi, Lesotho, Swaziland, Mauritius, Madagascar, Seychelles	Aims to promote sustainable and equitable economic growth among its member states Has successfully facilitated increased trade and cooperation among its member states Faces challenges in fully implementing its objectives, including remaining trade barriers among member states
Economic Community of West African States (ECOWAS)	Nigeria, Ghana, Côte d'Ivoire, Senegal, Burkina Faso, Niger, Mali, Benin, Sierra Leone, Liberia, Guinea, Cape Verde, The Gambia, Togo, Guinea-Bissau	Aims to foster economic integration among its member states Has successfully implemented some measures to facilitate integration Faces challenges in fully achieving its goals, including political instability in some member states
African Continental Free Trade Area (AfCTFA)	All of SADC (see above), all of ECOWAS (see above), plus Egypt, Morocco, Algeria, Kenya, Tunisia, Cameroon, Uganda, Rwanda, Libya, Chad, Djibouti, Eritrea, Somalia, South Sudan, Equatorial Guinea, Sao Tome and Principe, Comoros	AfCTFA, if successfully implemented, would be one of the largest free trade areas in the world Implementation is still in the early stages with negotiations still ongoing, and limited trade volumes
Caribbean Community (CARICOM / Caribbean Single Market and Economy (CSME)	Trinidad and Tobago, Jamaica, Guyana, Barbados, Suriname, Belize, Saint Lucia, Antigua and Barbuda, Saint Vincent and the Grenadines, Grenada, Dominica, Saint Kitts and Nevis, Montserrat, Haiti	Aims to foster economic integration and cooperation among its member states in the Caribbean region There has been some progress in the free movement of goods and services within the region, with the removal of barriers to trade and the harmonization of standards and regulations There are significant gaps in the implementation of the CSME, with many member states lagging in the adoption of necessary legal and regulatory changes Many CARICOM member states lack the necessary resources and institutional capacity to fully implement the CSME

Notes: Although not listed explicitly, in our analysis we have included Switzerland and the United Kingdom in the European grouping because of bilateral trade agreements between those nations and the EU, even though at the time of writing neither country is inside the EU or the EEA. Also, at the time of writing in early 2024 Bolivia is still in the process of becoming an associate member of MERCOSUR, while Venezuela has been suspended from the organization since 2016, and the future of Argentina's membership is unknown.

APPENDIX: MODEL DOCUMENTATION

Overview

This appendix gives a description of the key features, mathematical equations and data used for the Steelpath model version used to produce the decarbonisation pathway analysis in this report. Steelpath is a spatially explicit intertemporal simulation model of the global steel production system that simulates technological change, energy use, and emissions over time. At the time of writing, the model is unique in that it represents the transformation of global steel production using a georeferenced database of over 1000 real world facilities that together comprise more than 97% of global production, with the remaining 3% inferred from a top-down analysis of global steel consumption (described in detail in following sections). An earlier version of the Steelpath model was previously use to provide our 2021 report *"Global Facility Level Net-zero Steel Pathways: Technical Report on the First Scenarios of the Net-zero Steel Project* " which can be found at netzerosteel.org (Bataille et al., 2021a). For readers who are already familiar with that work, we can highlight that some major changes from the previous model version include (but are not limited to):

- the use of Global Energy Monitor's updated 2022 database for facility locations, which improves our baseline coverage of global steel production facilities to 97% (previously 85%)
- changing the decision-making process for steel facility deployment from a political economy model to instead perform resource allocation based on levelized cost minimisation, with costs grounded in a state-of-the-art review of the costs of steel production pathways
- enabling trade between model regions, trade tariffs, carbon border adjustments, carbon taxation, and the ability to assign countries to one or more trade alliances so that the future evolution of the global steel sector under different combinations of regional free trade areas with different trade and decarbonization policies can be explicitly explored
- improving regional detail such as differentiation of labor costs and financing costs by country, and improving the assessment of electricity system costs to include both wind and solar potential (the previous study only used solar power pricing)
- expanding technological options to explicitly include green iron produced from multiple pathways (i.e. the reduction gas can be blue hydrogen made with carbon capture and storage or green hydrogen from renewable electricity)
- the ability to exploring a range of emergent decarbonisation scenarios under different trade, climate policy and industrial policy decisions, which leads to outcomes that include both successful "net zero" transitions and transitions that only make it part of the way

Implementation and System Requirements

The equations and data for Steelpath are implemented in MathWorks MATLAB, a mathematical programming language and computation environment that is widely used in academia and industry. More technical details can be found at the developers' website (https://www.mathworks.com/). MATLAB is available for Microsoft Windows, Apple macOS and various Linux distributions. The main hardware constraints for Steelpath are: system memory due to the use of high-resolution geographical information data which leads to very large arrays (i.e. millions of data rows), CPU core count due to the requirement to perform large parallel operations on data tables holding aforementioned millions of rows of information, and the requirement for hardware accelerated graphics to produce the model outputs. The current version of Steelpath used in the production of this report is run on a process node with 128 GB of system RAM, 24 CPU cores, and a GPU with 24 GB VRAM.

Brief Description

Like all energy system analysis models, the design of Steelpath is designed to fit within the limitations of the available data, computational resources, and for a specific intended purpose. Specifically, Steelpath is used to illustrate the spatial and technological implications for different countries and existing steel manufacturing facilities of a rapid shift to zero carbon steel production in line with Paris Agreement targets and aspirations. The model focuses only on the global steel production sector and makes a number of assumptions about the wider energy system transition in other sectors (e.g. power generation) that will be described in later sections. Decision making in the model occurs at the level of individual countries (137 in total) which act as discrete agents in a bottom-up fashion. This may not capture the true behaviour of the real-world system where transnational actors (i.e. multinational corporations) may in fact drive decisions in concert with national governments, but is an acceptable simplification for the types of research question for which the latest version of the model is currently employed. Individual decision makers in Steelpath (i.e. countries) act to minimise their own system costs under various policy scenarios (e.g., inclusive of emission pricing, subsidies, trade groups and policies) and must compete with other actors in the system for resources. In our model universe we assume that the largest and most powerful economies have the greatest agency and strategic foresight capabilities and so the model is structured so that countries act in descending order of GDP, with GDP also being dynamic across time (so that as economies grow and become more powerful through time, they are increasingly able to act earlier than their competitors).

The intention is to explore various scenarios for the potential transformation of the global steel sector in the period 2021-2050 (including successful net zero transformations), with implications for individual real-world actors (market dynamics, investment planning, capital requirements etc.) then inferred in an *ex-post* fashion. In simple terms, the model is intended to show a few possible pathways for the decarbonisation of the steel sector as a jumping off point for discussions as to how this can be achieved. In contrast to our previous study (Bataille et al., 2021a), which only considered successful net zero transitions, we explicitly consider in this study scenarios that achieve partial decarbonisation and fall short of a true “net zero” goal.

Cost Data

Capital

Capital costs account for equipment purchases and installation of manufacturing plant, and are mainly drawn from the International Energy Agency’s Iron and Steel Roadmap (IEA, 2020e), with other sources used to corroborate final numbers used (Fischedick et al., 2014; Mayer et al., 2019; West, 2020a, 2020b). While the equipment costs themselves are the same for all countries, capital expenditure in different global regions is differentiated in two ways:

- **Cost of capital:** Technology deployments in different regions experience varying costs of capital, because investors perceive risks differently between countries. We can for example see this in the costs of capital being offered for investments in renewable energy projects.
- **“First of a Kind” vs. “Nth of a Kind” deployments:** perception of risk in near zero emission manufacturing facilities is affected strongly by whether or not concrete examples of similar projects have successfully been deployed already or not i.e. is a project the “first of a kind” (FOAK) or “Nth of a kind” (NOAK) e.g.(Bataille & Stiebert, 2022; Stiebert & Bataille, 2022).

In reality every project will be assessed on a case-by-case basis, and may also change across time as investor sentiment towards different countries, or broader shifts in the global economy also change. For modelling purposes in our analysis here we have differentiated between OECD economies and non-OECD economies and kept this static across the time horizon.

Table 7. Cost of Capital

Cost of Capital	OECD	Non-OECD
First of a Kind (FOAK)	12%	16%
Nth of a Kind (NOAK)	8%	12%

Maintenance

Maintenance costs capture all expenditures associated with continued facility operation outside of capital or labour costs. These are drawn from the same sources as our capital costs.

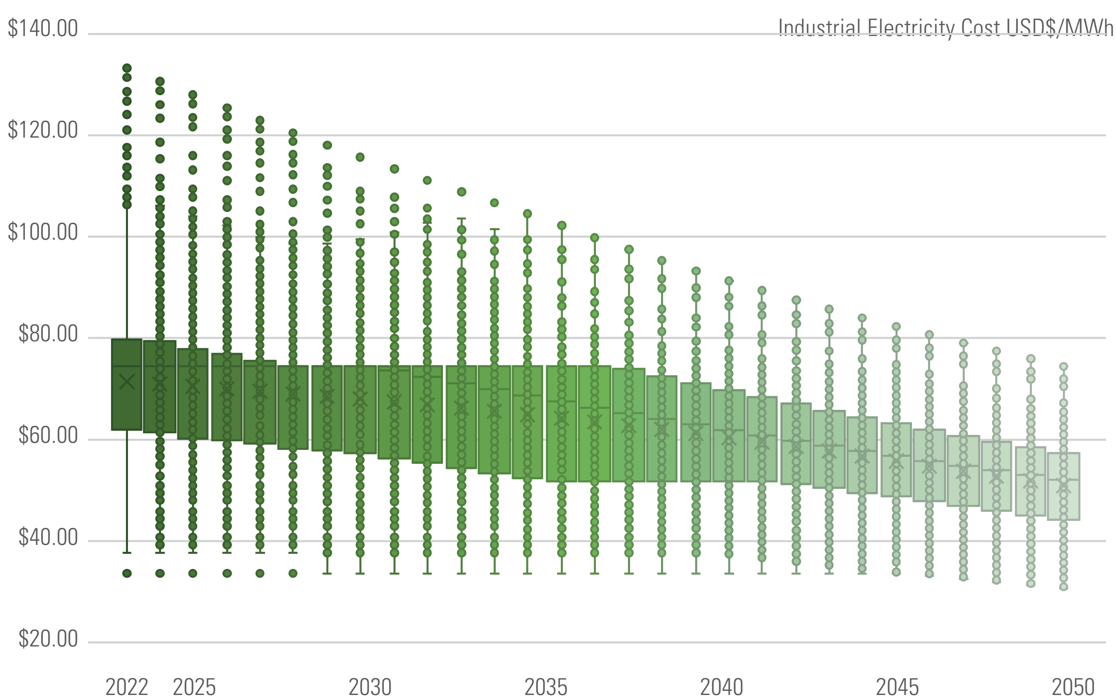
Labour

Labour costs in the model are differentiated by country as well as by technology, and change both in different countries and through the model time horizon from 2021 to 2050. Average labour costs per tonne of steel production are based on a relationship between the cost of labour per tonne of steel produced in a select group of 13 major producer countries (M'barek et al., 2022) and the relative $GDP/ capita of those countries using GDP data and forecasts from the World Bank and the OECD (OECD, 2023b; World Bank, 2023). This means that as different countries are assumed to grow economically, their labour costs also increase proportionally.

Energy

We rely on energy balances from the scientific literature on steel manufacturing to understand the type and quantity of energy required to make each unit of steel in the model from each technology pathway (Cavaliere, 2019, 2022; Hasanbeigi et al., 2013; Ho et al., 2008, 2013; House et al., 2009; Kildahl et al., 2023; Li et al., 2018; Nduagu et al., 2022; Ozbayoglu, 2018; Prasad et al., 2011; Song et al., 2019; Vasudevan et al., 2016; Vogl et al., 2018; West, 2020a, 2020b). Each manufacturing site in the model then has different costs for electricity and fuels. **Electricity:** Retail electricity prices for industrial facilities like iron and steel mills depends in large part on the decarbonization transition of the electricity sector for respective countries. In principle net zero scenarios anticipate falling costs for renewable electricity such as wind and solar, as well as falling costs for utility-scale battery storage that can support high renewable penetration. In general, most countries can expect falling industrial electricity prices even as they decarbonize, despite additional costs for transmission, distribution and storage. In order to build a database of industrial electricity prices at each steel production site in the model, we first establish average baseline industrial electricity prices in 2022 informed by data from a number of different sources (DESNZ, 2023; Eurostat, 2022; Howdle, 2021). We then consider how large industrial user electricity prices are likely to evolve in time under the assumption that electricity decarbonization in each

Figure 35. Distribution of Production Site Electricity Costs for Steel Production ($/MWh)



country will develop by 2050. Price projections for each potential manufacturing site in the model reflect expected costs of wind and solar combined with utility scale battery storage in plus costs for transmission and distribution. This means that we assess the wind and solar irradiation potential near every site to determine an average supply cost forecast to 2050. Solar irradiation data is taken from the Global Solar Atlas project (Solargis & World Bank, 2023), while wind energy data is taken from the Global Wind Atlas project (Davis et al., 2023; DTU & World Bank, 2023). We then transition the baseline 2022 electricity grid price to the lowest cost wind or solar renewable price supported by utility scale battery storage over time, if the lowest cost wind or solar is less expensive. **Figure 35** below indicates the distribution of electricity costs for steel production at all available sites in the model.

Natural Gas: in our model analysis we group regions into areas that: (i) do not have a natural gas supply and are not assumed to develop one at the speed or scale required for large steel manufacturing facilities, (ii) are able to receive natural gas deliveries via LNG imports, and (iii) have an existing pipeline supply. We then further differentiate (iii) pipeline supply by world region based on data from the International Energy Agency, the United States Energy Information Administration, and the Gas Exporting Countries Forum (EIA, 2023b; GECF, 2021; IEA, 2022b). This gives us six groupings of natural gas prices in total. We differentiate prices at each potential steel manufacturing site rather than by country. This is because certain large countries have natural gas pipeline networks and/or LNG infrastructure in some areas (typically coastal areas) but not others (often interior regions hundreds of kilometres from the coast that may also be separated from natural gas supply infrastructure by mountains). All of these databases consistently identify the lowest natural gas prices for North America and the Middle East (approximately a third lower than in Europe), with the highest prices in Asia and South America. Prices do not include carbon pricing which is added to production costs separately (see Section 10.4.8). Natural gas prices are assumed to shift over time in line with IEA's assumptions in their Net Zero by 2050 Scenario (IEA, 2022b).

Table 8. Natural Gas - Cost of Capital

Regions	Countries	Cost Assumptions
Pipeline Gas Supply		
Countries in Middle East and in North America	Bahrain, Canada, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Mexico, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, United States, Yemen	USD$5.72 in 2022 rising to $6.10 in 2050
Europe, Russia and Central Asia	Albania, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Luxembourg, Malta, Moldova Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Tajikistan, Türkiye, Turkmenistan, Ukraine, United Kingdom, Uzbekistan	USD$21.10 in 2022 falling to $6.80 in 2024 and rising to $10.20 in 2050
Latin American Regions with Natural Gas Pipeline Networks	Argentina, Bolivia, Brazil, Chile, Colombia, Cuba, Ecuador, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela	USD$9.30 in 2022 rising to $10.95 in 2050
Asia and Oceania with Natural Gas Pipeline Networks	Australia, Bangladesh, Cambodia, India, Indonesia, Japan, Malaysia, Myanmar, New Zealand, Philippines, Singapore, South Korea, Thailand, Vietnam	USD$ $9.30 in 2022 rising to $10.20 in 2050
LNG Only Gas Supply		
Coastal Sites located in Egypt, Nigeria, Pakistan, South Africa, and coastal Chinese Provinces (Fuijan, Guandong, Guangxi, Hebei, Heilongjuang, Jiangsu, Jilin, Liaoning, Shandong, Shanghai, Tianjin, Yunnan, Zhejiang)	Algeria, Angola, Benin, Dijibouti, Dominican Republic, El Salvador, Equitorial Guinea, Gabon, Ghana, Guatemala, Guinea, Hong Kong, Jamaica, Libya, Mauritania, Morocco, Mozambique, Nicaragua, Panama, Senegal, Sri Lanka, Taiwan, Tanzania, Togo, Tunisia	USD$12 per MMBtu to 2050
No Gas Supply		
Inland Sites located in Egypt, Nigeria, Pakistan, South Africa, and inland Chinese Provinces (Anhui, Chongqing, Gansu, Guizhou, Henan, Hubei, Inner Mongolia, Jiangzi, Ningxia, Qinghai, Shannxi, Shanxi, Sichuan, Xinjiang)	Cameroon, Costa Rica, Cote d'Ivoire, D.R. Congo, Ethiopia, Honduras, Kenya, Madagascar, Mauritius, Mongolia, Namibia, North Korea, Sudan, Uganda, Zambia, Zimbabwe	No Gas Available

Coal: coal is a globally traded commodity with its own regional dynamics. Direct price comparisons of coal across regions are complex, because not only does coal vary in quality (such as sulfur content and calorific value for different types of coal) but a significant portion of coal is traded in bilateral contracts where prices are not publicly disclosed. This makes the coal market more opaque than oil or gas markets, which have benchmark prices from major indices (Brent or WTI for oil, Henry Hub for natural gas etc.) In the absence of benchmark regional price data, we assume a future global market cost for coal of USD$140/tonne, based on historical data from the United States Energy Information Administration (EIA, 2023a).

Raw Materials

Raw material requirements per unit of steel produced are derived from mass balances in the scientific literature on steel manufacturing via different technology pathways. We draw from the same references as those used for energy balances (Cavaliere, 2019, 2022; Hasanbeigi et al., 2013; Ho et al., 2008, 2013; House et al., 2009; Kildahl et al., 2023; Li et al., 2018; Nduagu et al., 2022; Ozbayoglu, 2018; Prasad et al., 2011; Song et al., 2019; Vasudevan et al., 2016; Vogl et al., 2018; West, 2020a, 2020b). Ferrous scrap (i.e. scrap steel) and iron ore are the main inputs.

- **Ferrous scrap:** scrap steel is an important input in our model into processes that use recycled steel, such as electric arc furnaces. Prices are influenced by factors like quality and grade of the scrap, demand for steel of different grades, and the transportation costs from the scrap source to the destination. Sources of data on ferrous scrap pricing includes the Platts TSI Heavy Melting Scrap and the American Metal Market (AMM) Midwest Scrap Index. For our model analysis we have used a global cost for ferrous scrap based on historical USGS data (USGS, 2023a).
- **Iron ore:** iron ore is the key commodity for primary steel manufacturing, and is widely traded internationally. Iron ore prices are influenced by grade (i.e. iron content), and regional demand supply dynamics. The major index tracking iron ore pricing is the Platts Iron Ore Index (IODEX) which measures the flow of a specific grade of iron ore (62% Fe) to China, which is the major steel market at the time of writing. Most contracts for iron ore in at different grades or in different physical forms (e.g. concentrate, lump ore) are computed with formulae (i.e. negative weighting for lower grades) that are based on the Platts IODEX. For our model analysis, we have used a global cost for iron ore of around USD$90/tonne in the base year based on historical USGS data (USGS, 2023b). Most steel manufacturing pathways that rely on direct reduction of iron (DRI) actually require a higher grade of iron, 67% Fe than what is commonly traded today. To handle this, our assumptions for material and energy requirements per unit have assumed that in DRI-based production pathways, iron ore at lower grades must be upgraded first to increase its iron content per unit mass (in the iron industry this is called "beneficiation") but we have assumed 62% Fe grade iron ore as the input for this process and not lower grade ores.

Support Infrastructure Costs

Our analysis differentiates between construction of manufacturing plants at existing industrial sites that are well served by utility connections and transport links, and those which are not. Infrastructure for existing supply chains for steel production and trade have considerable value and adding capacity or building new greenfield sites requires significant capital investments. These investments include transportation connections (typically rail) as well as utility connections such as water, electricity and oil or gas pipelines. Developing greenfield sites also have additional costs including land acquisitions and the cost of permitting and approval for new projects. Incumbent steel production at new sites faces significant barriers and there is a strong deterrence for entry into the market especially since at the moment an increase in demand for steel can easily be met by existing facilities due to worldwide excess capacity.

In order to differentiate capital and operating costs between existing sites and greenfield sites and between existing available capacity and increased capacity, research was conducted on the costs for supporting steel infrastructure. For example, it is anticipated that global investment costs required between today and 2050 for increased generation and electricity transmission and distribution infrastructure for low carbon steel production may be on the order of 3-3.8 trillion dollars (Mission Possible Partnership, 2022). While our model estimates full cost of electricity delivered to the site, so in theory counts these costs, real world establishment of industrial facilities typically incurs further additional costs for utility connections. It is estimated that transportation connections, utility connections and land acquisition and preparation for new industrial sites is in the range of 5% to 14% of current capital and operating costs ($21-62$/tonne of steel).

The model includes the following supporting infrastructure cost adders as described in **Table 8** for different sites to capture incremental costs of building greenfield sites and for expanding the capacity of sites.

Table 9. Supporting Infrastructure for New Sites and Expanding Capacity of Existing Sites

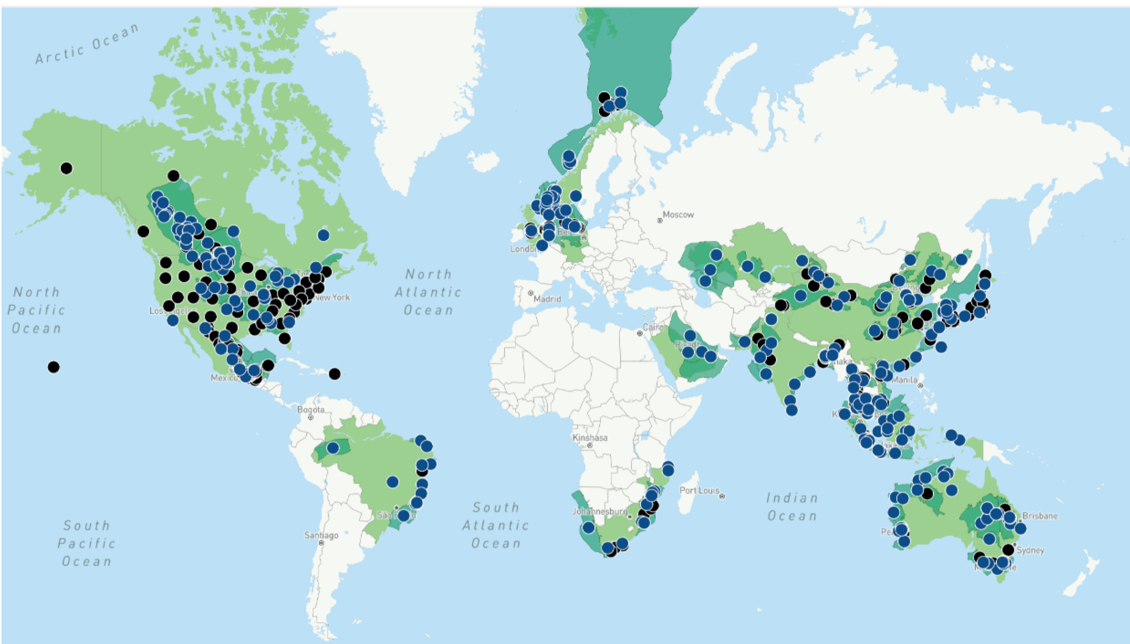
Type of Site	Infrastructure Requirement	Cost Adder ($/tonne steel)
New Build Site (Greenfield)	Scrap-EAF or HBI Production	$21
	All Other Steel Production Technologies	$62
Existing Scrap-EAF Sites	Expanded Scrap-EAF capacity	$7
	Expanded capacity for all other Steel Production Technologies	$36
All Other Sites	Expanded Scrap-EAF capacity	$15
	Expanded capacity for all other Steel Production Technologies	$21

Carbon Capture and Storage

The availability of carbon capture and storage is assessed on a per coordinate basis using data from the OGCI 2021 CO_2 Storage Resource Catalog (OGCI & GCCSI, 2021), which can be visualized below. The distance from each steel production site in the model to the centroid of the identified storage locations is assessed using a range of maximum distances (these are orthodromic or "great-circle" distances that take into account the curvature of the earth). Real world constraints that make the construction of CO_2 pipelines infrastructure more or less feasible include issues such as topography, land-rights or access, subsurface geology, hydrology (need to cross rivers etc.), possible interference with artificial barriers and human structures such as highways, railroads, buildings, or other buried infrastructure (other pipelines, buried storage facilities etc.).

For our analysis in this study, we have assessed 100km as a maximum pipeline construction distance. For context, at the time of writing the largest CCS network in the world is the Alberta Carbon Trunk Line, which

Figure 36. Distribution of Production Site Electricity Costs for Steel Production ($/MWh)



comprises 240km of pipeline in total across a linear distance of approximately 150km in flat terrain without routes passing through major urban areas (Cole & Itani, 2013). Costs for providing carbon capture and storage are then drawn from the literature on pipeline construction and geological sequestration with appropriate corrections for inflation and currency conversions to 2022 USD$ (IEA, 2020e; IPCC, 2005; Rubin et al., 2015; van der Zwaan et al., 2011).

Carbon Price

Emissions pricing is controlled at the country level, reflecting a wide range of regulatory costs and constraints. Carbon pricing values the externality presented by GHG pollution (Hallegatte et al., 2013), which increases the perceived cost of GHG-intensive steel production pathways when the model is making selections on which technologies to deploy. Different model scenarios feature different countries following a variety of carbon price trajectories, reflecting the principle of common but differentiated responsibilities in the Paris Agreement (UNFCCC, 2015). In our scenarios, carbon pricing typically increases in incremental steps over time as a steadily rising cost, reflecting the fact that it may be difficult to make rapid near-term step changes in how industrial pollution is regulated, although we do also test "shock" scenarios where increases in CO_2 pricing are rapid, which can be used to effectively simulate a ban or stringent phase out policy for carbon emitting technologies.

Subsidies

Subsidies can be applied for individual technologies and differentiated by country, with the ability to have subsidies rising or falling over time for different countries/technologies. Subsidies reflect policy decisions that make investment in technologies more attractive. Subsidies reduce the perceived costs of selected technologies when the model is carrying out its economic assessment and making technology deployment choices.

The model can also handle perverse subsidies not related to low carbon technological innovation. Subsidies and government support to steel firms are pervasive industrial policies in many countries, although the lack of transparency makes their quantification difficult (OECD, 2023a). Subsidies aimed at R&D, new investment and capital equipment tend to be the highest but some countries also significantly subsidize energy, raw materials, land acquisition and provide export support.

The government of China has been frequently accused of dumping cheap steel on the global market to beat out competitors. The EU and the United States have recently announced a new round of anti-subsidy investigations against Chinese steelmakers and have imposed antidumping duties on most categories of Chinese steel imports. The EU has also introduced a carbon border adjustment mechanism that is scheduled to start charging importers in 2026 (European Commission, 2021; Kortum & Weisbach, 2017).

The Chinese government has been found to support the country's steel industry primarily through cash grants, equity infusions, government-mandated mergers and acquisitions, preferential loans and directed credit, land use subsidies, subsidies for utilities, raw material price controls, tax policies and benefits, currency policies, and lax enforcement of environmental regulation (OECD, 2023a). The OECD estimates that, on average, Chinese public support for production amounts to 4.5% of the revenues of the Chinese firms covered, from 2005 to 2019, with 0.63% from direct subsidies, 0.75% through preferential taxation, 2.35% via credits and around 0.75% through equity injections (OECD, 2023a; OECD, 2021). This subsidy level of 4.5% of revenue for a typical steel price around $500 per tonne for BF-BOF steel from China is equivalent to $22.50 per tonne of steel produced. It is possible that steel firms have even higher rates of subsidy as they also benefit disproportionately from large energy input subsidies as well as preferential rates of access to capital. For example, rates of capital that are 2% on average lower for state enterprises (Harrison et al., 2019), is equivalent to an estimated subsidy of $11.50/ tonne of steel. Historical estimates of energy subsidies in the range of $12.00/tonne of steel (Brun, 2016; Hagemann et al., 2016; Krishnamurthy, 2022) were noted between 2000 and 2007; however, it is likely that the level of energy subsidies has subsided significantly in recent years. For the purposes of modelling Chinese BF-BOFs in this project, we introduce a subsidy, with a total value of $20/tonne of steel in 2022 but falling linearly overtime to zero by 2050.

Transport

Transport costs reflect the additional effort required to ship goods from where they might be produced to their target destination. In our analysis we have mainly sought to capture the cost/tonne of international long-distance transportation of steel or green iron by ship, and do not capture the costs of road or rail freight within the borders of individual country economies. In the real world the global shipping system is complex, potentially volatile, and contracts for moving bulk goods will vary in cost by origin-destination pairs and be subject to market forces. In our case, we rely on historical analysis of global shipping costs for iron ore (Adland et al., 2018; Jégourel, 2020; Lim, 2022; Yang et al., 2020), and abstract this to use a flat cost of $20/tonne.

Trade Tariffs

The model is able to place different countries into trade groups and impose both percentage based tariffs on total production costs in $USD and/or use emission based tariffs that take into account the GHG intensity of steel production e.g. to simulate carbon border adjustment type tariffs (Kortum & Weisbach, 2017). Both import and exit tariffs can be simulated. We base our representative GHG tariff on a Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2021; Kortum & Weisbach, 2017). The CBAM is based on the difference of the average national emission intensity between the import country and the region it is being exported to as well as the difference in carbon price representing the climate policy stringency of the country or region. The following equation provides an example of how a CBAM is calculated:

$$CBAM = (\Delta\ in\ national\ averge\ emission\ intensity) \times (\Delta\ in\ carbon\ price)$$

$$CBAM = (EI_{export\ country} - EI_{import\ region}) \times (CP_{import\ region} - CP_{export\ country})$$

$$CBAM = (1.2\frac{tCO2e}{tsteel} - 0.8\frac{tCO2e}{tsteel}) \times (\frac{\$200}{tCO2e} - \frac{\$100}{tCO2e})$$

$$CBAM = \frac{\$40}{tsteel}$$

If the difference in EI or carbon price are negative the CBAM is zero.

Technology Data

Table 10 shows the specific overnight investment costs and the mass and energy balances applied in the scenarios featured in this study.

Method

The model operates in three distinct phases:

- Importing baseline year data for 2021
- Projecting forward the transition from 2022-2050
- Visualising the transformation of the global steel sector by producing geospatial graphics and time-series animations

Importing baseline year data for 2021

This phase constructs the base year data, a global snapshot of steel production and demand in 2021. The process is as follows:

1. The 1,070 production sites in Global Energy Monitor's Steel Plant Tracker Database are disaggregated into 1,536 sub-facilities, in order to obtain separate entries by steel manufacturing process. For example, it is common to find steel manufacturing plants that have both a Blast Furnace-Basic Oxygen Furnace (BF-BOF) production pathway and also an Electric Arc Furnace (EAF).
2. The February 2021 edition of Global Energy Monitor's Steel Plant Tracker Database does not include facilities that are under 500 kt per year in size. The authors have additional information from the GIEDS database and the OECD national capacity database on 46 facilities in 29 countries (15 additional countries not in the GEM Database) but do not have a specific georeferenced location for these plants. The approach taken to spatially

Table 10. Overview of available technologies and characteristics used in the current model version

<table>
<tr><th>Technology Pathway</th><th>Start Year Availability in Model</th><th>Capital Costs, (USD$2022/ tonne steel)</th><th>Electricity (MWh/ tonne steel)</th><th>Natural Gas (m3/ tonne steel)</th><th>Coal (tonnes/ tonne steel)</th><th>Ferrous Scrap (tonnes/ tonne steel)</th><th>Iron Ore (tonnes/ tonne steel)</th><th>Hot Briquetted Iron (tonnes/ tonne steel)</th></tr>
<tr><td>BF-BOF
(Blast Furnace with Basic Oxygen Furnace)</td><td>2022 (mature technology available 1952)</td><td>721</td><td>0.21</td><td>-</td><td>0.62</td><td>-</td><td>1.83</td><td>-</td></tr>
<tr><td>DRI-GAS-EAF
(Direct Reduced Iron with Natural Gas, followed by Electric Arc Furnace)</td><td>2022 (mature technology available 1970)</td><td>1047</td><td>0.84</td><td>264</td><td>-</td><td>-</td><td>1.38</td><td>-</td></tr>
<tr><td>DRI-COAL-EAF
(Direct Reduction of Iron with Coal, followed by Electric Arc Furnace)</td><td>2022</td><td>1047</td><td>0.73</td><td>-</td><td>1.1</td><td>-</td><td>1.57</td><td>-</td></tr>
<tr><td>EAF-SCRAP
(Electric Arc Furnace used with Scrap)</td><td rowspan="2">2022 (mature technology available 1905)</td><td rowspan="2">582</td><td rowspan="2">0.63</td><td rowspan="2">-</td><td rowspan="2">-</td><td>1.15</td><td rowspan="2">-</td><td>-</td></tr>
<tr><td>EAF-PRIMARY
(Electric Arc Furnace used with Green Iron / Hot Briquetted Iron)</td><td>-</td><td>1</td></tr>
<tr><td>DRI-GAS--CCS-EAF
(Direct Reduced Iron with Natural Gas, followed by Electric Arc Furnace, CO_2 Captured and Stored)</td><td>2022 (mature technology available 2016)</td><td>1187</td><td>0.9</td><td>281</td><td>-</td><td>-</td><td>1.38</td><td>-</td></tr>
<tr><td>DRI-H_2-EAF
(Direct Reduced Iron with Green Hydrogen, followed by Electric Arc Furnace)</td><td>2028 (projects under construction with pre-2028 completion dates are captured)</td><td>1408 (2028)
763 (2050)</td><td>4.85</td><td>-</td><td>-</td><td>-</td><td>1.5</td><td>-</td></tr>
<tr><td>DRI-GAS-CCS
(Direct Reduced Iron with Natural Gas, CO_2 Captured and Stored)</td><td>2022 (mature technology available 2016)</td><td>605</td><td>0.28</td><td>330</td><td>-</td><td>-</td><td>1.38</td><td>-</td></tr>
<tr><td>DRI-H_2
(Direct Reduced Iron with Green Hydrogen)</td><td>2028</td><td>826 (2028)
447 (2050)</td><td>4</td><td>-</td><td>-</td><td>-</td><td>1.5</td><td>-</td></tr>
</table>

locate these additional 46 facilities is to position them near identified existing production or in major country industry centres. Including these facilities, defines production in 100 countries overall for 2021.

3. The 136 countries in Worldsteel Association data are compared against the 85 countries in Global Energy Monitor's Steel Plant Tracker Database and the 15 countries where the authors have information on additional production. As most countries have some domestic capacity to produce steel from recycled scrap, the assumption is made that any countries without explicit scrap facilities (Electric Arc Furnaces) in the database have one plant added for this purpose (this enables secondary steel production from scrap to contribute to meeting demand in future model years). These plants are located in the national capital for each country.
4. Following the data import phases detailed above, the model starts with a 2021 baseline dataset of 1,637 sub-facilities at 1,132 unique coordinates.
5. Age data is not available for all steel manufacturing facilities in the database. Plants without accompanying information on their age are assumed to be in the middle of their respective investment cycles.
6. All coordinates in the model are assessed to understand their proximity to subsurface geology suitable for long-term storage of captured CO_2 underground using the OGCI 2021 CO_2 Storage Resource Catalogue (OGCI & GCCSI, 2021). This is used later to understand whether or not various facilities can be transformed to employ carbon capture and storage technology.
7. All coordinates in the model are have their electricity costs assessed individually. Average baseline industrial electricity prices for 2022 are informed by data from a number of different sources (DESNZ, 2023; Eurostat,

2022; Howdle, 2021). Future projections for large industrial user electricity prices are then made over time under the assumption that electricity decarbonization in each country in the model will develop by 2050. Price projections for each potential manufacturing site in the model reflect expected costs of wind and solar combined with utility scale battery storage in plus costs for transmission and distribution. Solar irradiation data is taken from the Global Solar Atlas project (Solargis & World Bank, 2023), while wind energy data is taken from the Global Wind Atlas project (Davis et al., 2023; DTU & World Bank, 2023). The baseline 2022 electricity grid price is then projected to the lowest cost wind or solar renewable price supported by utility scale battery storage over time, if the lowest cost wind or solar is less expensive.

Projecting forward the transition from 2022-2050

1. Our analysis begins with the global steel production fleet for 2021 represented at 1114 unique locations in 137 countries, with data on their nominal capacity, last known output, age, technology production pathway, renewable energy (wind and solar) resources, and their proximity to potential carbon capture and storage injection sites. All facilities are assessed to understand if they have any remaining spare production capacity or not.
2. Depending on the scenario being assessed, different countries may:
   - Operate varying degrees of domestic climate policy stringency, expressed as a price on GHG emissions per tonne of steel in USD$2022/tonne
   - Provide domestic technology subsidies for different steel production pathways
   - Have formed trade alliances with other nations and impose trade tariffs on imports of steel from producers outside of their trade group. Trade tariffs can both be levied as a percentage of total production costs or explicitly designed to bring emission pricing for imports of steel in-line with whatever emission price level is inside the bloc, using a carbon border adjustment (CBAM) style mechanism.
   - Have access to finance at different costs of capital, which affects investment costs for building new plant and equipment.
3. We project forward across the model time horizon from 2022-2050 with estimates of total steel demand and total ferrous scrap availability by country, derived from an econometric analysis of population and GDP growth. We have a single demand scenario for this study which sees total global demand for steel grow in aggregate to 1290 Gt by 2050.
4. Within every model year, countries are assessed in descending order ranked by their projected GDP (IMF, 2022), so the largest economic actors go first and have the broadest set of choices.
5. In every model year, for all countries:
   - All steel production facilities in all countries have their age checked against our assumed economic lifetime interval of 20 years (or 17 in the Vogl et al 2021 sensitivity analysis). Any plants that reach this limit are brought forward for relining.
   - Any domestic plants that are operating below nominal capacity have their production increased to a maximum value of 90% rated capacity to attempt to satisfy domestic demand and close the production gap. If domestic demand is not met, the model moves to the next phase.
   - Scrap steel remelting plants (i.e. electric arc furnaces) are the next category of production used to try and close any gap in production, but scrap use is constrained by both total domestic scrap availability in each country and also a maximum limit for secondary steel, set at 90% of demand.
   - If the production gap is not closed by using domestic spare capacity and expanding the use of domestic scrap steel, the model tries to import steel from other countries. For each country, spare capacity from all facilities globally is ranked in terms of their production costs, with the lowest cost steel being imported first. Different countries may rank otherwise identical sets of facilities differently due to different costs associated with importing the steel, e.g. different transport costs between countries, different trade tariffs etc. Very high-cost spare capacity (due to tariffs, GHG pricing etc.) from existing facilities that will cost more than building new facilities (we calculate this as the unit cost of production from an entirely new facility plus a reserve margin of 20%) is not imported.

- If all options for using domestic production or importing spare capacity are exhausted, but there is still a gap in production required to meet national demand, countries will build new production facilities. The expansion of production capacity can be located anywhere in the world, but again, trade tariffs and transport costs are factored in to the economic cost assessment matrix alongside capital costs, operating costs, labor costs, energy costs and raw material costs. Notably, costs of capital, labor costs and energy costs vary significantly between countries, and technology costs vary between different production pathways and in time (certain key low carbon production technologies are assumed to mature and decrease gradually in cost across the time horizon). The global steel fleet is expanded one increment at a time until the production gap is closed. Other notable constraints include:
  - Total capacity constraints. All steel production sites in the model (1114 total) have been assessed and had constraints placed on how large each can become in terms of total production capacity. When a site is full, new production cannot be added until some of the capacity is retired (at the end of its economic lifecycle). This is intended to capture real world limits on the size to which any single industrial production facility can grow based on footprint and local infrastructure congestion. For this project if the initial site was under 10 Mt/yr we allowed it to triple in size to max of 10 Mt/yr. If sites were above 10 Mt we allowed it to go to 20 Mt/yr. If sites were greater than 15 Mt existing we allowed them to go to 25 Mt/yr.
  - Build rate constraints. There are limits on how quickly new capacity can be added to any site, reflecting real world constraints (regulatory and permitting requirements, supply chain and material availability, labor availability and skill sets) in terms of the speed of construction.
  - National fleet expansion constraints. Similar to item (ii), this constraint captures limits on how rapidly the overall steel production fleet in each country can expand, again reflecting constraints on available skilled labor, materials, obtaining regulatory approvals etc. not only on a single site but across an entire national economy. Over 10kt a 10% capacity growth rate was imposed.

6. Potential for green iron is assessed at 14 locations in 9 countries, capturing production from the most significant known iron ore deposits worldwide (Hagemann et al., 2016; Krishnamurthy, 2022). The cost of producing green iron is assessed dynamically in every year, and the costs of producing steel from green iron include shipping the iron across borders, paying any tariffs and transport costs, and remelting the iron in the destination country in electric arc furnaces using local labor and energy costs. Producing steel from imported green iron therefore competes with all other options to meet steel demand including domestic production or importing of primary steel.
7. Having balanced production and demand across the time horizon 2022 – 2050 for all 137 countries, and spatially allocated all capacity to one of the 1000+ locations, the model is then in a position to carry out an ex-post assessment of the energy, emissions and investment cost implications of the steel sector transition.

Visualising the transformation of the global steel sector

This phase produces visualisations for the globe, for all model countries individually and for a number of large global sub-regions (e.g. North America, Europe). Any geographical aggregations (e.g. how to determine "Europe") follow country region classifications from Worldsteel. Typical graphs/charts/animations include:

- Demand and production over time
- Capacity by technology over time
- Production by technology over time
- Technological shares of production over time
- Emissions over time
- Emissions intensity over time (all facilities)
- Emissions intensity over time (primary production)
- Emissions intensity over time (secondary production)
- Emissions by technology over time
- Energy use over time
- Energy intensity over time
- Geospatial distribution of steel production over time
- Geospatial distribution of emissions over time

Given the limitations of space, most of these visualizations are not shown in this report, but the figures and data are available at labour cost. The model can also be rerun on request with alternative assumptions and basic reporting for labour cost

REFERENCES

- Adland, R., Jia, H., & Strandenes, S. P. (2018). The determinants of vessel capacity utilization: The case of Brazilian iron ore exports. *Transportation Research Part A: Policy and Practice*, *110*, 191–201. https://doi.org/10.1016/j.tra.2016.11.023
- Agora Energiewende - Industry, Wuppertal Institute, Lund University, Witecka, W. K., von Eitzen-Toni, O., Scott, J., Burmeister, H., Wang, L., Schneider, C., Lechtenböhmer, S., & Åhman, M. (2021). *Global Steel at a Crossroads Global Steel at a Crossroads: Why the global steel sector needs to invest in climate-neutral technologies in the 2020s*. www.agora-industry.de
- AGORA Industry. (2023). *15 insights on the global steel transformation*. https://www.agora-industry.org/publications/15-insights-on-the-global-steel-transformation
- ArcelorMittal. (2019). *Climate Action Report 1*. https://corporate.arcelormittal.com/media/press-releases/arcelormittal-publishes-first-climate-action-report
- Bataille, C., Al Khourdajie, A., de Coninck, H., de Kleijne, K., Nilsson, L. J., Bashmakov, I., Davis, S., & Fennell, P. (2023). *A Paris Agreement Compliant Definition for "Abated Fossil Fuels"* (SSRN Scholarly Paper 4574502). https://doi.org/10.2139/ssrn.4574502
- Bataille, C., & Stiebert, S. (2022). *Opportunities for Decarbonisation of Canadian Heavy Industry*. https://doi.org/10.13140/RG.2.2.17844.83849
- Bataille, C., Stiebert, S., Hebeda, O., Trollip, H., McCall, B., & Vishwanathan, S. S. (2023a). Towards net-zero emissions concrete and steel in India, Brazil and South Africa. *Climate Policy*, *0*(0), 1–16. https://doi.org/10.1080/14693062.2023.2187750
- Bataille, C., Stiebert, S., Hebeda, O., Trollip, H., McCall, B., & Vishwanathan, S. S. (2023b). Towards net-zero emissions concrete and steel in India, Brazil and South Africa. *Climate Policy*, *0*(0), 1–16. https://doi.org/10.1080/14693062.2023.2187750
- Bataille, C., Stiebert, S., & Li, F. G. N. (2021a). *Global Facility Level Net-zero Steel Pathways: Technical Report on the First Scenarios of the Net-zero Steel Project*. IDDRI.org. https://netzerosteel.org/
- Bataille, C., Stiebert, S., & Li, F. G. N. (2021b). *Global facility level net-zero steel pathways: Technical report on the first scenarios of the Net-zero Steel Project*. IDDRI.org/Global Energy Monitor. https://netzerosteel.org/
- BHP. (2023). *Pathways to decarbonisation episode seven: The electric smelting furnace*. https://www.bhp.com/news/prospects/2023/06/pathways-to-decarbonisation-episode-seven-the-electric-smelting-furnace
- BIR. (2022). *World Steel Recycling in Figures, 13th Edition: 2017-2021*. Bureau of International Recycling (BIR), Brussels, Belgium. https://www.bir.org/publications/facts-figures
- BIR. (2023). *World Steel Recycling in Figures, 14th Edition: 2018-2022*. Bureau of International Recycling (BIR), Brussels, Belgium. https://www.bir.org/publications/facts-figures
- Brun, L. C. (2016). *Overcapacity in Steel: China's Role in a Global Problem*. Center on Globalization, Governance & Competitiveness, Duke University and Alliance for American Manufacturing, Washington D.C. https://www.americanmanufacturing.org/wp-content/uploads/2023/08/OvercapacityReport2016_R3.pdf
- Cavaliere, P. (2019). Electrolysis of Iron Ores: Most Efficient Technologies for Greenhouse Emissions Abatement. In P. Cavaliere (Ed.), *Clean Ironmaking and Steelmaking Processes: Efficient Technologies for Greenhouse Emissions Abatement* (pp. 555–576). Springer International Publishing. https://doi.org/10.1007/978-3-030-21209-4_10
- Cavaliere, P. (2022). Hydrogen Direct Reduced Iron. In P. Cavaliere (Ed.), *Hydrogen Assisted Direct Reduction of Iron Oxides* (pp. 233–319). Springer International Publishing. https://doi.org/10.1007/978-3-030-98056-6_7
- Cole, S., & Itani, S. (2013). The Alberta Carbon Trunk Line and the Benefits of CO_2. *Energy Procedia*, *37*, 6133–6139. https://doi.org/10.1016/j.egypro.2013.06.542
- COURSE50 T. J. I. and S. (2021, February 9). *COURSE50 | The Japan Iron and Steel Federation*. COURSE50 |. https://www.course50.com/en/
- Daehn, K. E., Cabrera Serrenho, A., & Allwood, J. M. (2017). How Will Copper Contamination Constrain Future Global Steel Recycling? *Environmental Science and Technology*, *51*(11), 6599–6606. https://doi.org/10.1021/acs.est.7b00997
- Davis, N. N., Badger, J., Hahmann, A. N., Hansen, B. O., Mortensen, N. G., Kelly, M., Larsén, X. G., Olsen, B. T., Floors, R., Lizcano, G., Casso, P., Lacave, O., Bosch, A., Bauwens, I., Knight, O. J., Loon, A. P. van, Fox, R., Parvanyan, T., Hansen, S. B. K., … Drummond, R. (2023). The Global Wind Atlas: A High-Resolution Dataset of Climatologies and Associated Web-Based Application. *Bulletin of the American Meteorological Society*, *104*(8), E1507–E1525. https://doi.org/10.1175/BAMS-D-21-0075.1
- DESNZ. (2023). *International industrial energy prices*. UK Department for Energy Security and Net Zero (DESNZ), London, United Kingdom. https://www.gov.uk/government/statistical-data-sets/international-industrial-energy-prices
- Devlin, A., Kossen, J., Goldie-Jones, H., & Yang, A. (2023). Global green hydrogen-based steel opportunities surrounding high quality renewable energy and iron ore deposits. *Nature Communications*, *14*(1), Article 1. https://doi.org/10.1038/s41467-023-38123-2
- Devlin, A., & Yang, A. (2022). Regional supply chains for decarbonising steel: Energy efficiency and green premium mitigation. *Energy Conversion and Management*, *254*, 115268. https://doi.org/10.1016/j.enconman.2022.115268
- DOE. (2015). *Wind Vision: A New Era for Wind Power in the United States: Appendix*. United States Department of Energy (DOE), DOE/GO-102015-4557. https://www.energy.gov/sites/prod/files/wv_appendix_final.pdf
- DTU & World Bank. (2023). *Global Wind Atlas*. Danmarks Tekniske Universitet, DTU (In English: Technical University of Denmark), Copenhagen, Denmark, and the World Bank, Washington D.C., USA. https://globalwindatlas.info/en
- Echterhof, T. (2021). Review on the Use of Alternative Carbon Sources in EAF Steelmaking. *Metals*, *11*(2), Article 2. https://doi.org/10.3390/met11020222
- EIA. (2023a). *Annual Coal Report 2022*. United States Energy Information Administration (EIA), Washington D.C., USA. https://www.eia.gov/coal/annual/
- EIA. (2023b). *Natural Gas Supply, Disposition and Prices. Annual Energy Outlook 2023*. Energy Information Administration (EIA), U.S. Department of Energy (DoE), Washington, D.C., USA. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=13-AEO2023&cases=ref2023&sourcekey=0
- European Commission. (2021). *Proposal for a Regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism: COM/2021/564 final*. European Commission, Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021PC0564
- European Parliament. (2003). *Consolidated text: Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC (Text with EEA relevance)Text with EEA relevance*. European Parliament, Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02003L0087-20230605

- Eurostat. (2022). *Eurostat Electricity Price Statistics: Electricity Prices for Non-household Consumers*. Eurostat, Luxembourg City, Luxembourg. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers
- Executive Office of the President of the United States. (2021). *Fact Sheet: The United States and European Union To Negotiate World's First Carbon-Based Sectoral Arrangement on Steel and Aluminum Trade*. Executive Office of the President of the United States. https://www.whitehouse.gov/briefing-room/statements-releases/2021/10/31/fact-sheet-the-united-states-and-european-union-to-negotiate-worlds-first-carbon-based-sectoral-arrangement-on-steel-and-aluminum-trade/
- Fan, Z., & Friedmann, S. J. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule*, *5*(4), 829–862. https://doi.org/10.1016/j.joule.2021.02.018
- Fischedick, M., Marzinkowski, J., Winzer, P., & Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, *84*, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063
- Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., Jackson, R. B., Jones, C. D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M. R., Sharifi, A., Smith, P., & Yamagata, Y. (2014). Betting on negative emissions. *Nature Climate Change*, *4*(10), 850–853. https://doi.org/10.1038/nclimate2392
- GECF. (2021). *GECF Global Gas Outlook 2050 Synopsis*. Gas Exporting Countries Forum (GECF), Doha, Qatar. https://www.gecf.org/_resources/files/events/gecf-to-unveil-latest-edition-of-flagship-publication-global-gas-outlook-2050/2020-edition-of-the-gecf-global-gas-outlook-2050.pdf
- Gielen, D., Saygin, D., Taibi, E., & Birat, J. P. (2020). Renewables-based decarbonization and relocation of iron and steel making: A case study. *Journal of Industrial Ecology*, *2018*, 1–13. https://doi.org/10.1111/jiec.12997
- Hagemann, S. G., Angerer, T., Duuring, P., Rosière, C. A., Figueiredo e Silva, R. C., Lobato, L., Hensler, A. S., & Walde, D. H. G. (2016). BIF-hosted iron mineral system: A review. *Ore Geology Reviews*, *76*, 317–359. https://doi.org/10.1016/j.oregeorev.2015.11.004
- Hallegatte, S., Fay, M., & Vogt-Schilb, A. (2013). *Green Industrial Policies: When and How: World Bank Policy Research Working Paper 6677*. The World Bank, Office of the Chief Economist, Sustainable Development Network. https://documents1.worldbank.org/curated/en/994641468156896733/pdf/WPS6677.pdf
- Harrison, A., Meyer, M., Wang, P., Zhao, L., & Zhao, M. (2019). *Can a Tiger Change Its Stripes? Reform of Chinese State-Owned Enterprises in the Penumbra of the State* (Working Paper 25475). National Bureau of Economic Research. https://doi.org/10.3386/w25475
- Hasanbeigi, A., Price, L., & Arens, M. (2013). *Emerging Energy-efficiency and Carbon Dioxide Emissions-reduction Technologies for the Iron and Steel Industry* (LBNL-6106E). Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States). https://doi.org/10.2172/1172118
- Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., & Williams, C. K. (2019a). The technological and economic prospects for CO_2 utilization and removal. *Nature*, *575*(7781), 87–97. https://doi.org/10.1038/s41586-019-1681-6
- Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., & Williams, C. K. (2019b). The technological and economic prospects for CO_2 utilization and removal. *Nature*, *575*(7781), 87–97. https://doi.org/10.1038/s41586-019-1681-6
- Ho, M. T., Allinson, G. W., & Wiley, D. E. (2008). Reducing the Cost of CO_2 Capture from Flue Gases Using Pressure Swing Adsorption. *Industrial & Engineering Chemistry Research*, *47*(14), 4883–4890. https://doi.org/10.1021/ie070831e
- Ho, M. T., Bustamante, A., & Wiley, D. E. (2013). Comparison of CO_2 capture economics for iron and steel mills. *International Journal of Greenhouse Gas Control*, *19*, 145–159. https://doi.org/10.1016/j.ijggc.2013.08.003
- House, K. Z., Harvey, C. F., Aziz, M. J., & Schrag, D. P. (2009). The energy penalty of post-combustion CO_2 capture & storage and its implications for retrofitting the U.S. installed base. *Energy & Environmental Science*, *2*(2), 193–205. https://doi.org/10.1039/B811608C
- Howdle, D. (2021). *The price of electricity per KWh in 230 countries*. cable.co.uk (Existent Ltd), Lichfield, United Kingdom. https://www.cable.co.uk/energy/worldwide-pricing/#highlights
- IEA. (2019a). *Material efficiency in clean energy transitions*.
- IEA. (2019b). *Material efficiency in clean energy transitions*. International Energy Agency (IEA), Paris, France. https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions
- IEA. (2020a). *Energy Technology Perspectives 2020*. International Energy Agency (IEA), Paris, France. https://www.iea.org/reports/energy-technology-perspectives-2020
- IEA. (2020b). *Energy Technology Perspectives (ETP) Clean Energy Technology Guide*.
- IEA. (2020c). *Iron and steel roadmap: Towards more sustainable steelmaking*.
- IEA. (2020d). Iron and Steel Technology Roadmap. *Iron and Steel Technology Roadmap*. https://doi.org/10.1787/3dcc2a1b-en
- IEA. (2020e). *Iron and Steel Technology Roadmap: Towards more sustainable steelmaking*. International Energy Agency (IEA), Paris, France. https://www.iea.org/reports/iron-and-steel-technology-roadmap
- IEA. (2020f). *World Energy Outlook 2020*. International Energy Agency (IEA), Paris, France. https://www.iea.org/reports/world-energy-outlook-2020
- IEA. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. https://www.iea.org/reports/net-zero-by-2050
- IEA. (2022a). *Achieving Net Zero Heavy Industry Sectors in G7 Members*. OECD. https://doi.org/10.1787/f25c9648-en
- IEA. (2022b). *Global Energy and Climate Model Documentation*. International Energy Agency (IEA), Paris, France. https://iea.blob.core.windows.net/assets/2db1f4ab-85c0-4dd0-9a57-32e542556a49/GlobalEnergyandClimateModelDocumentation2022.pdf
- IEA. (2023a). *Greenhouse Gas Emissions from Energy Database*. https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy
- IEA. (2023b). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach—2023 Update*. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach
- IEA. (2023c). *World Energy Outlook 2023*. https://www.iea.org/reports/world-energy-outlook-2023
- IMF. (2022). *World Economic Outlook 2022*. International Monetary Fund (IMF), Washington, D.C., USA. https://www.imf.org/en/Publications/WEO/Issues/2022/10/11/world-economic-outlook-october-2022
- IPCC. (2005). *Carbon Dioxide Capture and Storage: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- IPCC. (2022). Climate Change 2022: Mitigation of Climate Change—Summary for Policymakers. *Cambridge University Press*. https://www.ipcc.ch/report/ar6/wg3/
- Jégourel, Y. (2020). The global iron ore market: From cyclical developments to potential structural changes. *The Extractive Industries and Society*, *7*(3), 1128–1134. https://doi.org/10.1016/j.exis.2020.05.015

- Junjie, Y. (2018). Progress and Future of Breakthrough Low-carbon Steelmaking Technology (ULCOS) of EU. *International Journal of Mineral Processing and Extractive Metallurgy*, *3*(2), Article 2. https://doi.org/10.11648/j.ijmpem.20180302.11
- Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A Process for Capturing $CO_2$from the Atmosphere. *Joule*, 1–22. https://doi.org/10.1016/j.joule.2018.05.006
- Kildahl, H., Wang, L., Tong, L., & Ding, Y. (2023). Cost effective decarbonisation of blast furnace – basic oxygen furnace steel production through thermochemical sector coupling. *Journal of Cleaner Production*, *389*, 135963. https://doi.org/10.1016/j.jclepro.2023.135963
- Kortum, S., & Weisbach, D. (2017). The Design of Border Adjustments for Carbon Prices. *National Tax Journal*, *70*(2), 421–446. https://doi.org/10.17310/ntj.2017.2.07
- Krishnamurthy, K. V. (2022). Reserves and Resources of Iron Ores of India—A Perspective. *Journal of the Geological Society of India*, *98*(5), 647–653. https://doi.org/10.1007/s12594-022-2040-z
- Lei, T., Wang, D., Yu, X., Ma, S., Zhao, W., Cui, C., Meng, J., Tao, S., & Guan, D. (2023). Global iron and steel plant CO_2 emissions and carbon-neutrality pathways. *Nature*, *622*(7983), 514–520. https://doi.org/10.1038/s41586-023-06486-7
- Li, X., Sun, W., Zhao, L., & Cai, J. (2018). Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes. *Mineral Processing and Extractive Metallurgy Review*, *39*(1), 50–58. https://doi.org/10.1080/08827508.2017.1324440
- Lim, K. G. (2022). Endogeneity of commodity price in freight cost models. *Journal of Commodity Markets*, *26*, 100217. https://doi.org/10.1016/j.jcomm.2021.100217
- Lopez, G., Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C. (2023). Towards defossilised steel: Supply chain options for a green European steel industry. *Energy*, *273*, 127236. https://doi.org/10.1016/j.energy.2023.127236
- Mayer, J., Bachner, G., & Steininger, K. W. (2019). Macroeconomic implications of switching to process-emission-free iron and steel production in Europe. *Journal of Cleaner Production*, *210*, 1517–1533. https://doi.org/10.1016/j.jclepro.2018.11.118
- M'barek, B., Hasanbeigi, A., & Gray, M. (2022). *Global Steel Production Costs: A Country and Plant-Level Cost Analysis*. TransitionZero and Global Efficiency Intelligence. https://www.globalefficiencyintel.com/global-steel-production-costs-report
- Medarac, H., Moya, J. A., & Somers, J. (2020). *Production costs from iron and steel industry in the EU and third countries*. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-20886-0, doi:10.2760/705636, JRC121276. https://data.europa.eu/doi/10.2760/705636
- Mission Possible. (2022). *Making Net-Zero Steel Possible*. https://missionpossiblepartnership.org/wp-content/uploads/2022/09/Making-Net-Zero-Steel-possible.pdf
- Mission Possible Partnership. (2022). *Making Net-Zero Steel Possible: An Industry-Backed, 1.5°C-Aligned Transition Strategy*. Mission Possible Partnership (MPP), Energy Transitions Commission (ETC) and the Rocky Mountain Institute (RMI). https://missionpossiblepartnership.org/action-sectors/steel/
- Müller, N., Herz, G., Reichelt, E., Jahn, M., & Michaelis, A. (2021). Assessment of fossil-free steelmaking based on direct reduction applying high-temperature electrolysis. *Cleaner Engineering and Technology*, *4*, 100158. https://doi.org/10.1016/j.clet.2021.100158
- Nduagu, E. I., Yadav, D., Bhardwaj, N., Elango, S., Biswas, T., Banerjee, R., & Rajagopalan, S. (2022). Comparative life cycle assessment of natural gas and coal-based directly reduced iron (DRI) production: A case study for India. *Journal of Cleaner Production*, *347*, 131196. https://doi.org/10.1016/j.jclepro.2022.131196
- Nordhaus, W. (2015). Climate Clubs: Overcoming Free-riding in International Climate Policy. *American Economic Review*, *105*(4), 1339–1370. https://doi.org/10.1257/aer.15000001
- OECD. (2023a). *Latest developments in steelmaking capacity 2023*. https://www.oecd.org/industry/ind/latest-developments-in-steelmaking-capacity-2023.pdf
- OECD. (2023b). *Real GDP long-term forecast. Accessed at: Https://data.oecd.org/gdp/gdp-long-term-forecast.htm*. Organisation for Economic Co-operation and Development (OECD), Paris, France.
- OGCI & GCCSI. (2021). *CO_2 Storage Resource Catalogue 2021*. Oil and Gas Climate Initiative (OGCI) and Global CCS Institute (GCCSI). https://www.ogci.com/ccus/co2-storage-catalogue
- Ozbayoglu, G. (2018). 3.19 Energy Production From Coal. In I. Dincer (Ed.), *Comprehensive Energy Systems* (pp. 788–821). Elsevier. https://doi.org/10.1016/B978-0-12-809597-3.00341-2
- Panasiuk, D., Daigo, I., Hoshino, T., Hayashi, H., Yamasue, E., Tran, D. H., Sprecher, B., Shi, F., & Shatokha, V. (2022). International comparison of impurities mixing and accumulation in steel scrap. *Journal of Industrial Ecology*, *26*(3), 1040–1050. https://doi.org/10.1111/jiec.13246
- Prasad, A. K., Prasad, R. K., & Khanam, S. (2011). Design Modifications for Energy Conservation of Sponge Iron Plants. *Journal of Thermal Science and Engineering Applications*, *3*(1). https://doi.org/10.1115/1.4003506
- Quader, A. M., Ahmed, S., Dawal, S. Z., & Nukman, Y. (2016). Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO_2) Steelmaking (ULCOS) program. *Renewable and Sustainable Energy Reviews*, *55*, 537–549. https://doi.org/10.1016/j.rser.2015.10.101
- Ramasamy, V., Zuboy, J., O'Shaughnessy, E., Feldman, D., Desai, J., Woodhouse, M., Basore, P., & Margolis, R. (2022). *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2022*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-83586. https://www.nrel.gov/docs/fy22osti/83586.pdf
- Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*. https://doi.org/10.1016/j.ijggc.2015.05.018
- Solargis & World Bank. (2023). *Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. On behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP)*. Solargis s.r.o., Bratislava, Slovakia and the World Bank, Washington D.C., USA. https://globalsolaratlas.info
- Song, J., Jiang, Z., Bao, C., & Xu, A. (2019). Comparison of Energy Consumption and CO_2 Emission for Three Steel Production Routes—Integrated Steel Plant Equipped with Blast Furnace, Oxygen Blast Furnace or COREX. *Metals*, *9*(3), Article 3. https://doi.org/10.3390/met9030364
- Stehly, T., Beiter, P., & Duffy, P. (2020). *2019 Cost of Wind Energy Review*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-78471. https://www.nrel.gov/docs/fy21osti/78471.pdf
- Stiebert, S., & Bataille, C. (2022). *Leveraging Contracts for Difference for Heavy Industry Deep Decarbonisation Report Prepared for the Canadian Cement Association*. https://www.researchgate.net/publication/368874193_Leveraging_Contracts_for_Difference_for_Heavy_Industry_Deep_Decarbonisation_Report_Prepared_for_the_Canadian_Cement_Association
- Sun, Y., Tian, S., Ciais, P., Zeng, Z., Meng, J., & Zhang, Z. (2022). Decarbonising the iron and steel sector for a 2 °C target using inherent waste streams. *Nature Communications*, *13*(1), 297. https://doi.org/10.1038/s41467-021-27770-y

- Swalec, C., & Grigsby-Schulte, A. (2023). *Pedal to the Metal 2023: Time to Shift Steel Decarbonization into High Gear*. https://globalenergymonitor.org/report/pedal-to-the-metal-2023-time-to-shift-steel-decarbonization-into-high-gear/
- Tanzer, S. E., Blok, K., & Ramírez, A. (2020). Can bioenergy with carbon capture and storage result in carbon negative steel? *International Journal of Greenhouse Gas Control*, *100*, 103104. https://doi.org/10.1016/j.ijggc.2020.103104
- TERI, & ETC. (2022). *Achieving Green Steel: Roadmap to a Net Zero Steel Sector in India*. TERI/ETC. https://www.energy-transitions.org/publications/net-zero-steel-sector-india/
- ThyssenKrupp. (2022). *Into the future with green steel*. https://www.thyssenkrupp-steel.com/en/company/sustainability/climate-strategy/
- Toktarova, A., Göransson, L., & Johnsson, F. (2021). Design of Clean Steel Production with Hydrogen: Impact of Electricity System Composition. *Energies*, *14*(24), 8349. https://doi.org/10.3390/en14248349
- Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study. *Energies*, *13*(15), 3840. https://doi.org/10.3390/en13153840
- Toktarova, A., Walter, V., Göransson, L., & Johnsson, F. (2022). Interaction between electrified steel production and the north European electricity system. *Applied Energy*, *310*, 118584. https://doi.org/10.1016/j.apenergy.2022.118584
- Trollip, H., McCall, B., & Bataille, C. (2022). How green primary iron production in South Africa could help global decarbonization. *Climate Policy*, *22*(2), 236–247. https://doi.org/10.1080/14693062.2021.2024123
- UNFCCC. (2015). *Adoption of the Paris Agreement: Proposal by the President: Draft decision -/CP.21*.
- USGS. (2023a). *USGS, Mineral Commodity Summaries, "Iron and Steel Scrap," January 2023*. United States Geological Survey (USGS), Reston, Virginia, United States. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-iron-steel-scrap.pdf
- USGS. (2023b). *USGS, Mineral Commodity Summaries, "Iron and Steel Statistics and Information," January 2023*. United States Geological Survey (USGS), Reston, Virginia, United States. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-iron-steel.pdf
- van der Zwaan, B. C. C., Schoots, K., Rivera-Tinoco, R., & Verbong, G. P. J. (2011). The cost of pipelining climate change mitigation: An overview of the economics of CH_4, CO_2 and H_2 transportation. *Applied Energy*, *88*(11), 3821–3831. https://doi.org/10.1016/j.apenergy.2011.05.019
- Vasudevan, S., Farooq, S., Karimi, I. A., Saeys, M., Quah, M. C. G., & Agrawal, R. (2016). Energy penalty estimates for CO_2 capture: Comparison between fuel types and capture-combustion modes. *Energy*, *103*, 709–714. https://doi.org/10.1016/j.energy.2016.02.154
- Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, *203*, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279
- Vogl, V., Olsson, O., & Nykvist, B. (2021a). Phasing out the blast furnace to meet global climate targets. *Joule*, *5*(10), 2646–2662. https://doi.org/10.1016/j.joule.2021.09.007
- Vogl, V., Olsson, O., & Nykvist, B. (2021b). Phasing out the blast furnace to meet global climate targets. *Joule*, *5*(10), 2646–2662. https://doi.org/10.1016/j.joule.2021.09.007
- Vogl, V., Sanchez, F., Gerres, T., Lettow, F., Bhaskar, A., Swalec, C., Mete, G., Åhman, M., Lehne, J., Schenk, S., Witecka, W., Olsson, O., & Rootzén, J. (2021). *Green Steel Tracker: Lead it Group for Industry Transition*. https://www.industrytransition.org/insights/new-green-steel-tracker/
- Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., & Chen, W.-Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nature Communications*, *12*(1), 1–11. https://doi.org/10.1038/s41467-021-22245-6
- West, K. (2020a). *Technology Factsheet: High-temperature molten oxide electrolysis steelmaking (ULCOLYSIS)*. TNO (Dutch: Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, English: Netherlands Organisation for Applied Scientific Research), The Hague, Netherlands. https://energy.nl/media/data/Ulcolysis-Technology-Factsheet_080920.pdf
- West, K. (2020b). *Technology Factsheet: Low-temperature electrowinning for steelmaking (ULCOWIN)*. TNO (Dutch: Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek, English: Netherlands Organisation for Applied Scientific Research), The Hague, Netherlands. https://energy.nl/media/data/Ulcowin-Technology-Factsheet_080920.pdf
- World Bank. (2023). *World Development Indicators. Accessed at: Https://data.worldbank.org/indicator/NY.GDP.PCAP.CD*. World Bank, Washington D.C., USA.
- Xylia, M., Silveira, S., Duerinck, J., & Meinke-Hubeny, F. (2018). Weighing regional scrap availability in global pathways for steel production processes. *Energy Efficiency*, *11*(5), 1135–1159. https://doi.org/10.1007/s12053-017-9583-7
- Yang, D., Zhang, L., Luo, M., & Li, F. (2020). Does shipping market affect international iron ore trade?– An equilibrium analysis. *Transportation Research Part E: Logistics and Transportation Review*, *144*, 102107. https://doi.org/10.1016/j.tre.2020.102107
- Yu, S., Lehne, J., Blahut, N., & Charles, M. (2021). *1.5C Steel: Decarbonising the Steel Sector in Paris-Compatible Pathways*. https://www.e3g.org/publications/1-5c-steel-decarbonising-the-steel-sector-in-paris-compatible-pathways/

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