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TOWARDS NEAR-ZERO EMISSIONS STEEL: MODELLING-BASED POLICY INSIGHTS FOR MAJOR PRODUCERS

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Executive summary

1. Identifying the right policies to drive the transition to near-zero emissions steelmaking is important to future industrial competitiveness as well as to decarbonisation.
2. Scrap-based production is already a cost-competitive source of low-emissions steel, and should be maximised, but it cannot meet the entirety of global steel demand; introducing clean technologies in primary steel production is also essential.
3. Capacity limits on new high-emitting blast furnaces could help avert costly early plant retirements or retrofits in the future. However, on their own, they are unlikely to incentivise the deployment of near-zero emissions primary steel technologies.
4. The main effect of carbon pricing is likely to be a shift towards recycling of scrap steel, and in some cases to other intermediate technologies such as Gas Direct Reduced Iron (Gas-DRI). We find that even relatively high carbon prices may yield only modest emissions reductions and may not result in the deployment of near-zero emissions primary steelmaking technologies.
5. Subsidy and public procurement policies can be effective in driving the uptake of near-zero emissions primary steel production technologies such as Hydrogen Direct Reduced Iron – Electric Arc Furnace (H_2-DRI-EAF) and blast furnaces with carbon capture and storage. Clean steel mandates could support the further diffusion of these technologies. However, these policies alone may not prevent construction of new blast furnaces, or ensure full decarbonisation in line with national net zero targets.
6. The greatest technological shifts and emissions reductions arise when policies that promote clean steel deployment are combined with measures that constrain high-emission technologies, with the combined impact far exceeding that of any single policy alone.
7. The relative effectiveness of different policy options varies between countries, and is particularly influenced by the availability of scrap steel. Other uncertain factors that can influence policy outcomes include the price of fossil fuels and green hydrogen, the potential for carbon capture and storage, and the cost developments of clean steel technologies.

1. Introduction

The global transition to near-zero emissions steel production is beginning. Although steel has long been considered a 'hard-to-decarbonise' sector, this perception is changing as clean technologies improve, understanding of policy options grows and industry expectations shift. The need to identify effective policies to drive the transition now arises as much from national interests in future industrial competitiveness as from the imperative to reduce emissions. Different policies will have different effects on technological change, and on the structure of any given country's steel industry. In this study, we use a dynamic technology diffusion[1] model to test policy options and examine their impact on the uptake of new technologies, generating quantitative analysis that can complement the qualitative knowledge gained from consultations with industry and experts.

[1] The diffusion of technology incorporates innovation effects and learning-by-doing. The life expectancy of these technologies is also an important factor in determining the speed of transition. Due to learning-by-doing and increasing returns to adoption, the Future of Technology Transformation (FTT) model results in path-dependent technology scenarios that arise from specific sectoral policies (Vercoulen, 2023).

Context: Steel production and consumption

A key material for industrialisation and urbanisation, steel is the most widely used metal in modern society and a major contributor to employment. Estimates from 2017 suggest that the steel sector supported approximately 6m direct jobs globally and added value of approximately US$500bn (Oxford Economics, 2019). Overall, the sector provides employment to around 49m people, directly and indirectly (World Steel Association, 2025).

Global steel production has grown rapidly in recent years, increasing by 32% from 1,433 million tonnes (Mt) in 2010 to 1,892 Mt in 2023 (World Steel Association, 2023). This has been driven by rising demand from emerging economies such as China and India. In 2023, China was the largest producer and consumer of steel globally, contributing to 56% of total crude steel production. Other large producers include India, Japan, the US, South Korea and Germany (Figure 1).

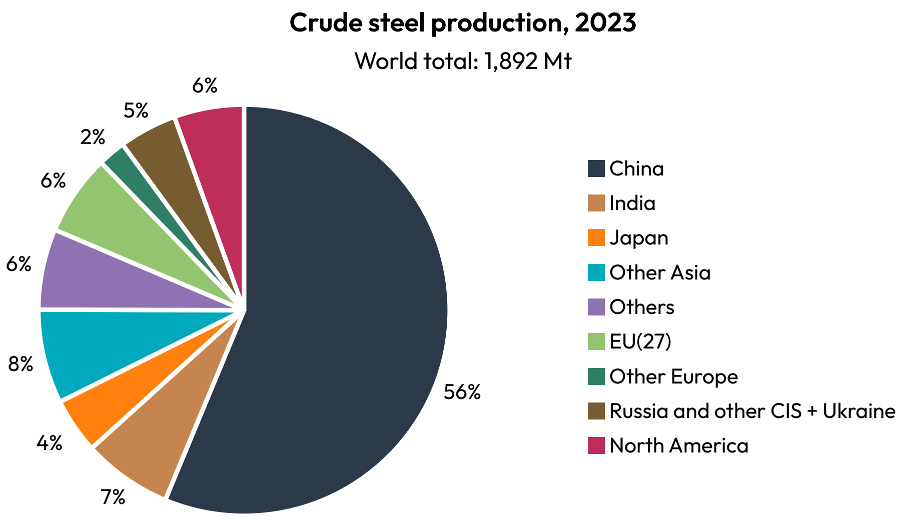

Figure 1. Regional share of global crude steel production in 2023 (%). Source: World Steel Association, 2023.

There are currently two main steel production routes: Blast-Furnace-Basic Oxygen Furnace (BF-BOF) and Electric Arc Furnace (EAF). In 2023, approximately 71% of steel was produced through the BF-BOF route, and the remaining 29% using EAF (World Steel Association, 2024). The EAF route can be used for both primary steel production, where iron ore is reduced in a shaft furnace to produce Direct Reduced Iron (DRI) before being smelted into steel in an EAF, and secondary steel production, where recycled scrap steel is melted in an EAF.

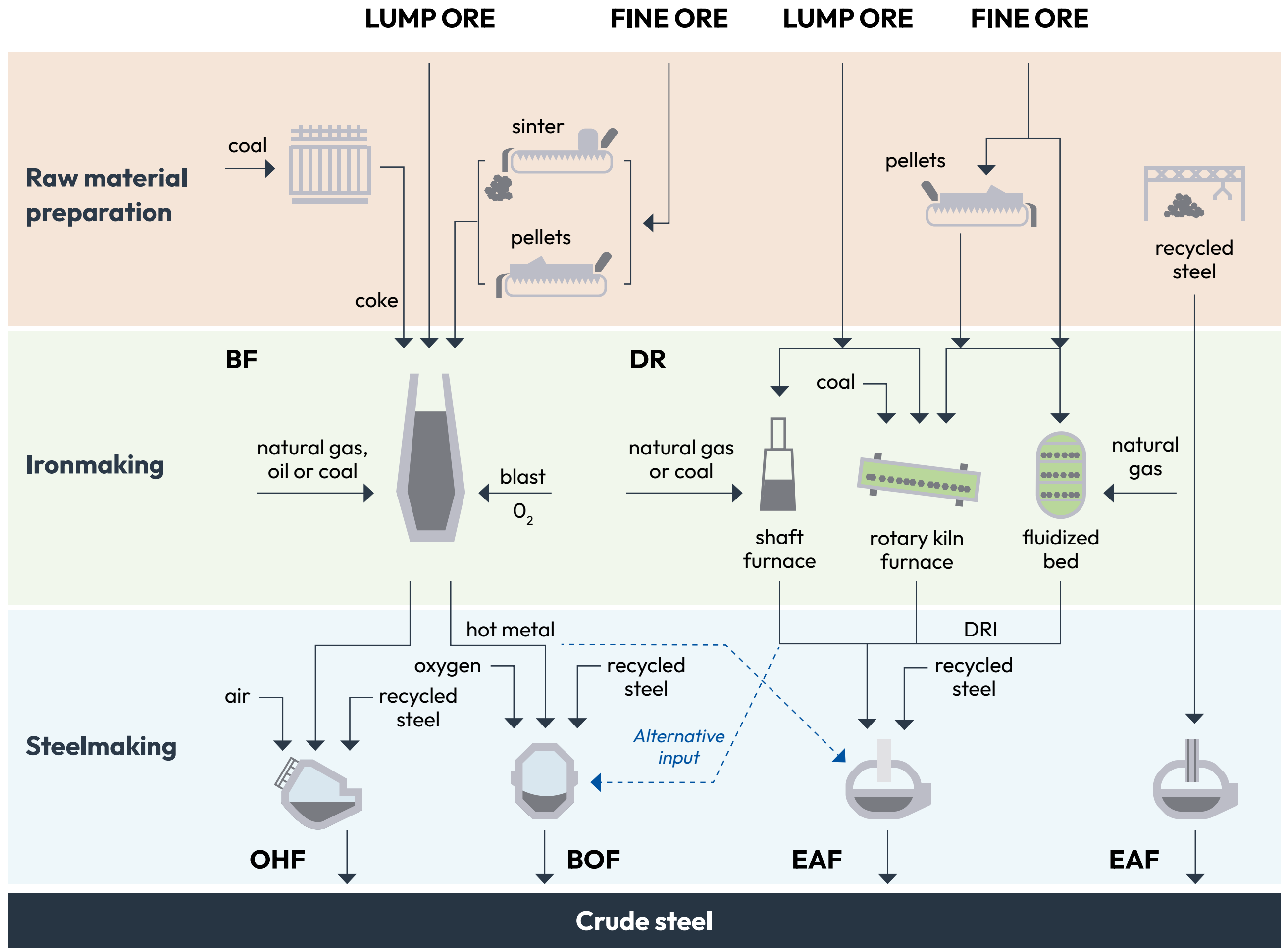

Figure 2. Simplified iron and steelmaking routes, showing Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF), Open Hearth Furnace (OHF), Direct Reduction (DR) and Blast Furnace (BF). Note that Hydrogen-Direct Reduced Iron – Electric Arc Furnace (H_2-DRI-EAF) is not pictured. Iron ore fines come from the natural raw iron ore through the process of mining, crushing and screening, where the iron ore is separated into lumps (i.e. sized ores) and fines. Source: Kim et al. 2022.

Global steel demand is driven primarily by four end-use sectors: construction (including both buildings and infrastructure), vehicles, machinery and consumer goods. In 2019, the building sector contributed to 33% of total steel demand, followed by infrastructure and mechanical and electrical equipment (both 20%), and vehicles and consumer goods (both 13%) (IEA, 2020). Demand is primarily driven by China, followed by India, the US, Japan and South Korea (Figure 3).

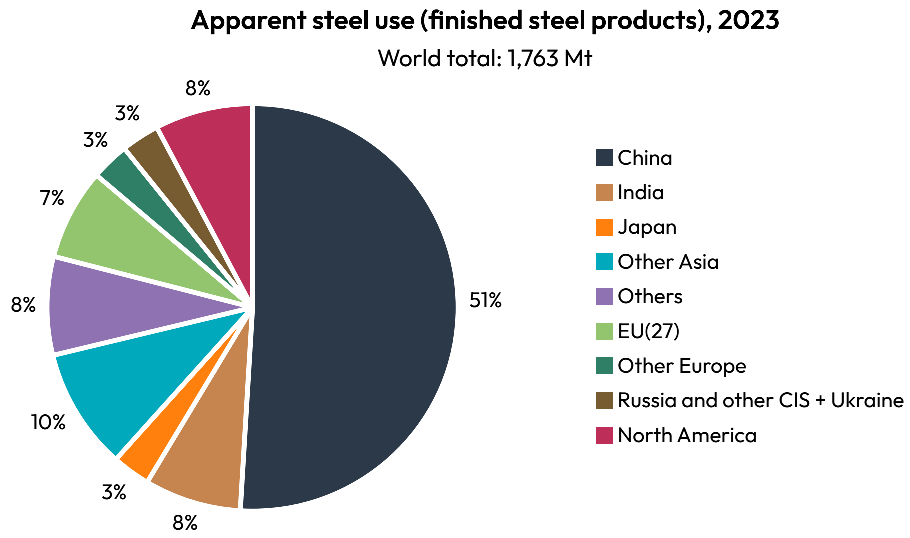

Figure 3. Regional share of global apparent steel use (finished products) in 2023 (%). Source: World Steel Association, 2024.

Growing emissions and the imperative for transition

The steel sector is a major contributor to global greenhouse gas emissions due to its energy-intensive production processes and reliance on carbon-intensive energy sources. Its CO_2 emissions have grown rapidly since 2000, in line with the growth in global steel production, at an annual rate of 3.7% (Zhang et al., 2023), and it currently accounts for 8% of global final energy demand and 7% of direct energy-related CO_2 emissions.

The sector relies on coal to meet 75% of its energy demand (IEA, 2021a). Metallurgical coal is used to produce coke, which serves as a crucial reactant in the BF-BOF process. Given this role, it cannot be replaced with another energy source; instead, a more fundamental change to the production process is required.

Annual global demand for steel is estimated to increase by as much as a third from 1.8 Gt today to around 2.1 Gt by 2050 (IEA, 2021a). A significant share of this is likely to be in low-income and emerging economies (India's demand is expected to reach 445 Mt by 2050 from 120 Mt today, driven by infrastructure and housing) with this increase more than offsetting declining demand in China, Europe, Japan and South Korea (Mission Possible Partnership, 2022a). Steel consumption per capita is closely linked to economic growth (Hall, Spencer and Kumar, 2020). As emerging economies continue to grow, steel use per capita these countries is likely to increase significantly, following a similar trajectory to advanced economies (Figure 4).

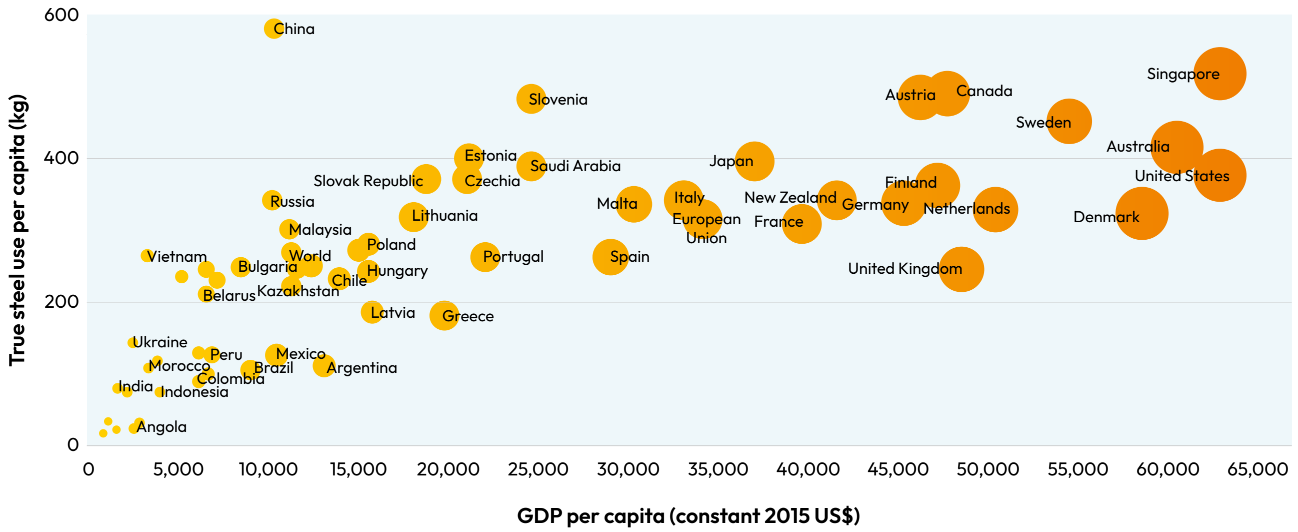

Figure 4. True steel consumption per capita versus GDP per capita. Source: World Steel Association, 2024 and World Bank, 2022. Note: Total steel use is equal to the total amount of steel consumed within a country (including steel produced domestically and imported steel) plus net indirect steel imports. Countries with GDP per capita greater than US$65,000 (constant 2015 US$) and true steel use per capita (kg) greater than 600 kg have been excluded.

Steel is also a critical raw material for technologies such as wind turbines, solar panels, geothermal plants and electric vehicles (Mission Possible Partnership, 2021). The sector will, therefore, play a critical role in the low-carbon transition. Direct emissions from the global steel sector would need to decline by around 90% from 2020 levels by 2050 to be consistent with the goals of the Paris Agreement (IEA, 2021b)[2]. The transition will require long-term development and deployment of various low-carbon production pathways, as well as demand-side support to create a market for new low-emission steel products. This process of technological change will inevitably have consequences for the relative competitiveness of the steel industry in different countries.

[2] In alignment with the IEA's Sustainable Development Scenario, which aims to achieve net-zero emissions for the energy system by 2070 (IEA, 2021b).

Policies for the transition at an early stage

Several countries have initiated policies, targets and actions towards decarbonising the steel sector. These include:

1) **Measures to promote industrial energy efficiency,** for example, through requiring the use of the best available technologies, setting benchmarking standards for efficient equipment and offering training and financial support to use energy-efficient technology.

2) **Carbon pricing and emissions trading systems,** such as those in place in the EU, China and the Republic of Korea, and similar systems under development in India and Brazil.

3) **Clean technology subsidy programmes** to support the development of clean steel technologies such as hydrogen-based production and carbon capture and storage. The US provided subsidies in the form of tax credits and Germany has developed them in the form of carbon contracts-for-difference (BMWK, 2025).

4) **Public procurement initiatives and private sector demand commitments** to create a market and drive demand for low-emissions steel. This approach is being led by countries within the Industrial Deep Decarbonisation Initiative.

5) **Trade policies** to reduce the risk of industry relocating to countries with weaker decarbonisation policies (often referred to as 'carbon leakage'). The EU's Carbon Border Adjustment Mechanism (CBAM) is the most well-known example.

Despite this array of policies, barely any near-zero emissions primary steel production is currently in operation globally, while over 100 Mt of such production is estimated to be required annually by 2030 in a scenario aligned with internationally agreed climate change goals (IEA, 2024). Governments therefore have a strong interest in understanding which policies are likely to be most effective and cost-efficient in mobilising investment in near-zero emissions steel production, as well as in reducing and eliminating emissions from the sector over time.

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2. Methodology

In this policy brief, we test policy options for the transition to near-zero emissions steel production in the four largest producers – China, India, Japan and the US – using a technology diffusion model. These countries collectively account for over 70% of current global steel production.

Policy options tested

For each country, the policy scenarios we test are:

- **A baseline scenario**. We assumed no additional policies beyond existing ones (as of 2024).
- **A capacity cap on conventional production pathways.** The capacity cap is implemented from 2030 onwards across all countries, and requires there to be no new BF-BOF plants (or coal-DRI plants, in India) beyond that point. The implementation year of 2030 was selected to ensure comparability across all countries.
- **Carbon pricing.** Carbon pricing policies are implemented in the form of a carbon tax, rising over time. The carbon tax trajectories were set according to the International Energy Agency's 'Announced Pledges Scenario', which is designed to be consistent with countries' net zero or carbon neutrality goals.
- **Clean steel subsidies and procurement.** Subsidies for near-zero emissions primary steel were set at the levels estimated to attain cost parity in the levelised cost of steel (LCOS) between the BF-BOF pathway and the BF-BOF-CCS and H_2-DRI-EAF pathways (Table 1). These were implemented together with a public procurement policy that acts as a catalyst to generate early demand for emerging technologies.[3]
- **Clean steel mandates.** Supply-side mandates specify the minimum share of primary steel production that must come from low-emission steel pathways. The mandate shares start at zero in 2025 for all countries and increase linearly, reaching a level equivalent to half of the baseline projected market share of conventional steel production technologies by 2050 in each country.
- **A combined policies scenario.** All the above policy measures are combined to understand their effectiveness when applied together.

We implemented mandates, subsidies and procurement policies to promote the uptake of mainly two clean steel production pathways: BF-BOF-CCS and H_2-DRI-EAF. These were chosen due to the potential role that the technologies could play in reducing emissions from the sector (IEA, 2021a; Mission Possible Partnership, 2022). The potential for BF-BOF-CCS to be deployed at scale remains debated, and in recent years it has been noted that investment in this technology and its development has stalled (Bataille et al., 2024). However, this route was regarded as important to test due to interest in several countries, and because of possible future competition between BF-BOF-CCS and hydrogen technologies.[4] We did not model targeted support for the DRI-NG-EAF-CCS route since it is generally expected to play a limited role in future.[5] The following table lays out the values and the implementation schedule of these policies in each of our four focus countries.

[3] The share of public sector procurement in each country's consumption of steel falls in the range of 25-35% (Hasanbeigi and Bhadbhade, 2023), (Hasanbeigi and Sibal, 2024) and (Hasanbeigi, Springer, and Bhadbhade, 2024).

[4] A limitation of our model is that it assumes that all facilities in the BF-BOF-CCS pathway are newly constructed, rather than retrofitted from existing BF-BOF facilities. This results in larger emissions reductions, because retrofitted BF-BOFs are likely to struggle to reduce emissions by more than 50% (Fan and Friedmann, 2021), but also higher costs. The analysis is simplified in this respect.

[5] See for example the future technology scenarios of Mission Possible Partnership (2022b), which projects a limited role for this pathway.

Policy option	Description	Country			
		China	India	United States	Japan
Capacity cap	No new conventional production capacity additions.	No new BF-BOF capacity from 2030 onwards	No new BF-BOF and DR-Coal capacity from 2030 onwards	No new BF-BOF capacity from 2030 onwards	No new BF-BOF capacity from 2030 onwards
Carbon pricing	Implemented in the form of a carbon tax (increases linearly from the start to end years).[6]	• 2025: \$15/tCO_2 in 2024 US\$ • 2060: \$218/tCO_2 in 2024 US\$	• 2025: \$0/tCO_2 in 2024 US\$ • 2070: \$287/tCO_2 in 2024 US\$	• 2025: \$0/tCO_2 in 2024 US\$ • 2050: \$200/tCO_2 in 2024 US\$	• 2025: \$63/tCO_2 in 2024 US\$ • 2050: \$200/tCO_2 in 2024 US\$
Subsidies (%) and Procurement (%)	Subsidies implemented to attain parity in the levelised cost of steel between the Conventional BF-BOF (Conv. BF-BOF) production pathway and low-emissions technology pathways. Public procurement: Share of low-emission steel in total steel procured by the public sector.	Subsidies – 2025 to 2060: • BF-BOF (CCS) – 16% • H_2-DRI-EAF – 31% Public procurement: implemented as 10% share of total public sector demand between 2030 to 2050. This is shared between H_2-DRI-EAF and BF-BOF (CCS).	Subsidies – 2025 to 2070: • BF-BOF (CCS) – 15% • BF-BOF Biomass (BBB) – 10% • H_2-DRI-EAF – 31% Public procurement: 10% share of total public sector demand implemented from 2030 to 2060. This is shared between H_2-DRI-EAF, BF-BOF (BB) and BF-BOF (CCS).	Subsidies – 2025 to 2050: • BF-BOF (CCS) – 8% • H_2-DRI-EAF – 22% Public procurement: 10% share of total public sector demand, implemented from 2030 to 2040. This is shared between H_2-DRI-EAF and BF-BOF (CCS).	Subsidies – 2025 to 2050: • BF-BOF (CCS) – 11% • H_2-DRI-EAF – 28% Public procurement: 10% share of total public sector demand implemented from 2030 to 2040. This is shared between H_2-DRI-EAF and BF-BOF (CCS).
Supply-side mandates[7] (%)	A deliberate shift to low-emissions steel, specifying the minimum share of primary steel production that must come from low-emissions production routes. The mandate is kept constant beyond 2050.	A minimum share of primary steel production each year (0% in 2025, rising linearly to 35.5% in 2050) must be from either BF-BOF (CCS) and/or H_2-DRI-EAF.	A minimum share of primary steel production each year (0% in 2025, rising linearly to 41.5% in 2050) must come from either BF-BOF (CCS), BF-BOF (BB) and/or H_2-DRI-EAF.	A minimum share of primary steel production each year (0% in 2025, rising linearly to 6% by 2050) must come from either BF-BOF (CCS), and/or H_2-DRI-EAF.	A minimum share of primary steel production each year (0% in 2025, rising linearly to 26% by 2050) must come from either BF-BOF (CCS), and/or H_2-DRI-EAF.

Table 1. Description of policy options and implementation schedules. Note: Carbon price trajectories were set based on the International Energy Agency's Announced Pledges Scenario. Subsidy levels were set based on the authors' estimates of the level required for near-zero emissions primary production routes to achieve cost parity with conventional BF-BOF production and vary by country and near-zero emissions technology pathway.

We compare the relative effectiveness of these policy options in each country in enabling the transition to near-zero emissions steel production, and we present the implications of this transition for technology pathways, emissions and investment.

[6] Each country's carbon price trajectory is based on the IEA's Announced Policy Scenarios for emerging and developed economies.

[7] The values for each country are half of the baseline conventional steel production technologies' market share projections in 2050.

Model structure and key assumptions

To test policy options, we use the Future Technology Transformations (FTT) steel sector model (Vercoulen et al., 2023).

The FTT family of models simulate the diffusion of technologies within a sector based on the perceived cost of the different available technology options, subject to meeting any specified regulations or mandates and in response to any incentives or taxes. The model accounts for innovation effects by incorporating technology cost reductions using 'Wright's Law' or 'learning-by-doing' – the principle where the cost of a technology falls in proportion to its cumulative global production.

FTT:Steel is a global model that includes 71 regions and 26 different technology pathways for steel production, which compete with one another for market share. The model represents the two stages of steel production – ironmaking and steelmaking – and the technology pathways are a combination of the two, as shown in Figure 5.

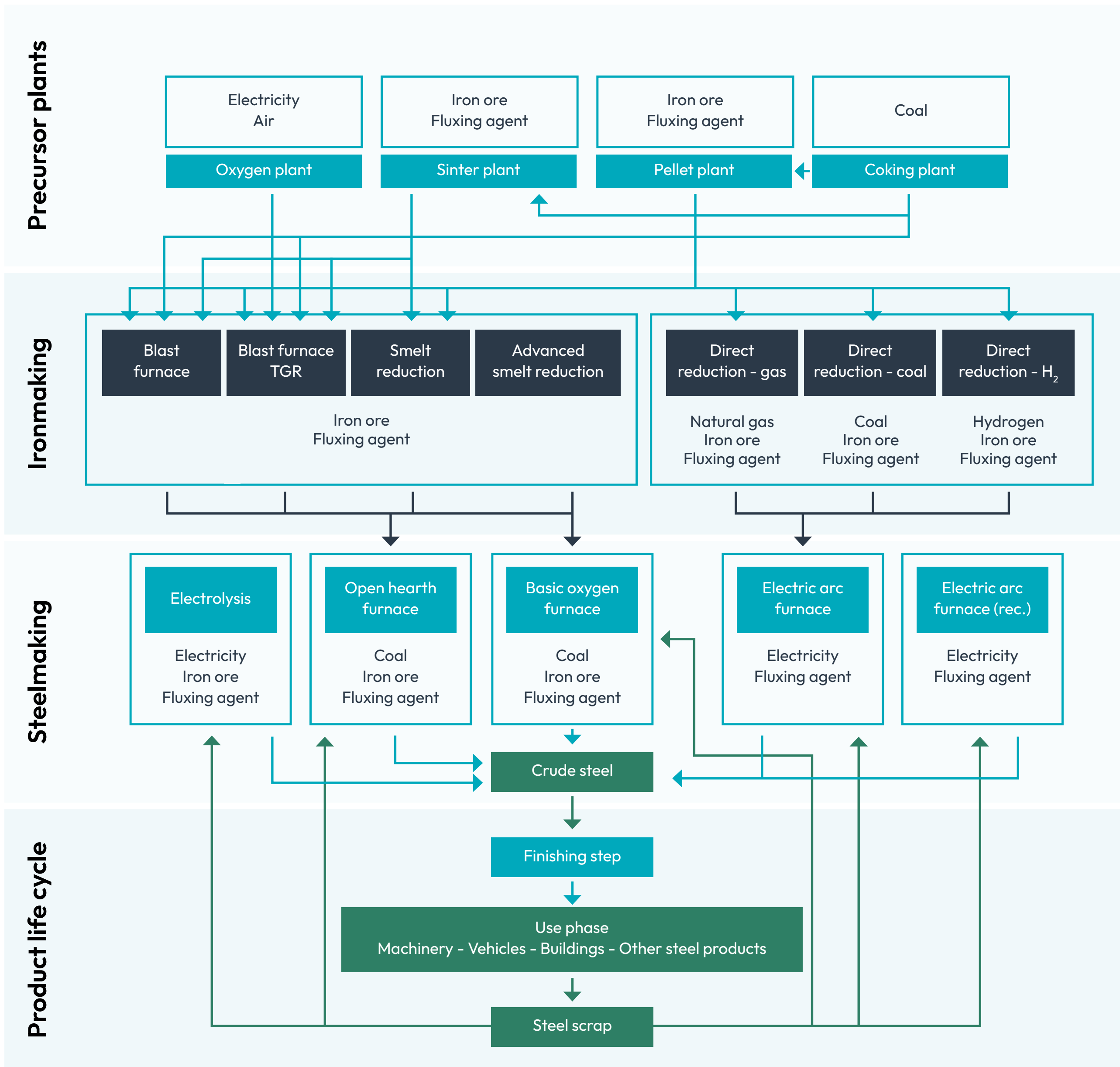


Figure 5. Steel production pathways represented in FTT:Steel. Source: Cambridge Econometrics.

The FTT:Steel model can also simulate the investments required in the decarbonisation of the steel sector, as well as the changes to the average LCOS as a result of the transition.

The model captures the ‘imitator effect’, whereby the more a technology is used, the more likely it is to be adopted, and the resultant reduction in costs through a learning-by-doing equation, at rates unique to each technology. The steel sector includes both mature technologies that do not have significant cost reductions, like Direct Reduced Iron-Electric Arc Furnace (DRI-EAF), Scrap-EAF, and Blast Furnace-Basic Oxygen Furnace (BF-BOF), and newer technologies such as carbon capture and storage (CCS) and Hydrogen-Direct Reduced Iron – Electric Arc Furnace (H_2-DRI-EAF), which may have learning curves associated with their growing use. Other clean steel technologies such as Molten Oxide Electrolysis (MOE) may have steeper learning curves but are not yet at a readiness level consistent with large-scale deployment and so were not included in this modelling study.

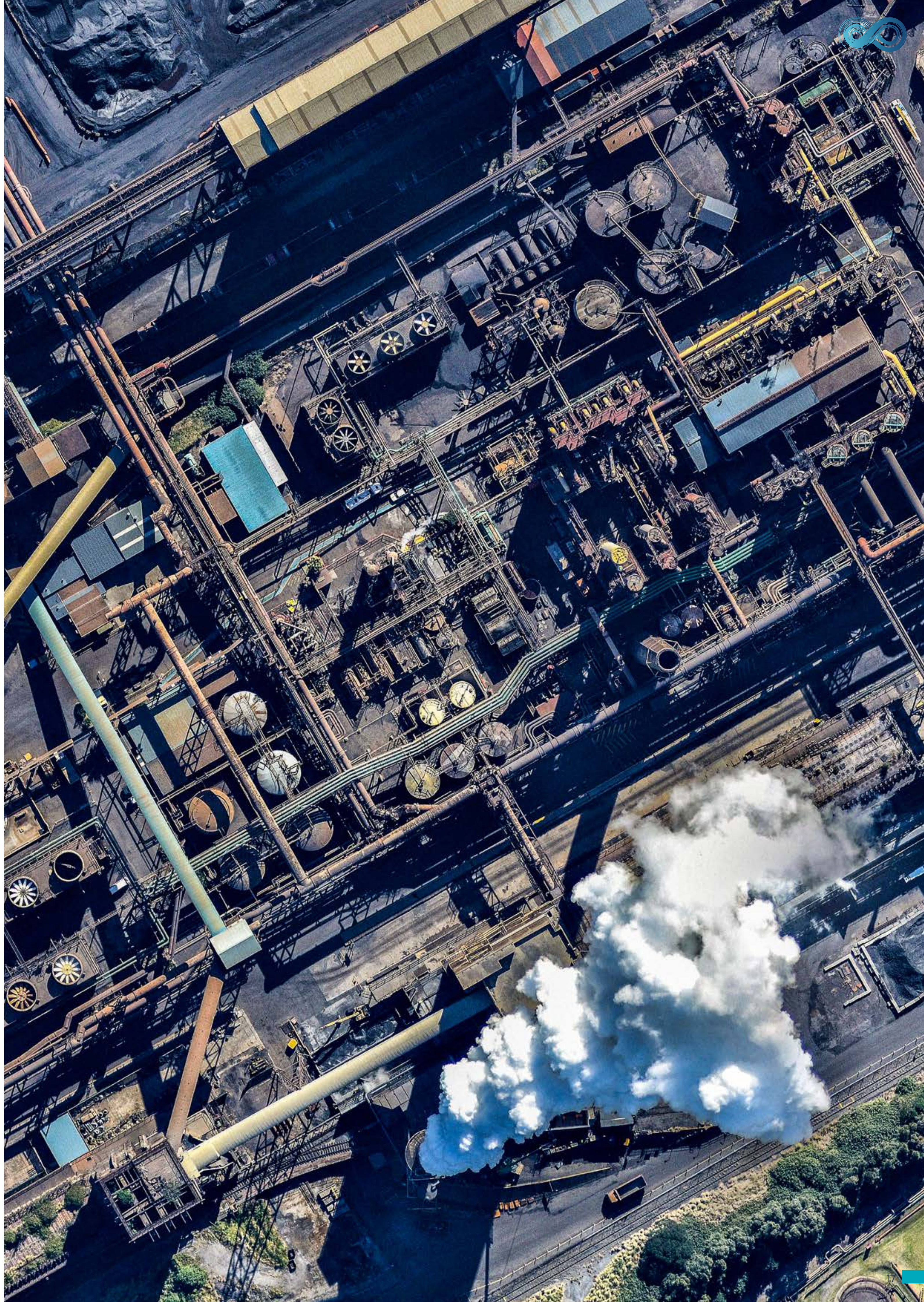
The scale of production by Scrap-EAF is limited by the availability of scrap steel, which the model calculates for each country based on the methodology in Pauliuk et al. (2013), pooling the scrap available globally and distributing it according to historical trends for scrap availability and use, taking into consideration historical crude steel production, end-use product lifetimes, loss and recycling rates. Export restrictions on scrap can be implemented in the model, but have not been tested in this analysis.

The model places no restrictions on the use of biomass, green hydrogen or land use for carbon capture and storage facilities. As a result, there is potential for overestimation in the use of these resources and technologies.

In addition to the simplifications described above, a significant limitation of the model is that it does not represent trade in steel between countries, meaning it does not consider the effect on the transition of competition between countries in the global market.

Other limitations of the model include:

- It cannot introduce new technologies that currently hold no market share; instead, a policy is needed to kickstart these new or innovative technologies, like electrolysis for steel production or direct reduction using hydrogen.[8]
- As a technology diffusion model, it does not feature wider economic impacts such as GDP and employment (although these effects can be investigated by linking FTT to the macroeconomic model E3ME).



[8] In each of the policy scenarios modelled here, we ‘seed’ the model with a very small amount of H_2-DRI and BF-BOF CCS so that the absence of these technologies from the market at the start of the simulation does not exclude the possibility of their deployment and diffusion later on. This enables a fair comparison between the policy options, in relation to the selected technology options.

3. Results: Comparing the effectiveness of individual policy options

This section compares the effectiveness of the policy options across four countries: China, India, Japan and the US. Each policy's impact on emissions reduction, technology adoption and investment needs are examined.

Policy option 1: Cap on capacity additions of high-emission production technologies

In 2024, 774 Mt/annum of steelmaking capacity was under development globally, of which 357 Mt/annum was BF-BOF, corresponding to around 200 mid-sized steel plants.[9] This poses a significant challenge for the steel sector of carbon lock-in, and a high risk of stranded assets. Around 53% of global planned BF-BOF capacity is concentrated in China and India (Global Energy Monitor, 2024). The average lifetime of BF-BOF plants ranges between 15 and 20 years, with a median of around 17 years (Hansbrough, Ashley and Lee, 2023).

The capacity cap policy restricts the construction of additional carbon-intensive BF-BOF facilities[10] across all four countries and also of DR-coal in India, implemented from 2030 onwards for comparability across the four countries.

Emissions: The capacity cap has the greatest effect in Japan, where it leads to approximately 60% of emissions reductions by 2050. In the US, where there is already a high utilisation of scrap-based production even in the baseline, there is only a minor reduction in emissions compared to the baseline trajectory. In India and China, emissions decline by approximately 39% and 17% in their respective net-zero years, compared to the baseline (Figure 6). The effect is larger in India because, without this policy, significantly more BF-BOF construction would be expected in the post-2030 period to meet growing domestic demand, whereas in China, domestic demand and production are already assumed to have reached a plateau, and even in the baseline we find that the steel production capacity is moving towards adding more Scrap-EAF capacity.

While the capacity cap has been implemented from 2030 onwards for all countries for the sake of simplicity and comparability, the feasibility of this is uncertain. For India, a capacity cap from 2030 onwards may be seen as too ambitious, as the conventional BF-BOF route is widely expected to have a major share in overall production, even up to 2040 (Khadeeja and Swalec, 2024) to meet growing demand (Sinha and Acharya, 2023). In contrast, in China, no permits have been given for new coal-based steel-making capacities since the first-half of 2024 (CREA, 2024). In Japan, emerging investment trends indicate a shift towards EAF production from conventional pathways (OECD, 2024a). It is possible that, for those two countries, capacity caps could be implemented from 2025 onwards, but no such policies are currently in place. In the US, a capacity cap from 2025 onwards may be implementable, but appears unlikely to be of interest to the Trump Administration (Zheng, 2024).

[9] Assuming average capacity of a mid-sized plant is 1.5 Mt/annum.

[10] Capacity declines in line with the natural depreciation rate proportional to the inverse of the lifetime. For BF-BOF, that would be 1/35.

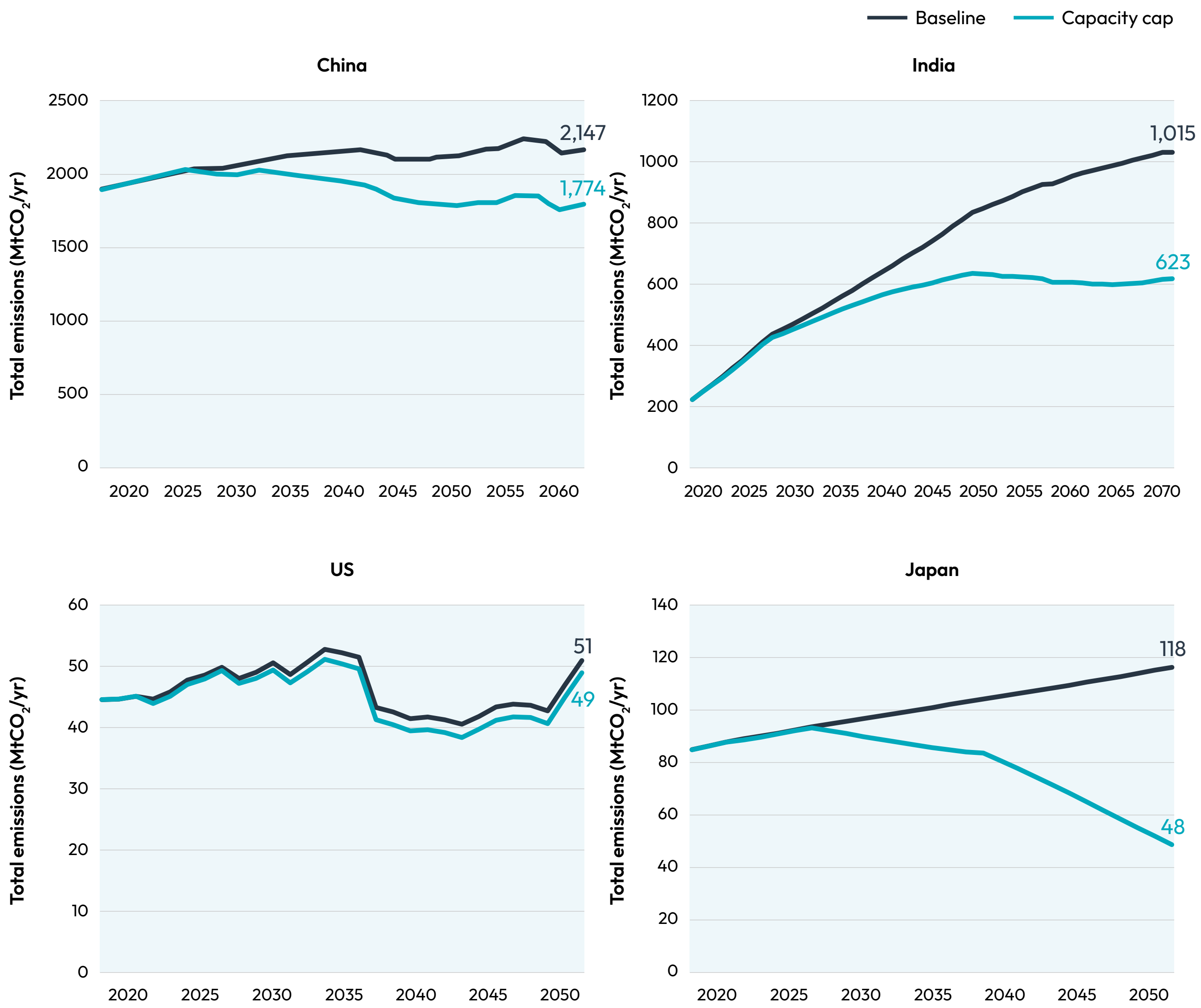


Figure 6. Total steel emissions ($MtCO_2$/yr) by country under the baseline and capacity cap scenarios.

Technologies: The capacity cap policy shifts production away from BF-BOF-based production and increases the share of scrap-based production across all four countries (Figure 7). Additionally, the shares of production through the DR-gas-EAF production and other pathways (SR-BOF, BF-TGR) see an increase in both India and China. These results suggest that while capacity caps are effective in reducing the share of production of the highest-emission pathways, they are not sufficient to drive investments in near-zero emissions primary steelmaking technologies and instead tend to favour intermediate solutions.

The result is influenced by the availability of relevant resources.[11] In India, the share of scrap-based production is the lowest of the four countries in both the baseline and the capacity cap scenarios. Consequently, India sees the largest growth in use of the DR-gas-EAF route. Policies such as the Steel Scrap Recycling Policy (Ministry of Steel, 2019) and the Vehicle Scrappage Policy (Ministry of Road Transport and Highways, 2022) will play a role in increasing the amount of scrap available domestically; additional support to set up and scale recycling facilities will be critical.

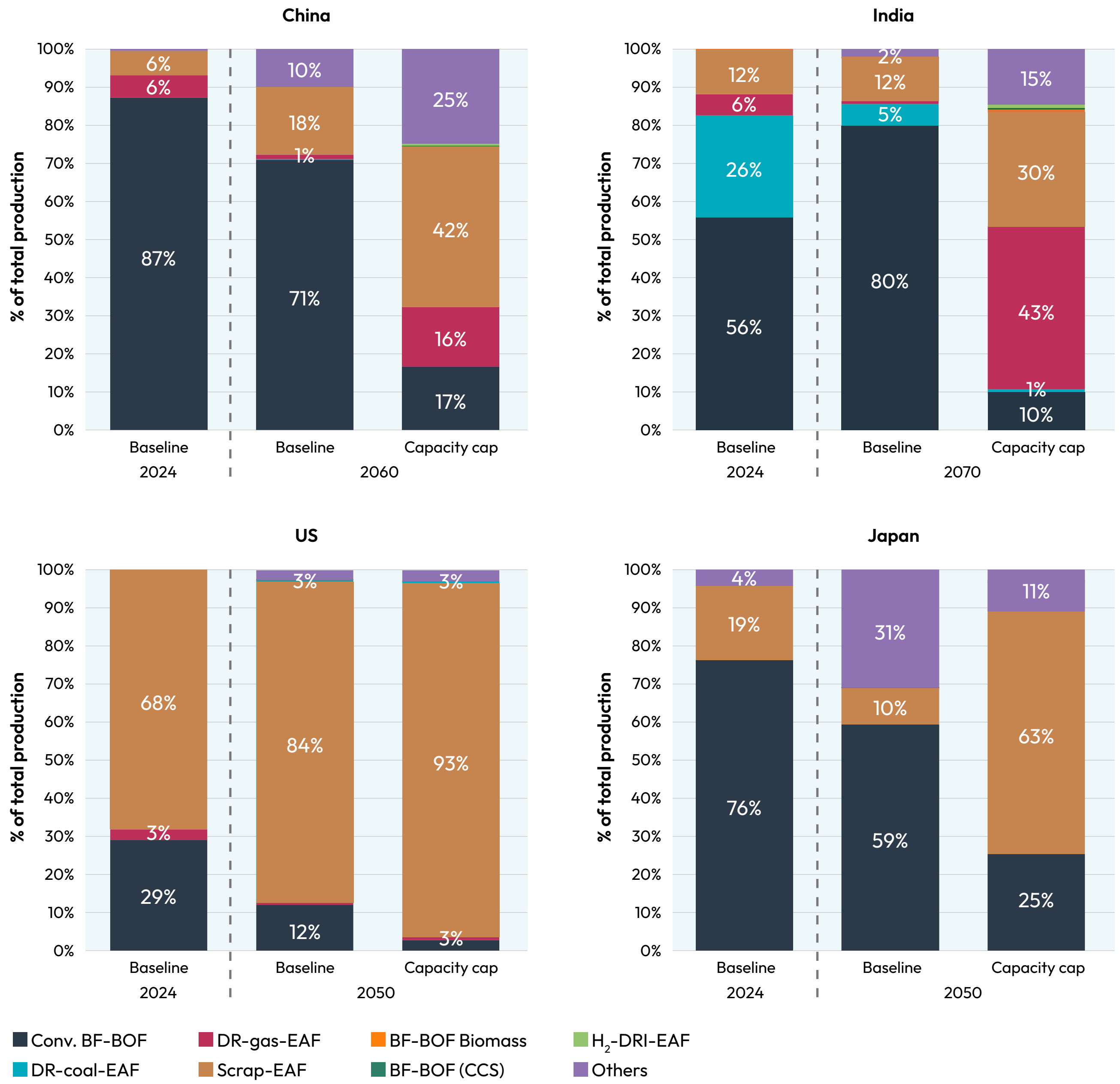


Figure 7. Technology mix by country under baseline scenario and under a capacity cap scenario. Note: We refer to the following technologies: conventional Blast Furnace – Basic Oxygen Furnace (conv. BF-BOF), Direct Reduction (DR), Electric Arc Furnace (EAF), and Carbon Capture and Storage (CCS). 'Others' includes Molten Oxide Electrolysis (MOE), Smelt-reduction – Basic Oxygen Furnace (SR-BOF), Blast furnace – Top Gas Recovery (BF TGR–BOF), and other smaller production pathways.

Investment: In this scenario, cumulative investments in scrap-based production and DR-gas-based production are estimated to be around US$330bn (51% Scrap-EAF; 49% DR-gas) in China between 2025 and 2060, and approximately US$370bn (15% Scrap-EAF; 85% DR-gas) in India between 2025 and 2070. Investments in the two technologies are aligned with the increase in the share of total production of both pathways. Cumulative investments of around US$30bn in the US and US$14bn in Japan between 2025 and 2050 are estimated for the Scrap-EAF route, which has the largest share in overall production.

[11] For India, our projections for the share of Scrap-EAF fall in a similar range as estimates made by Hall et al. (2022) of 22% in their net zero by 2070 scenario. For China, our estimates are similar to OECD (2024b) for 2050, which indicate that the Scrap-EAF share of steelmaking could surpass 50% by 2050.

Policy option 2: Carbon pricing

Carbon pricing in the form of country-level carbon taxes is implemented with rising trajectories based on the IEA's Announced Pledges Scenario, which is designed to be consistent with national decarbonisation goals, as described in Table 1.

Emissions: The carbon tax is most effective in reducing emissions in Japan. In China and India, it has only a small impact for around the next two decades, and only begins to achieve substantial emissions reductions when it rises to the highest values, in later decades (Figure 8). As with the capacity cap, the carbon tax has no significant impact on reducing emissions in the US. These disparate effects can be understood from the policy's interactions with the different technology shares and costs across the four countries.

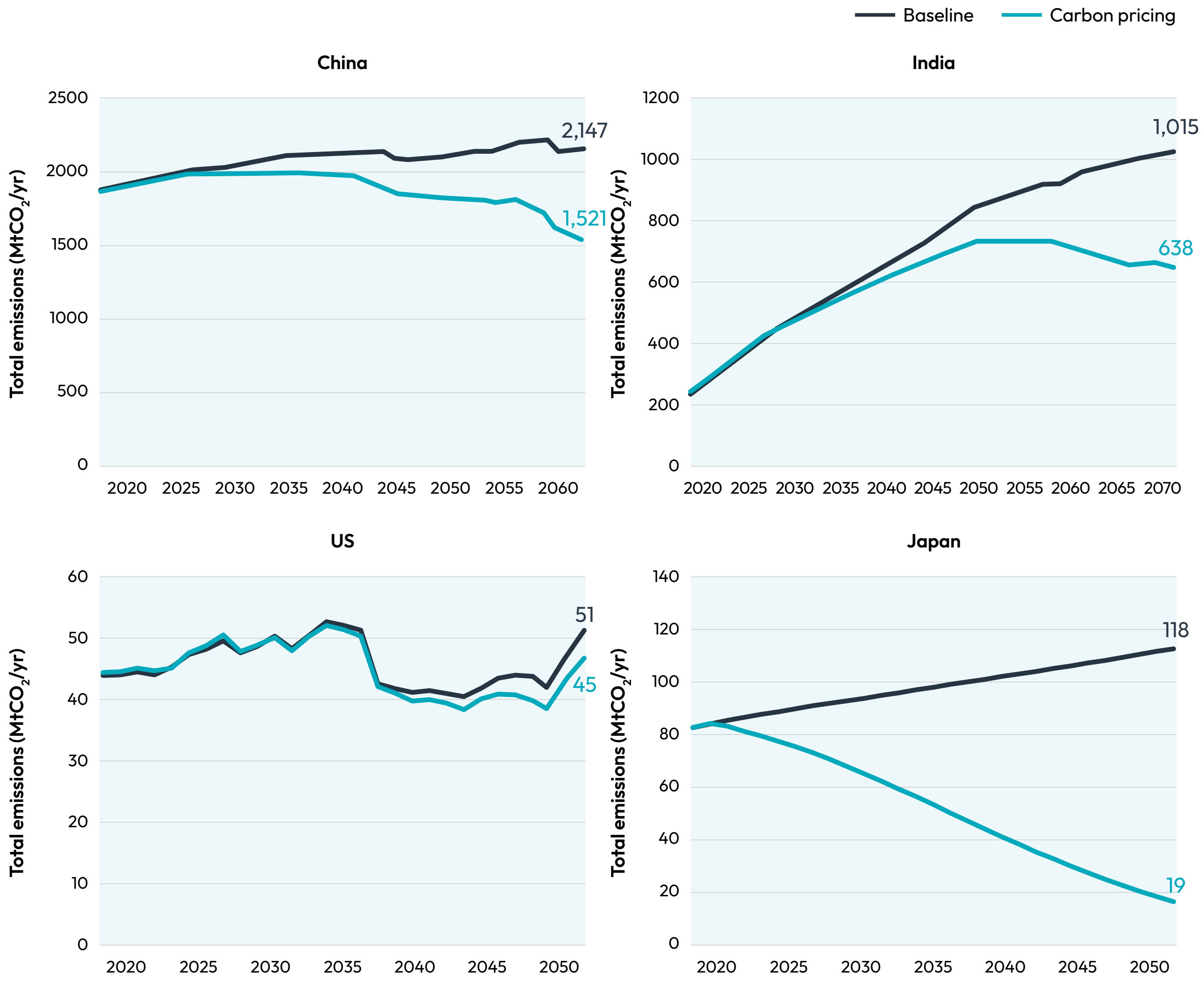


Figure 8. Total steel emissions ($MtCO_2$/yr) by country under the baseline and carbon price scenario.

Technologies: The main effect of the carbon tax is to encourage a shift from conventional BF-BOF production towards Scrap-EAF production. This takes place in all four countries, but to differing extents (Figure 9). The effect is greatest in Japan, where nearly three-quarters of the BF-BOF capacity in the baseline scenario is replaced with Scrap-EAF. This is because, as a scrap-rich country, Japan currently exports its scrap, but with the carbon tax applied in this scenario it consumes more domestically. Since BF-BOF makes up such a large share of the current fleet in Japan, and Scrap-EAF a very small share, this has a large effect on emissions. In the US, a quarter of the BF-BOF capacity share at the end of the baseline scenario is replaced with Scrap-EAF, but this has a small effect on emissions because BF-BOF production begins as a small share of the total.

In India and China, while the share of conventional BF-BOF production declines compared to the baseline, BF-BOF still accounts for 31% and 35% of production in 2070 and 2060 in the two countries respectively. In India the transition is limited by restrictions in scrap availability, however, we do see the share of Scrap-EAF rising to 34% by 2070 compared to the baseline value of 12% in 2070. In both China and India, high carbon prices in later years combined with limited scrap availability lead to the emergence of DR-gas-based production – 23% in India in 2070, and 12% in China in 2060. We also see marginal shares of H_2-DRI-EAF, BF-BOF (CCS) and other such low-carbon technologies.

The results suggest that a carbon tax policy alone is unlikely to be effective in increasing the uptake of near-zero emissions primary steelmaking technologies, and instead, similar to the capacity cap, is more likely to support a shift towards scrap-based steelmaking and other incrementally lower-emission solutions. This corresponds to a limited effect on emissions reduction over the course of the coming decades.

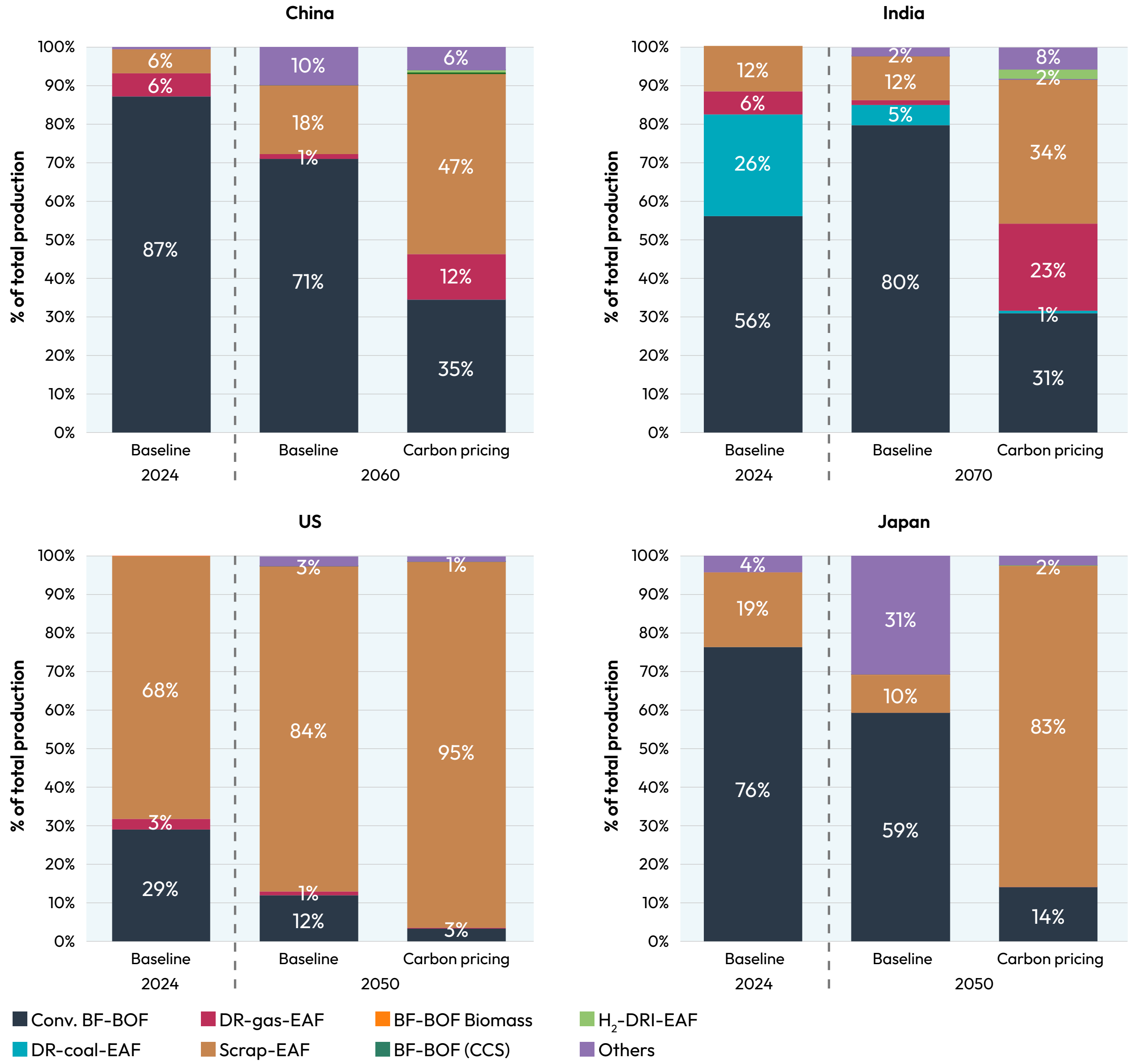


Figure 9. Technology mix of steel production by country under the baseline and carbon pricing scenarios.

Investment: Cumulative investments in the scrap-based production and DR-gas-based production pathways are estimated to be nearly US$135bn (85% Scrap-EAF, 15% DR-gas) in China between 2025 and 2060, approximately US$126bn (76% Scrap–EAF and 24% DR-gas) in India between 2025 and 2070, around US$21bn in the US, and around US$15bn in Japan between 2025 and 2050, towards the scrap-based and DR-gas-based production.

Policy option 3: Subsidies and procurement

Operational subsidies are applied as percentage reductions in the levelised cost of steel (LCOS) for targeted technologies for near-zero emissions primary steel production. In each country, the target technologies are the BF-BOF-CCS and H_2-DRI-EAF pathways. In India, this policy is also extended to the BF-BOF with biomass (BBB) route, in alignment with the Ministry of Steel's focus on the use of biomass in the BF-BOF pathway (Ministry of Steel 2024a). In each country, the subsidies are modelled in combination with public procurement policies that operate on a very small scale (10% of public sector demand) from 2030 onwards up to 10 years prior to the country-specific net zero target year,[12] creating foundational demand for the near-zero emissions product.[13]

Emissions: The subsidy and procurement policies reduce emissions substantially in all four countries, with reductions in the range of 30-40% by 2050 compared to the baseline trajectory in the US and Japan. The most significant declines are observed in China and India, which see emissions fall by around 50% by 2060 and 2070 respectively (Figure 10).

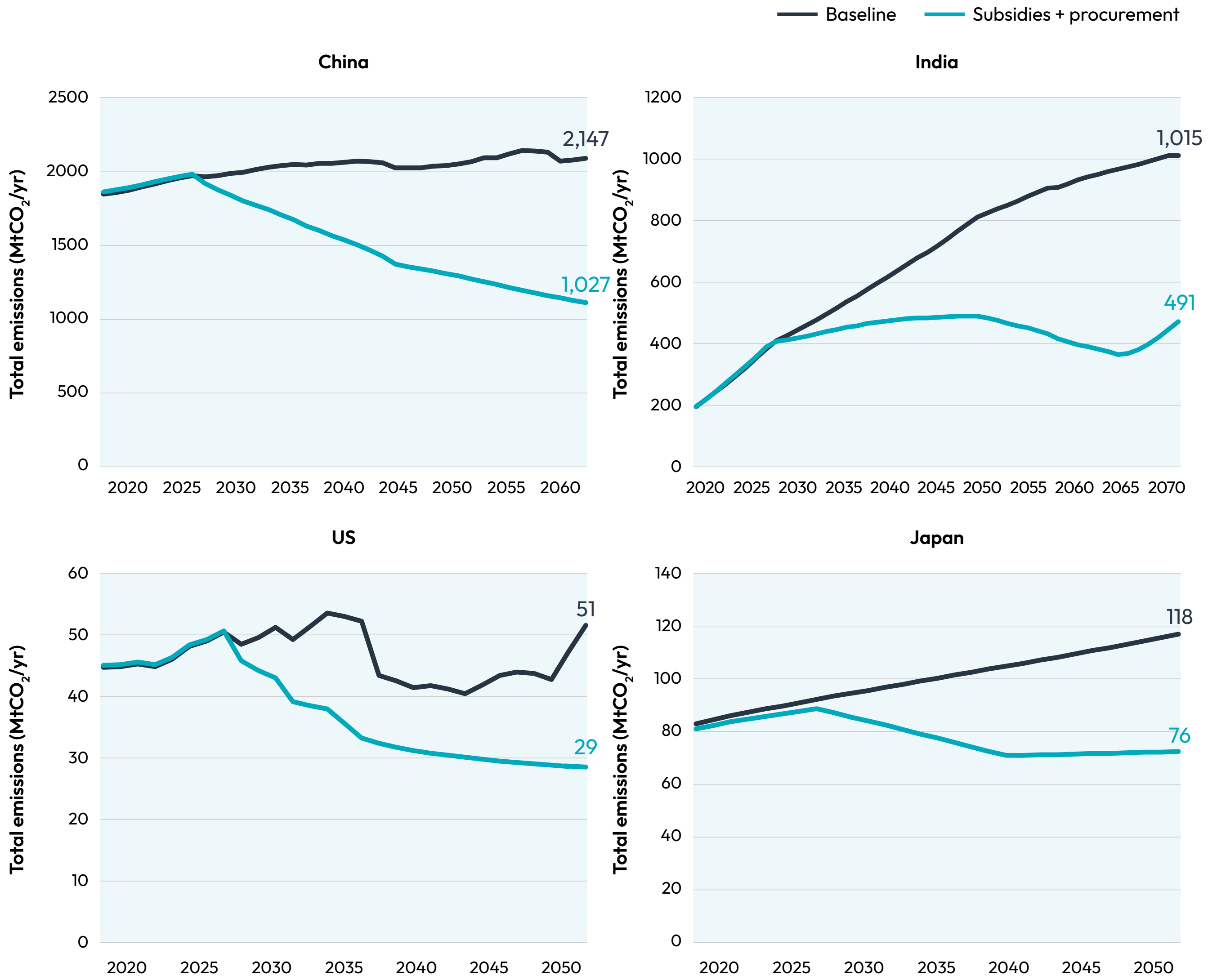


Figure 10. Total steel emissions ($MtCO_2$/yr) by country under a baseline scenario and under a scenario with subsidies and public procurement.

[12] In China the procurement policy is implemented between 2030 and 2050, in India between 2030 and 2060 and in the US and Japan between 2030 and 2040. In each case the end year is 10 years before the national net zero emissions or carbon neutrality target year.

[13] Public procurement is modelled as an exogenous addition of market share of the relevant technology. This is the same method as used for modelling the clean steel mandate, except for its duration. Consequently, this option can also be interpreted as a short-term production mandate.

Technologies: The subsidy and procurement policy leads to an increase in production from the BF-BOF (CCS) pathway and the H_2-DRI-EAF production pathway in all four countries (Figure 11). In China, India and Japan, the increase in near-zero emissions primary production largely displaces high-emission BF-BOF production. In the US, there is greater displacement of Scrap-EAF production, which is dominant in the baseline scenario, and only a minor reduction in the BF-BOF fleet. In India, although the share of near-zero emissions primary production increases significantly, the share of conventional BF-BOF capacity in total production remains significant at around 35%, even in 2070. This is due in part to India's low uptake of Scrap-EAF production, resulting from the low scrap availability in the country.

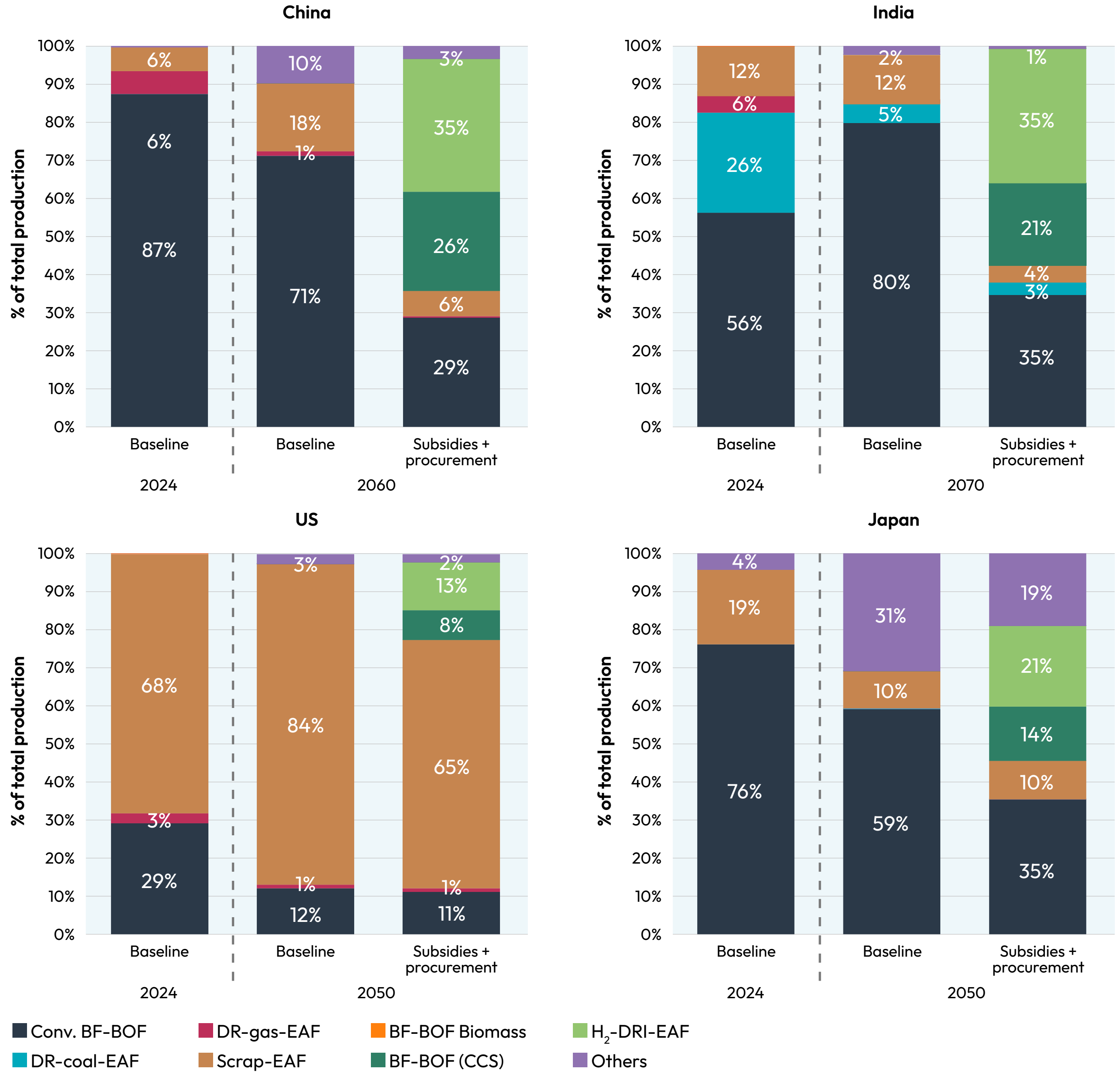


Figure 11. Technology mix of steel production by country under a baseline scenario and under a scenario with subsidies and procurement.

Investment: Cumulative investments in the near-zero emissions technologies are estimated to be nearly US$1tn (51% BF-BOF (CCS) and 49% H_2-DRI-EAF) in China between 2025 and 2060, approximately US$315bn (43% BF-BOF (CCS) and 57% H_2-DRI-EAF) in India between 2025 and 2070. In the US around US$33bn, and approximately US$40bn in Japan between 2025 and 2050, primarily going towards the H_2-DRI-EAF pathway. Compared to the baseline, around 30% of the cumulative investment in the new technologies across the four countries on average can be seen as a reallocation of investment that would have gone into new BF-BOF plants, while the remaining 70% represents the additional net investment required.

Policy option 4: Clean steel mandate

The clean steel mandate policy has been implemented by requiring a minimum share of steel production to come from the chosen low-emissions steel production pathways, with this share rising each year (Table 1). These are BF-BOF (CCS) and H_2-DRI-EAF, and in India's case also BBB. The mandates increase linearly to at least half of the projected conventional primary steel production in 2050 and remain at the same minimum levels beyond 2050 in each country.

Emissions: The clean steel mandate leads to emission reductions in all four countries, with the largest effect being in China at approximately 60%, followed by India at around 30%. The relative effects are smaller in Japan and the US, with reductions of around 20-23% in the two countries (Figure 12).

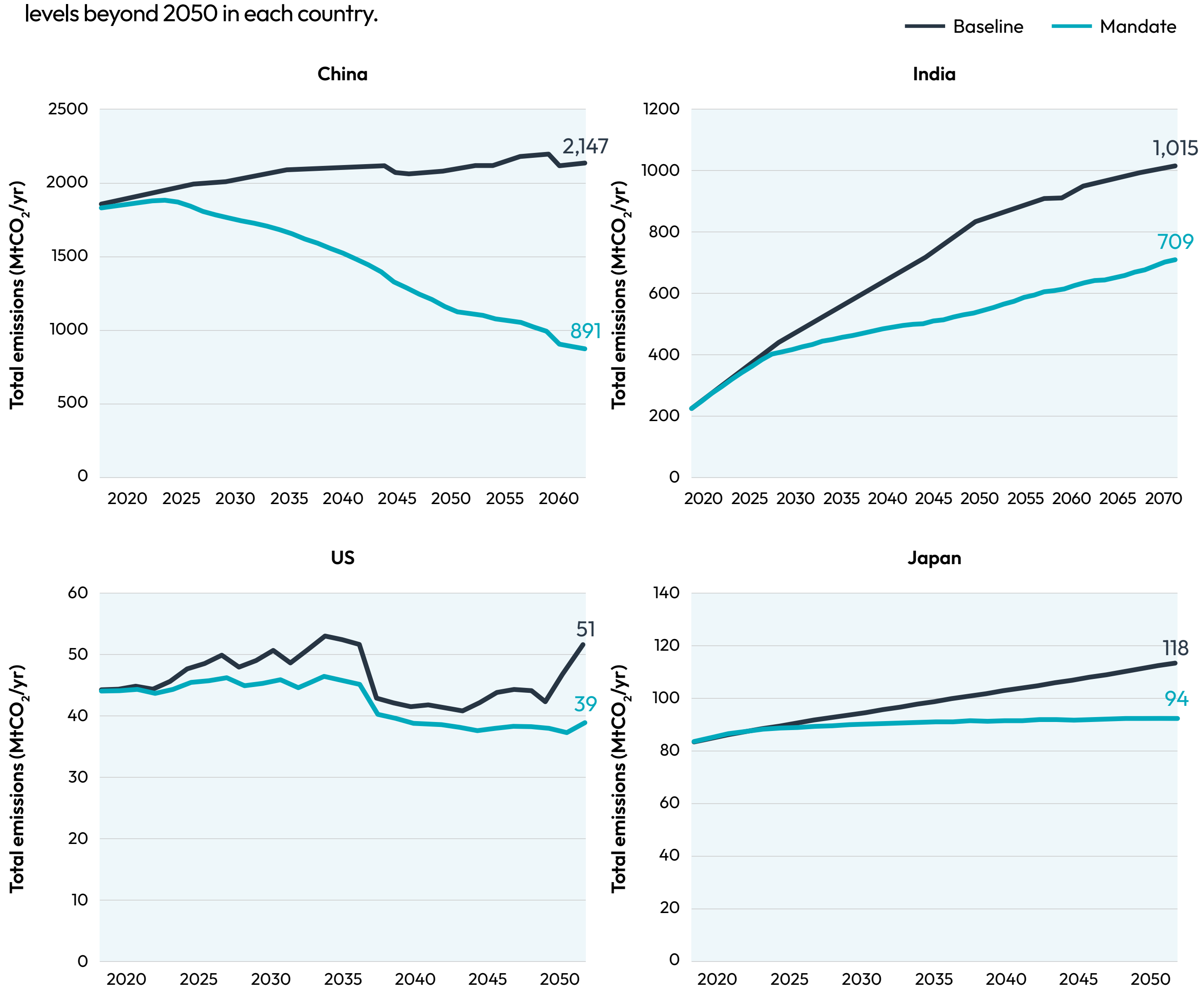


Figure 12. Total steel emissions ($MtCO_2$/yr) by country under a baseline scenario and a mandate scenario.

Technologies: The clean steel mandates force the introduction of near-zero emissions primary steel production technologies in all four countries (Figure 13). In China and India, this displaces large amounts of BF-BOF capacity, compared to the baseline. In the US, the effect is small because the mandate is set to only apply to primary production (not displacing investment in Scrap-EAF), and since Scrap-EAF is already dominant in the baseline, this leaves only a small share of investment for the policy to influence. Notably, the share of BF-BOF in the US does not fall compared to the baseline, even though the total capacity in the US rises over time, reflecting that the mandate specifications do not in this case require all primary steel production to be near-zero emissions.

In Japan, we see an uptake of Smelt-Reduction-Basic Oxygen Furnace, and Blast Furnace-Basic Oxygen Furnace (Top-Gas-Recovery), reflecting these technologies' competitiveness against hydrogen-based steel or BF-BOF (CCS) in this country. The growth of the new technologies displaces a mixture of BF-BOF and Scrap-EAF, compared to the baseline.

In all four countries, the share of BF-BOF (CCS) deployed by the clean steel mandate is larger than the share of H_2-DRI-EAF. This reflects assumptions about the levelised cost of steel production of the two technology routes. An important uncertainty is the cost of green hydrogen. Since hydrogen prices remain constant in the model, the effects of potentially falling green hydrogen prices (which could be passed on to the steel sector by deployment of green hydrogen in other sectors) are not seen.

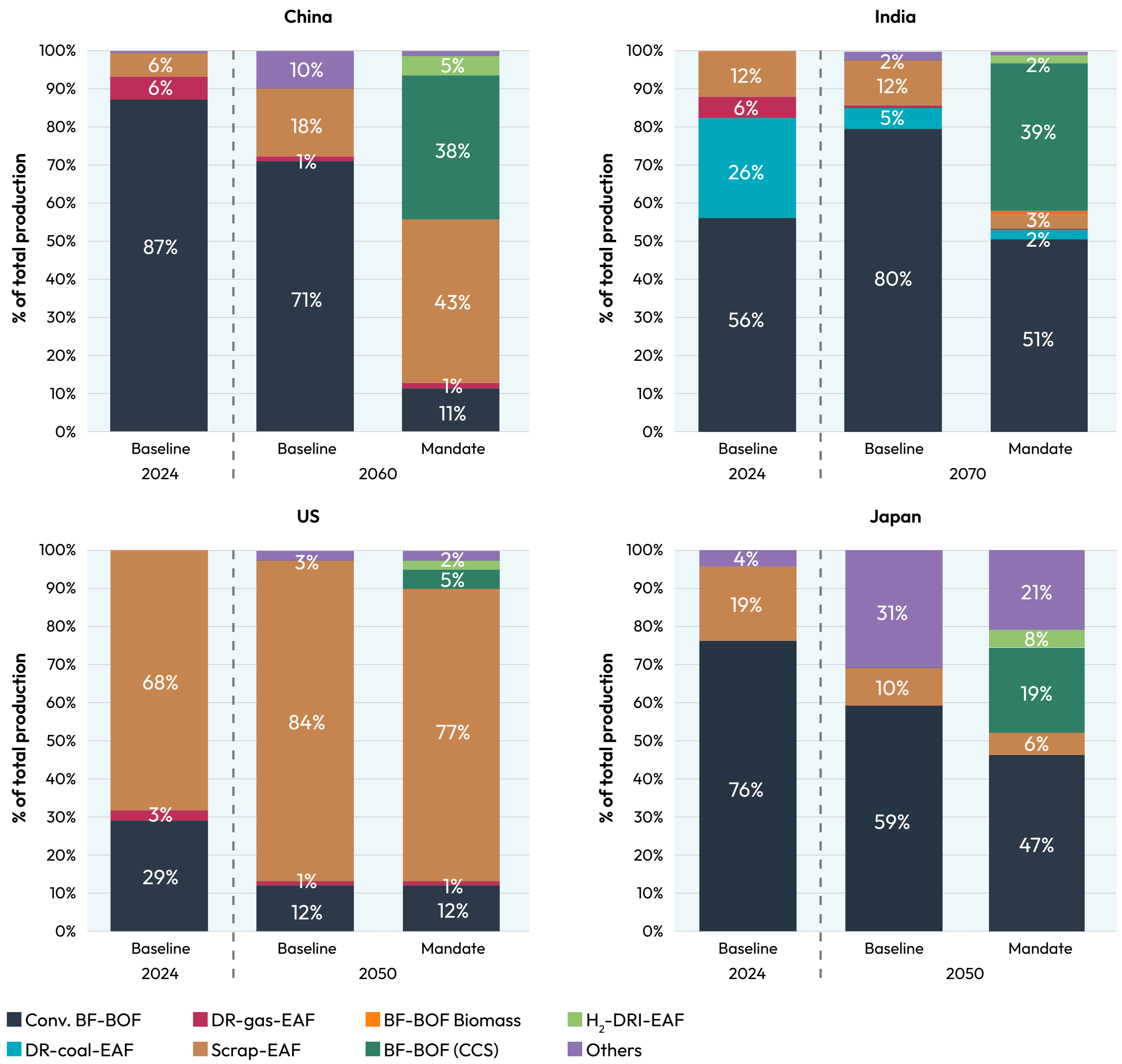


Figure 13. Technology mix of steel production by country under a baseline scenario and a mandate scenario.

Investment: Mandates lead to higher cumulative investments in H_2-DRI-EAF and BF-BOF (CCS) across all four countries. In China, cumulative investments are projected to be approximately US$600bn, of which around 86% is in BF-BOF (CCS) and 14% H_2-DRI-EAF, between 2025 and 2060. In India, cumulative investments are approximately US$310bn for both technologies (87% BF-BOF (CCS) and 13% H_2-DRI-EAF) between 2025 and 2070. In the US and Japan, cumulative investments for both technologies are projected to be around US$6bn and US$17bn respectively between 2025 and 2050, with a majority share of 70-74% going towards the H_2-DRI-EAF route.

Policy option 5: Combined policies scenario

This scenario involves all the policies from the previous scenarios used in combination and helps us understand whether there are any compounding effects that arise. Unsurprisingly, we see that this combination of policies is more effective than any of the individual policy scenarios alone.

Emissions: The combined policies drive emissions from the steel sector close to zero by 2050 in the US and Japan. Emissions reductions are around 90-95% below the baseline in China and India, by 2060 and 2070 respectively (Figure 14).

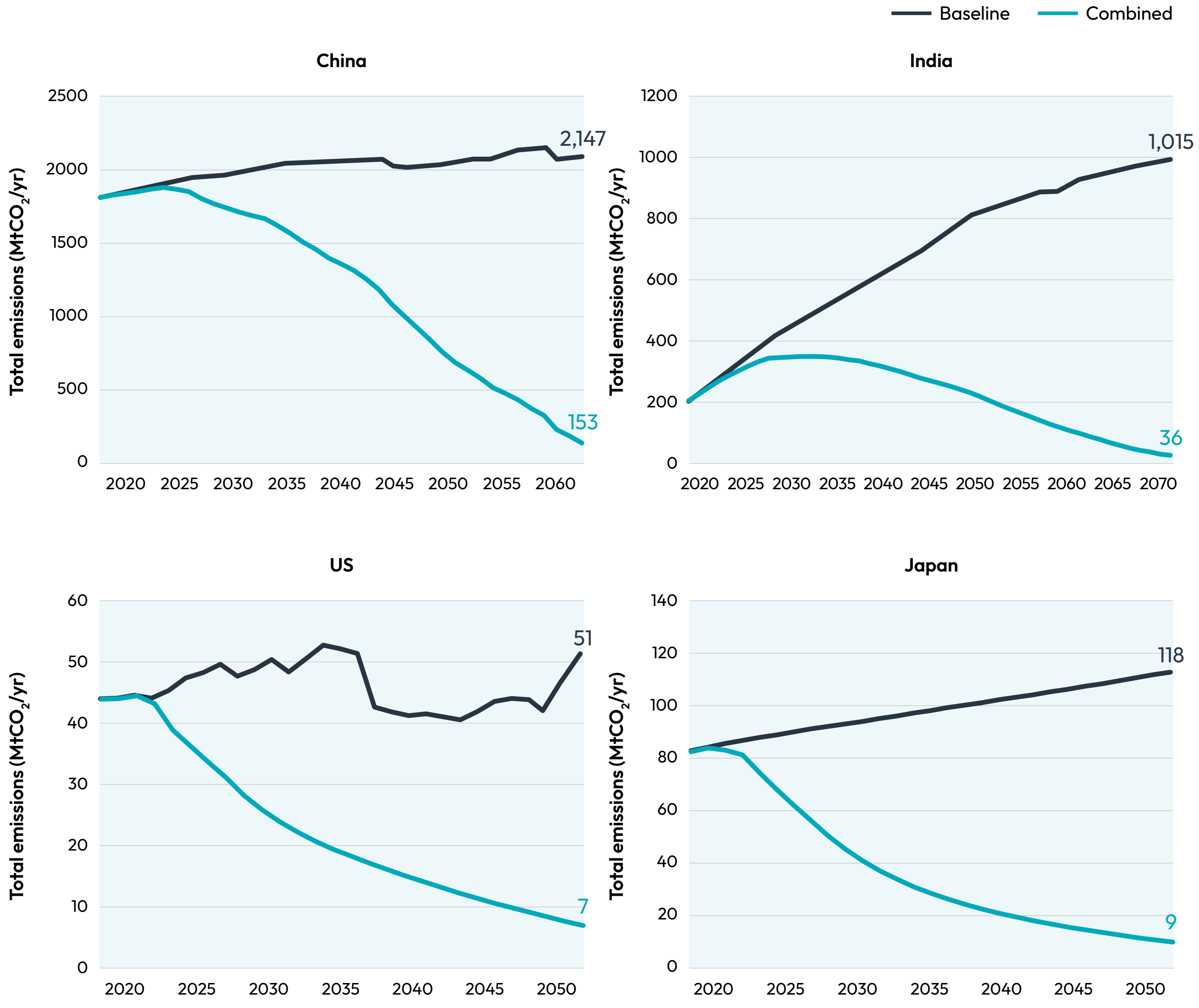


Figure 14. Total steel emissions ($MtCO_2$/yr) by country under a baseline scenario and a combined policy scenario.

Technologies: In the combined policies scenario, there is a large expansion of H_2-DRI-EAF in all four countries, with the largest increases in India and Japan. There is a much smaller expansion of BF-BOF (CCS) across all four countries. In all four countries, the rapid growth of primary clean steel technologies almost entirely pushes BF-BOF production out of the market (Figure 15). While the capacity cap and carbon tax policies are effective in reducing the share of conventional BF-BOF, across all four countries, the subsidies and procurement and mandate policies are critical to drive the uptake of low-emission technologies. The policies in combination achieve far greater deployment of clean steel technologies than any policy achieves individually.

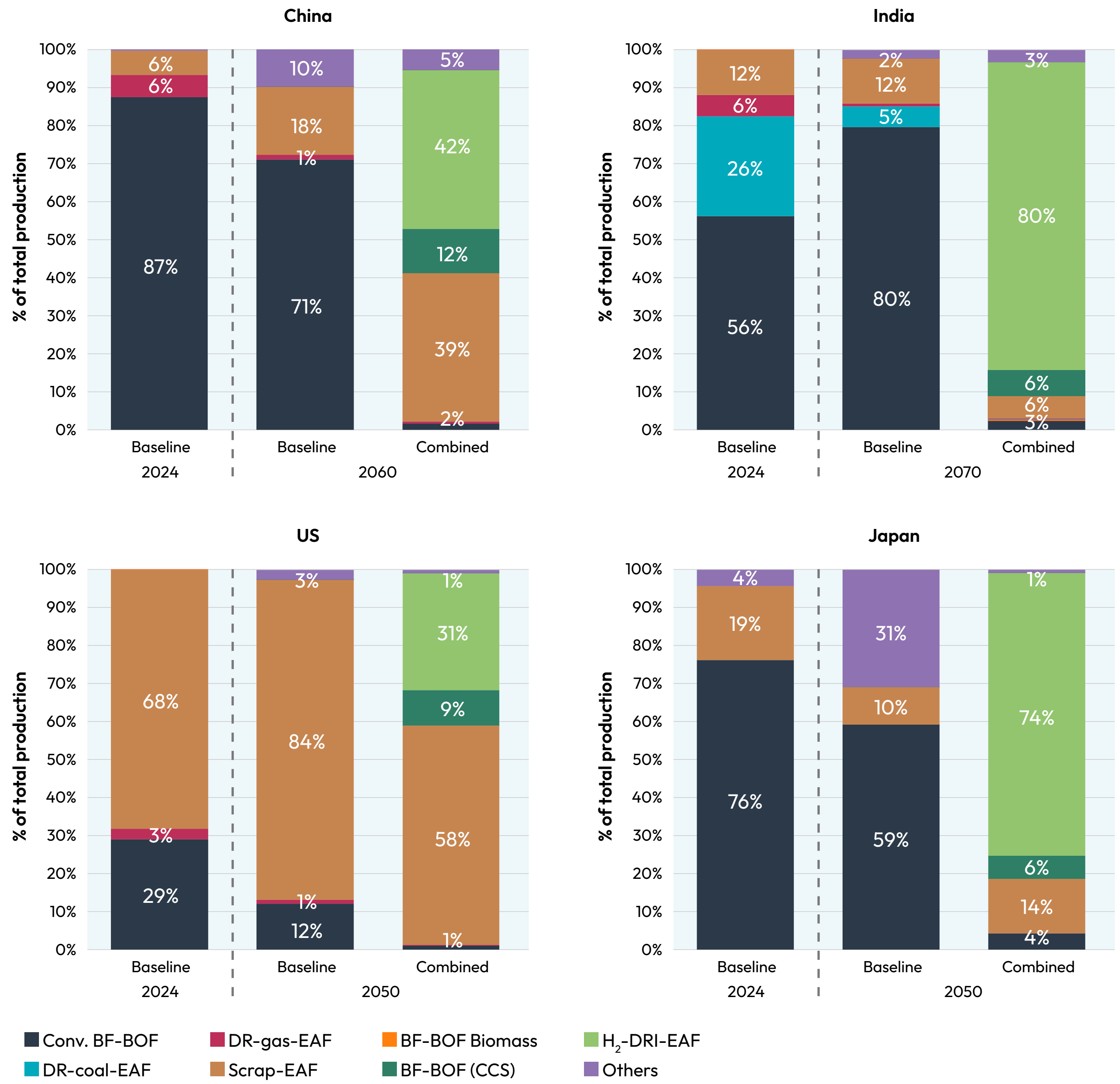


Figure 15. Technology mix of steel production by country under a baseline scenario and a combined policy scenario.

Investment: The combined scenario leads to higher cumulative investments in H_2-DRI-EAF and BF-BOF (CCS) across all four countries. In China, cumulative investments are projected to be approximately US$500bn, of which around 48% are for H_2-DRI-EAF between 2025 and 2060. In India, cumulative investments range around US$385bn for both technologies between 2025 and 2070, with around 85% of this going towards H_2-DRI-EAF. In the US and Japan, cumulative investments for BF-BOF (CCS) and H_2-DRI-EAF are projected to be around US$29bn and $40bn between 2025 and 2050, with more than 50% going towards the H_2-DRI-EAF route.

Case study: India

Among the four largest steel producers, India is on a unique trajectory.

The steel sector expects to keep adding to its BF-BOF capacity significantly in a business-as-usual scenario. Even in a high carbon prices scenario, the BF-BOF production route still retains a large share of India's steel capacity. With a capacity cap, our modelling finds that BF-BOF is more substantially reduced, but is replaced by Gas-DRI-EAF and Scrap-EAF. As for the other countries, we find that subsidies and public procurement, or clean steel mandates, are needed to drive deployment of near-zero emissions primary steel production through the H_2-DRI-EAF and BF-BOF-CCS routes. We also find that the deepest emissions reductions are achieved by using all policy levers together.

While the overall pattern of policy effectiveness is similar across the four countries, India has several context-specific constraints that need to be overcome. Firstly, being a developing country with relatively young infrastructure, scrap availability is limited, and with growing demand for steel in the country and globally, this challenge might be exacerbated. Policy measures such as India's Vehicle Scrappage Policy and related incentives aim to address this challenge.

Secondly, as simulated in our capacity cap scenario, Gas-DRI-EAF could potentially be a steel production technology that India uses as a transition technology. However, in the absence of reserves of natural gas, this could involve expensive imports. Long-term bilateral agreements with countries such as Australia, the UAE and other gas-rich economies could prove useful in enabling such capacity shifts by ensuring security of supply and increased stability of prices.

A difficulty with respect to the clean steel technology of H_2-DRI-EAF, is that India's iron ore reserves do not provide pure enough ore for such processes. Investing in pelletising domestic ore and removing impurities could address this issue, but at a cost. The alternative would be increased reliance on iron ore imports.

The BF-BOF-CCS route, on the other hand, may be subject to geographical constraints. Adding CCS to steel plants could be limited by land ownership restrictions and the lack of storage locations close to the steel plants. The cost of CCS, the investment needs to develop CCS technologies and uncertainty around what is technically possible are other restrictions for Indian industry. On this issue, experts tend to look at CCU as a possible option to offset the costs of installing and operating CCS capacity.

This set of challenges could deter Indian industry or policymakers from embarking on the steel transition. However, if a shift towards clean steel in global markets – as implied by all countries' decarbonisation targets – is seen as a realistic possibility, then there may be high value for India in experimenting with clean steel solutions sooner rather than later.

The country's proposed National Carbon Market (NCM), an expansion of the Perform, Achieve and Trade Scheme, will prescribe emissions intensity targets for nine sectors, including the iron and steel sector (BEE 2023). Our analysis suggests that this could drive a shift from BF-BOF towards Scrap-EAF, to the extent that scrap steel is available.

While development of a policy framework for CCS implementation is ongoing (Ranevska 2024), subsidies could help bring down the cost of CCS and hydrogen-DRI, enable the first deployment of plants using these technologies, and test their feasibility for the transition.

Subsidies for primary near-zero emissions steel production are often assumed to be unaffordable, but this need not be the case. A revenue-neutral approach would be to fund clean steel subsidies with a tax, or charge, on all steel consumption (or production) at a flat rate per ton. Applying this charge equally to all steel domestically produced or imported would avoid any negative effects on competitiveness.[14]

In our subsidy and procurement scenario described above, the first five BF-BOF-CCS plants and the first five H_2-DRI-EAF plants in India are deployed by around the year 2030.[15] We find that the subsidies to enable this deployment, at the levels ensuring cost-parity with BF-BOF production as shown in Table 1 above, could be funded by a consumption charge equivalent to around 1.2% of the cost of conventional BF-BOF steel production. For the first 10 and 20 plants using each of those technologies, the charge would be around 2.4% and 4.3% respectively, with these levels of deployment expected to be reached in 2034 and 2039 respectively. In our simulation, the highest rate of charge reached is 10%, during the early 2060s, when BF-BOF-CCS and H_2-DRI-EAF together reach around 50% of India's total steel production.

These costs compare favourably to those of carbon pricing. In our carbon price scenario, this policy increases the levelised cost of BF-BOF steel production by around 3% at the start of the transition in 2026, rising to 16% in 2030, 47% in 2040, and around 94% by the end of the simulation in 2070 compared to the baseline scenario. The subsidy scenario also achieves deeper emissions reduction.

With the right policy design, the effect of steel decarbonisation on consumer costs can be very small. The Energy Transitions Commission has estimated that an additional cost of 20% in steel production would translate into an increase of around 1% in the cost of a car.[16] Using the same ratio, our estimated 1.2% charge to fund the first 10 near-zero emissions primary steel plants would affect the cost of a car by around 0.06%, and our maximum 10% charge levied in the 2060s would affect the cost of a car by around 0.5%.

[14] The tax, or charge, could be applied to either consumption or production, with roughly equivalent effects (assuming steel producers pass on additional costs to consumers). A negative effect on competitiveness can be avoided by applying the charge equally to imported steel and domestically produced steel, and in the case of the charge being levied on production, by giving an exemption or rebate to exported steel. For discussion of how such an approach can be combined with an emissions trading scheme, see Neuhoff et al. (2025) **Industrial decarbonisation in a fragmented world: an effective carbon price with a 'climate contribution'.**

[15] Here we assume an average plant capacity of 1.5 Mt/year to convert primary clean steel production capacity, as simulated by the model, into an indicative number of plants.

[16] Energy Transitions Commission, 2018. **Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors.**

4. Policy implications and uncertainties

The results suggest that the main effect of policies that put pressure on high-emissions steel production – a carbon tax, or a cap on investment in new blast furnaces – is to provoke a shift towards recycling of scrap steel, and in some cases to other intermediate technologies, such as gas-DRI or blast furnace with top gas recovery (TGR). Even relatively high carbon prices, considered in other studies to be consistent with national net zero targets, yield only modest emissions reductions in three of the four countries (the exception being Japan), and do not result in the deployment of near-zero emissions primary steelmaking technologies (Figure 16).

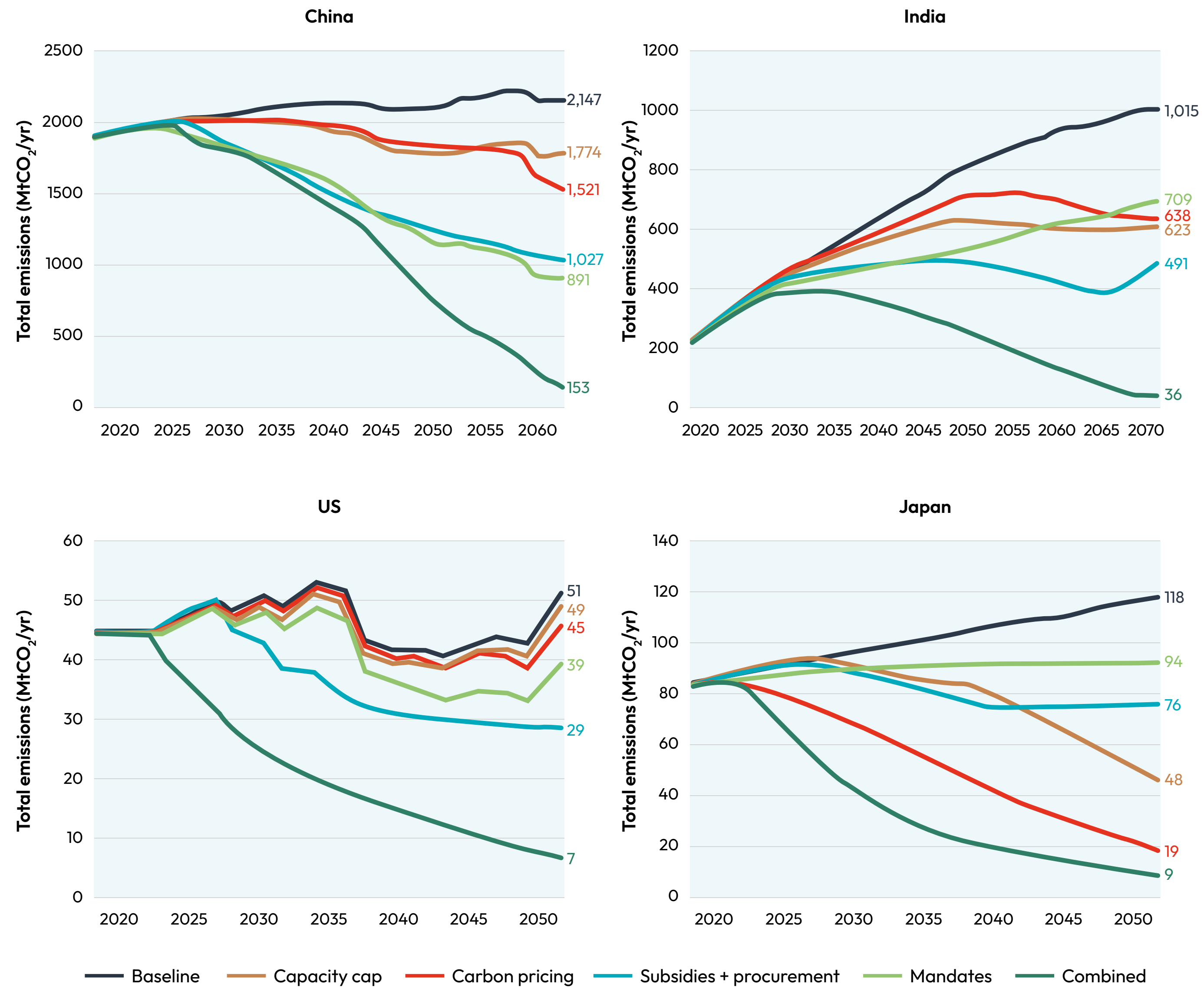


Figure 16. Total emissions ($MtCO_2$/yr) by country across scenarios.

We find that either targeted subsidies together with public procurement, or clean steel mandates, are necessary to deploy near-zero emissions technologies for primary steel production – and that either of these approaches can achieve that deployment at a substantial level. Without other measures, we find that these policies lead to clean primary steel technologies displacing some but not all high-emission blast furnace production.

The finding that demand creation and subsidy policies are likely to be needed to make near-zero emissions primary steel production viable is consistent with recent academic literature (Bataille et al., 2024), industry surveys (WBCSD and Bain and Company, 2024) and policy reports (Industrial Transition Accelerator, 2024).

Our simulation suggests that a combination of policy measures can be highly effective, as subsidies and clean steel mandates deploy technologies for near-zero emissions primary steel production, and carbon taxes and capacity caps drive a shift from blast furnaces to Scrap-EAF plants. This combination of policies leads to a technology mix with a dominant role for H_2-DRI in primary steelmaking, which is generally consistent with the deep decarbonisation scenarios of other modelling studies such as IEA (2021a), Jyoti Gulia et al. (2023), and Hasanbeigi, Lu and Zhou (2023).

We recommend as near-term measures:

- **Targeted subsidies** to introduce near-zero emissions primary steel production technologies to the market, set at a level that ensures commercial viability. These would not have any adverse effects on competitiveness and could be funded by a charge on all steel domestically produced or imported.
- **Public procurement** of near-zero emissions steel, to create initial demand. Together with subsidies, this can provide an additional incentive for investment in the new technologies.
- **A capacity cap** on blast furnaces, to prevent investment in new high-emitting steel production capacity. This would reduce the risk of expensive early retirement or retrofitting being needed in future either to meet policy goals or to comply with any low emission standards in global markets. Growth in capacity could instead come from Scrap-EAF at first, and increasingly also from near-zero emissions primary production.

And as medium- to long-term measures:

- **Clean steel mandates** that require a rising proportion of primary steel production to be near-zero emissions, to accelerate the diffusion of these technologies.
- **Increasing carbon pricing** to encourage a shift from BF-BOF to Scrap-EAF.
- **Continuation of subsidies**, for as long as these are needed to ensure the commercial viability of near-zero emissions primary steel.

At the same time, these findings are subject to several caveats and uncertainties. An important caveat is that any of the policies could be adopted with different stringencies, and alternative policy designs are also available. Earlier implementation of the blast furnace capacity cap, or higher carbon taxes, could drive a deeper shift away from blast furnaces. Subsidies at different levels could achieve different market shares for primary near-zero emissions technologies, potentially including less mature technology options such as direct electrolysis, which we have not included in this analysis. Clean steel mandates could be set to rise to 100% of all primary steel production, to achieve full decarbonisation without need for carbon taxes or blast furnace capacity caps.

Policy options not modelled in this study include carbon intensity regulations, emissions trading schemes (a variant of carbon pricing), concessional lending (domestic or international) and demand-side incentives or mandates for the use of near-zero emissions steel in specific sectors. Private sector procurement initiatives can also contribute to creating demand for near-zero emissions steel. Standards and definitions for near-zero emission or low-emission steel are important as precursors to many of these policies.

The most important limitation of the model is that it does not simulate trade and the competition between steel firms in the global market, which is an important consideration in policymaking. For any of the policy options that increase the cost of production – the carbon tax, blast furnace capacity cap, and the clean steel mandate – to have their desired effects in a given country without undermining the industry's competitiveness, they would need to be accompanied by trade protections such as a carbon border adjustment, with rebates for exporters. The subsidy and public procurement policy is the exception, since it does not add to the costs of production.

While clean steel subsidies are often assumed to be difficult for governments to afford, an option is to fund them through a charge on all steel domestically produced or imported – an approach that can be revenue neutral without having any negative effect on competitiveness (Neuhoff K et al., 2025).

A significant uncertainty is the cost of green hydrogen. In this study, we have assumed a cost of US$2.2/kg, common to all countries, and fixed throughout the simulation. The cost is likely to vary significantly by location and could fall over time as a result of the decreasing cost of clean electricity, and the falling cost of electrolysers. Estimates of the future cost of green hydrogen range from US$2-4/kg in 2030 to US$1.5-3/kg in 2050 (Baker, 2024). If green hydrogen costs do fall below the level used in our simulation, we would expect a larger shift towards H_2-DRI to take place, with this displacing more BF-BOF, Scrap-EAF, or BF-BOF-CCS depending on the scenario. There could also be limits to a country's ability to produce green hydrogen, given that this could imply large additions to power-generating capacity and extensions to electricity grids.

A further significant caveat relates to infrastructure. The potential scale of deployment of CCS is limited by a country's geology, but no such limits are imposed in our model. Lin et al. (2024) find that China's CO_2 storage capacity exceeds its current steel sector emissions, though there are uncertainties about injection rates and seismic risks. In India, the theoretical potential for geological storage has been estimated to be 649 Gt (Bakshi, Mallya and Yadav, 2023), but the actual potential may be much lower (perhaps around 100-360 Gt) given factors that may prevent storage being sited in areas such as biodiversity zones, special economic zones, high population density areas, plantation and fallow lands. Estimates of Japan's geological storage potential range from 0.1-10 Gt (METI, 2019), dependent on transport infrastructure (Mizuho Bank, 2023). The US has a technical potential of 400 Gt across seven key basins, considering access, permitting, geological risk and economic factors (Larson et al., 2021). It is not possible to directly compare these estimates with our results because the storage capacity needed would depend on the duration of use of CCS in steel production, as well as on the needs of other sectors for use of the CCS infrastructure. The significant increase in CCS in the mandates scenario, particularly in India, may test the limits of what is possible.

Finally, there is uncertainty over scrap availability. China, the US and Japan have the advantage here compared to India, due to their more mature infrastructure; even so, they may face challenges accessing the volumes required as Scrap-EAF takes a growing share of the market (Boston Consulting Group, 2024). India's challenges with respect to scrap availability are more severe and likely to persist (S&P Global, 2024) and the extent to which scrap steel will be available for import is difficult to predict.

5. Conclusions

No single policy is likely to be sufficient to drive the transition to a near-zero emissions steel sector. While the transition is subject to many uncertainties, full decarbonisation is likely to require a combination of policies targeted towards deploying and diffusing the new near-zero emissions production technologies, such as subsidies, clean steel mandates and public procurement, and measures such as carbon taxes or capacity caps to ensure a shift away from blast furnace production and towards recycling, to the maximum extent that scrap steel resources allow.

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