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APPENDIX 5

PROSPECTS AND STRATEGIES FOR LOW-CARBON STEEL

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Context of steel sector emissions

Globally, the steel sector directly emits 2.6 Gt of CO_2 emissions per year via combustion and chemical process emissions, and 3.7 Gt per year in total, including indirect emissions from electricity consumption. These emissions account for about 30% of direct industrial emissions, and over 7% of global energy systems' CO_2 emissions (including process emissions) (IEA, 2020).

About half the steel produced is used in construction (including buildings, bridges, power plants, pipelines and sanitation systems), with most of the rest being used in vehicles (15% of demand), machinery (20%) and consumer goods (15%) (IEA, 2020). Global steel demand stands at 1.5 Gt/yr of finished steel products across all end-uses (IEA, 2020). For most end-uses, there are no or limited good substitute materials for steel, and therefore significant steel production is regarded as unavoidable. Production levels of *crude* steel stand at 1.9 Gt/yr (World Steel Association, 2021). Losses arise during various stages of the manufacturing process. This pre-consumer scrap is incorporated in the next batch of production.

According to the IEA, global demand for finished steel is forecasted to increase by 10-40% by 2050. The lower estimate assumes increased material efficiency, extended lifetimes of steel-containing end-products and improving manufacturing yields. Under such assumptions, global steel demand for finished products is expected to grow to 1.8 Gt/yr. This is what the IEA refers to as the Sustainable Development Scenario. The higher estimate is less optimistic on such factors and is in line with current trends (Stated Policies Scenario). In that scenario, global steel demand will grow to 2.1 Gt/yr (IEA, 2020).

Steel demand and production are regional, with China accounting for over 50% of steel production (IEA, 2020). India, the second-largest producer and third-largest consumer, has the biggest projected demand growth, with steel demand growing three to fourfold from the recent levels of 100 Mt/yr (Hall, Spencer, Renjith, & Dayal, 2020). Indian demand for steel has outpaced its domestic supply over recent years (World Steel Association, 2021).

Existing steel production processes

Carbon is the main 'reducing agent' used to chemically convert iron ore, as mined from the ground, into usable metallic iron. This is currently commonly done in a blast furnace (BF), by mixing iron ore with coke (pure carbon derived from coal) and reacting the two at high temperature. This chemical step emits CO_2 and is followed by refining the intermediate product (iron) in a basic oxygen furnace (BOF), which uses substantial additional amounts of energy, generally from fossil fuels. The whole standard industrial route (BF-BOF in short) emits on average 1.8 t CO_2 per ton ne of crude steel production.

Other techniques exist to process iron ore; they require natural gas or use coal in a different way, and still emit CO_2. A small share (about 111 MT) of global primary steel production uses direct reduction through (DRI) to reduce the iron ore, which can then be fed into an electric arc furnace. Indian steelmaking is unique for the incorporation of the coal-gasification DRI variant (~36 MT 2019) which is not found in many other steelmaking systems in the rest of the world. Indian steel plants use this route, using domestic coal which is too low-quality to serve as coking coal and therefore unsuitable as input for the blast furnace process. Using coal in this way is even more carbon-intensive, though similar technology using natural gas instead does lower emissions. Part of steel demand can be (and is) met from recycling. This approach uses scrap steel and electricity as inputs in an electric arc furnace (EAF), and 26% of global crude steel was produced in this way in 2020 (World Steel Association, 2021). Such production can be 'green' by design if the electricity comes from appropriate low-carbon sources. According to the World Steel Association, each tonne of steel scrap saves 1.5 tonnes CO_2.

The scale of recycled contribution will depend on scrap availability as much as production technology investments: globally, recycling rates are already at 85%, but the proportion of steel production from recycled steel is around 35-38% (IEA 2021b; Gielen et al. 2020).[1] There are significant amounts of in-use steel stocks that will become end-of-life scrap over the coming decades, but at a global level, scrap availability will likely limit the amount of steel demand which can be met through recycling. It may take some decades before much of the new steel in China (and other major emerging economies) will become available for recycling; and much of Africa, for example, has yet to construct most of its steel-using infrastructure. The demand for steel will substantially outweigh the availability of scrap, at least without huge advances in material efficiency (Morfeldt, Nijs, & Silveira, 2015). The IEA States Policies scenario sees EAF meeting 47% of produced steel by 2050, increasing to 57% in the Sustainable Development scenario (IEA, 2020). Steel quality requirements can also limit the use of scrap in some applications, although new technologies may ameliorate this constraint.

Low-carbon steel: technologies, progress and policies

The three main technological pathways for reducing emissions to net-zero levels in steel production are:

1. Direct reduction of iron ore with low-carbon hydrogen followed by electric arc furnace (H2 DRI-EAF).

2. Direct reduction of iron ore using natural gas with carbon capture sequestration (CCS) followed by an electric arc furnace (gas-based DRI-EAF with CCS).

3. Carbon-based smelting reduction processes with CCS and basic oxygen furnace (SR-BOF with CCS) (IEA, 2020).

The economics of the latter two (CCS) routes could be improved if the captured CO_2 can be utilised, but the sheer volume of CO_2 involved in major steel plants likely limits this.

None of these technologies are widely commercially available, but all have now been demonstrated.

- The first pathway, via green hydrogen-based production, has been demonstrated in the HYBRIT project in Sweden in 2021 (HYBRIT, 2021).

- The second pathway includes natural gas-based DRI plants in Abu Dhabi and Mexico, with a portion of CO2 emissions captured and used for other industries (IEA, 2020).

- The third pathway, advanced smelt reduction (SR-BOF with CCS), has been demonstrated at the HI sarna project in the Netherlands, although it is not yet connected to CO_2 storage.

The competitiveness of the three routes depends on costs of local inputs (fossil fuels and renewable electricity costs), availability of CCS , existing infrastructure, and CO_2 prices.

Thus, low-carbon steel is currently at a much earlier stage of its evolution than electric vehicles (our other forward-looking case study), being confined to a small number of demonstration plants, but the field is evolving rapidly and other technology routes may be possible.[2]

Correspondingly, the dominant element of policy support for progress to date has been 'technology push' mechanisms, with a variety of funding sources, rather than 'demand pull'.[3] However a significant policy element for low-carbon steel has been the EU Emissions Trading System (EU ETS). In terms of direct incentives, the impact of the EU ETS has been muted both by the historically low prices (which have however risen dramatically in recent years), and by the fact that steel has continued to receive free allowances, to protect plants from the adverse competitiveness impacts of foreign manufacturers that do not face a carbon price. The bigger impact of the EU ETS has derived from the 'set-aside' provisions for allowances, which in essence created a substantial, EU-wide fund for low-carbon technology innovation and demonstration.

[1] A major contribution is cast-off during the production of primary steel and manufacturing; for end-of-life scrap the ratio declined from 30% in 1995-2010 to 21–25% after 2010 (Gielen et al. 2020; Wang et al. 2021), due in part to the surge in steel demand in China, very little of which has yet reached end-of-life.

[2] For an overview, see the forthcoming IPCC Sixth Assessment Report: Mitigation, Chapter 11 (due April 2022).

[3] See the C1 main report, The New Economics of Innovation and Transition: Evaluating Opportunities and Risks, Figure 1: www.eeist.co.uk

Looking forward, the EU ETS (or other carbon-pricing mechanisms) could start to have a bigger demand-pull impact through two main routes. One would be the use of 'carbon contracts for differences', which would guarantee that steel from low-carbon steel plants receives a financial premium corresponding to the value of the CO_2 saved.[4] The other, more direct, would be if a carbon border adjustment mechanism (CBAM) were to be implemented in a way that enabled phase-out of free emission allowances for existing steel plants, i.e., a move to full auctioning.

In addition, other kinds of interventions do affect overall incentives in the sector. The Chinese government has mandated the phase-out of smaller, outdated and carbon-intensive steelmaking facilities (IEA, 2020). However, efficiency measures are limited and cannot decarbonise the industry.

Finally, as noted in our main report, 3 the dynamics of transition will necessarily reflect some of the inherent dynamics of the steel sector. The up-front investments required are large and the infrastructure and capital required are long-lived (40-60 years). There is strong industrial lock-in to traditional coal-based technologies. The low-carbon technologies as indicated are only just emerging, at the scale of demonstration plants: they lack both an established market, and for key pathways (notably, hydrogen) essential inputs are currently high-cost, combined with inadequate infrastructure.

Given this, the transition to low-carbon steel may be substantially harder and slower than that for electric vehicles, and require a different set of policy interventions, while different issues might feature in a 'Risk-Opportunity Assessment'. It is, however, amenable to exploration with similar ROA-compatible modelling approaches, and the rest of this paper outlines our study using the same modelling family.

Modelling the transition

The simulations were performed using FTT:Steel, an ROA-compatible model which combines technology learning-and-adoption dynamics with a macroeconomic framework (see box next page).

[4] See Jörn C. Richstein, Mats Kröger, Karsten Neuhoff, Olga Chiappinelli, and Frederik Lettow (2021), *Carbon Contracts for Difference - An assessment of selected socioeconomic impacts for Germany,* https://climatestrategies.org/wp-content/uploads/2021/04/CFM-Traction-Germany_FINAL.pdf

The Future Technology Transformations (FTT) Model for Steel

The 'Future Technology Transformations' (FTT) family of technology models aims at projecting, through simulation, the technology composition of certain chosen sectors that contribute significantly to CO2 emissions worldwide. The technology models are linked to E3ME, a macro-econometric model (Mercure, et al., 2019), which dynamically estimates trends in the rest of the economy. E3ME covers the globe in 70 regions and subdivides the economy into 70 sectors for European countries and 44 sectors for non-European countries.

The models are based on a similar and comparable time step simulation framework that seeks to reproduce the observed S-shaped diffusion curve of technologies. FTT models exist for power generation (Mercure, 2012; Mercure, et al., 2014), road transport (Mercure, Lam, Billington, & Pollitt, 2018; Lam & Mercure, 2021), heat (Knobloch, Pollitt, Chewpreecha, Daioglou, & Mercure, 2018; Knobloch, et al., 2020) and steelmaking (Vercoulen, et al., 2020). They involve all major low and high-carbon technologies in use in their respective sectors, together covering 88 technologies.

FTT models assume that each year or quarter, a new tranche of technology units enter the fleet (whether cars, power plants, etc) and statistically lives for a duration determined by a survival likelihood. The technology composition of the new tranche of units is determined by choices of heterogenous agents with different expectations, different valuation of the future, and facing different local conditions (e.g. distance from supply chains). For example, steelmaking processes in early phases of diffusion are considered by few agents, as risk aversion is dominant at that stage. At the same time, only few engineering companies will possess the know-how with respect to such novel processes. The more technologies diffuse, the more they become available to agents, in a positive feedback. The learning-by-doing curve reinforces this effect, where with growing sales volumes, the costs of new technologies also come down.

Steel demand is derived from the economy module of E3ME, while FTT:Steel feeds back investments in new capacity, energy use, employment, steel prices and emissions. The model follows a path-dependent evolutionary approach to simulate technological diffusion. It dynamically estimates investor preferences by considering levelised cost differentials between technology options, which incorporates the effects of certain policies such as subsidies and taxes, as well as learning-by-doing effects. Levelised cost estimates vary according to local conditions, with differences in perceptions of costs to mimic the heterogenous character of investors and imperfect foresight. Once vintage capital approaches its end-of-life, investors will decide what technology to apply to fill the gap. FTT:Steel also considers premature scrappage of existing capital. Premature scrappage is only considered if the payback costs of an alternative technology are lower than the marginal costs of the existing technology.

The result of this model is an ever-changing technology composition, with new units entering the fleets and old units scrapped, as costs and preferences evolve. Policy instruments can either influence costs or what can be or is being sold. They can accelerate the observed changes or alter the direction of evolution of the model.

The role of different types of policy

Using the model (E3ME-FTT:Steel), the case study modelled the impact of a range of different policies on technological diffusion, focused particularly on the three major emerging economics of core focus in the EEIST programme. We group policies into two main types:

1. 'Carrot' policies involve ways of directly reducing the cost of clean steel technologies, or enhancing demand for 'green steel'.
2. 'Stick' policies are those which in one way or another raise the cost of traditional, carbon-intensive steel production, or constrain its output.

The 'carrot' policy package includes:

- Upfront subsidies on capital, starting in 2021:
  - 25% on CCS applications
  - 50% on hydrogen-based steelmaking and scrap recycling
- Subsidies on low-carbon energy carriers, starting in 2021:
  - 25% on electricity, charcoal and biogas
  - 75% on hydrogen
- Government procurement, starting in 2025:
  - Hydrogen-based steelmaking capacity addition, translating to 0.005% per annum

The 'stick' policy package includes:

- Carbon tax, starting at €50 per tonne CO2, gradually growing to €298 per tonne CO2in 2045, and levels off afterwards.
- Phase-out regulations on carbon-intensive technologies that prevent the uptake of new plants, starting in 2021.
- Energy tax, starting in 2021, of 25% on coal and gas.

Whereas the carrot package induces public costs because of funding for subsidies, the stick package generates public revenues. The net number leads to changes in fiscal policies to maintain neutrality of government revenues. This revenue rebalancing scheme affects consumption and therefore has a (modest) impact on steel demand, to which the steel sector responds.

Results and conclusions

The benefit of FTT:Steel is the ability to simulate policies such as the carrot and stick packages. Simulated policies either affect the perceived levelised costs (e.g. subsidies and taxes) or interfere with the competition dynamic (e.g. phase-out regulations, government procurement programme), while decision-making simultaneously responds to external effects, such as changing global scrap supply, demand for steel, or energy prices. On the former, FTT:Steel tracks scrap availability by tracking historic production with assumed product splits and related lifetimes (following Pauliuk et al., (2013)). On the latter, fossil fuel prices follow from a cost-supply curve approach (Mercure & Salas, 2013); electricity prices follow from FTT:Power (Mercure, FTT:Power : A global model of the power sector with induced technological change and natural resource depletion, 2012); but our analysis tools lack treatment of hydrogen prices.

At this stage, large uncertainties exist on both the hydrogen supply and demand side. Our main report3 presented results if green hydrogen prices could reach cost parity with blue or grey hydrogen within the timeframe relevant to the large-scale take-up of hydrogen-based steelmaking. Here, a sensitivity is added to explore diffusion pathways in an environment with much higher hydrogen prices, to represent scenarios with a much more pessimistic view of developments in hydrogen supply. In these sensitivity scenarios, the hydrogen price starts at €6,000/t H2 and drops to around €3,000/t H2, making the price much higher than present day prices of hydrogen from fossil fuel (around 2,000 €/t H2.).

Hydrogen prices play a big role in the potential uptake of hydrogen-based steelmaking. The levelised cost metric used to model technological competition shows that under the higher hydrogen price assumptions (approximating today's cost of green hydrogen), hydrogen-based steelmaking is far above other technologies (Figure 1).

However, considering the economic environment in each of the countries, a greater relative difference in costs is noted in China and India between the hydrogen- and fossil-based process, compared to Brazil. Assuming lower hydrogen prices (in line with fossil-based hydrogen prices), cost difference is small in the Brazilian context. The carrot policies significantly lower the cost of hydrogen-based steelmaking. Cost parity between the hydrogen-based and the blast furnace process is achieved regardless of what the hydrogen price is. Though, in China – under higher hydrogen price assumptions – it is not immediate upon implementation; the crossover point is expected in 2030. Stick policies increase the cost of the blast furnace process. When applied, cost parity is achieved if lower hydrogen prices prevail. The timing differs per country. In China the crossover occurs in 2030 and in India around 2032, while in Brazil it is immediate. Cost parity is not achieved when higher hydrogen prices prevail, apart from Brazil. Combining the carrot and stick policies will both decrease costs for the hydrogen-based process and increase the cost for the blast furnace process. It leads to the largest differences in favour of the hydrogen-based process, which will increase the likelihood of investors choosing to invest in it.

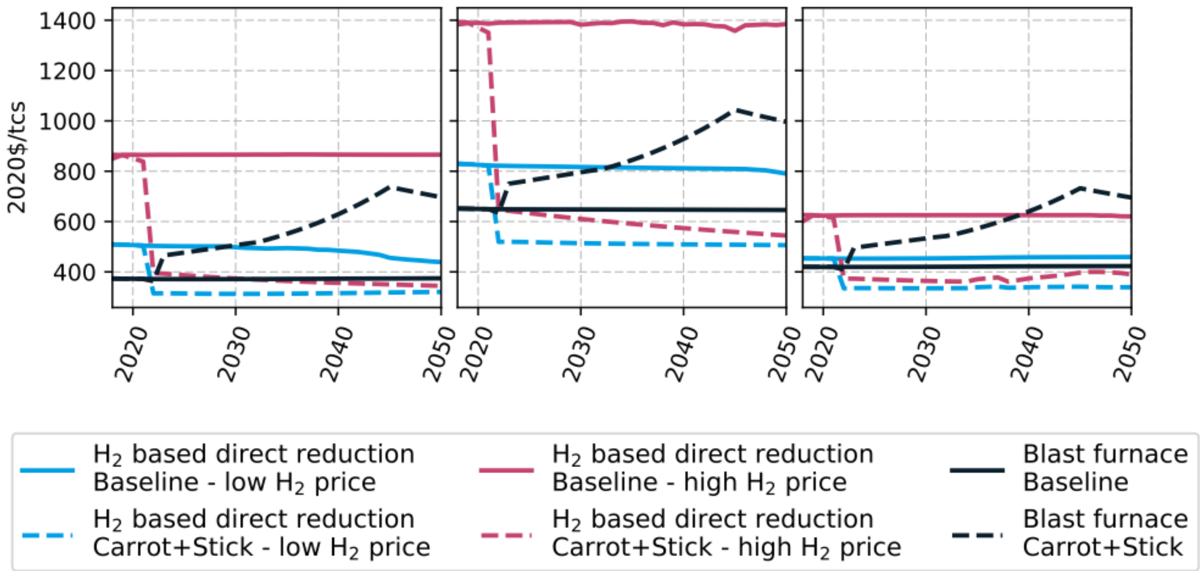

Figure 1: Estimated levelised break-even prices for the BF-BOF route and the DR-EAF (H2) route in different scenarios and in each of the regions of interest. The estimates include all cost components with endogenous learning effects and policy effects (i.e. subsidies on upfront investment, subsidies/taxes on specific energy carriers, and carbon taxes).

Turning to the dynamics of how these systems evolve, the effects of policies on perceived costs by investors naturally significantly influence investments and the consequent adoption of low-carbon steel. Figure 2 shows the evolution of steel production in the three countries for different combinations of the policy packages:

- **First column:** Shows how technologies diffuse under baseline conditions when neither carrot nor stick policies are applied. These scenarios represent business-as-usual. Hydrogen-based steelmaking does not diffuse into the steelmaking systems in China, India or Brazil. Steelmaking incorporating the blast furnace process will remain dominant in China and Brazil. However, a portion of blast furnaces employed in Brazil rely on charcoal inputs rather than coal. In India, we note a shift from the blast furnace process to the coal-based direct reduction process.

- **Second column:** Shows how a carbon price might affect technology diffusion. In each country we see a greater uptake of the recycling process at the expense of the blast furnace process. In addition, CCS is applied to many blast furnaces (not shown in figure 2), contributing to the decrease of the average emission intensity. However, solely implementing a carbon tax will not promote low-carbon alternatives such as hydrogen-based steelmaking. While considerable emission reductions can be achieved, it remains far from deep decarbonisation.

- **Third column:** Shows the effect of the carrot policies when the steel industry faces lower hydrogen prices (in line with fossil-based prices). Hydrogen-based steelmaking now manages to diffuse into the respective systems. In China and India, it mainly replaces blast furnaces, but in Brazil it also replaces some of the recycling capacity. While the system has been successfully seeded with low-carbon alternatives, the lack of penalties on carbon-intensive processes does not incentivise investors enough to move away on a large scale. The average emission intensity of the whole industry decreases by comparable levels to the previous scenario.

- **Fourth column:** Shows the effect of carrot policies when the steel industry faces higher hydrogen prices. It halves the diffusion of the hydrogen-based process compared to the scenarios where low hydrogen prices prevail. Instead, slightly more CCS is incorporated within carbon-based steelmaking processes.

- **Fifth column:** Shows the combined effect of carrot and stick policies when the steel industry faces lower hydrogen prices. Because carbon-intensive processes are now penalised directly, more hydrogen-based steelmaking diffuses into the system; it has doubled compared to the scenario depicted in the third column. Each country also sees an increase of steel recycling and most of the remaining carbon-based steelmaking utilises CCS. Altogether, the combined policy package can achieve large-scale decarbonisation. The Brazilian steel industry achieves net-zero status by 2050.

- **Sixth column:** Shows the combined effect of carrot and stick policies when the steel industry faces higher hydrogen prices. The higher prices perturb diffusion of hydrogen-based steelmaking, which is approximately halved compared the low hydrogen price equivalent scenario. This leaves slightly more unmitigated carbon-based steelmaking in the system. Yet, also under these conditions, deep decarbonisation can be achieved and outperforms the scenarios that includes either the stick or carrot policy package alone.

Overall, therefore, only the combination of carrot and stick policies delivers deep decarbonisation. Under low hydrogen price assumptions, hydrogen-based steelmaking becomes the dominant primary steelmaking technology. However, higher assumed hydrogen prices greatly reduce the take-up of hydrogen-based steelmaking. Investors prefer even more the recycling option and CCS applications to incumbent processes. Yet, in China and India, hydrogen steel is still likely to grow to sizeable market shares regardless of the pessimistic view of hydrogen price developments.

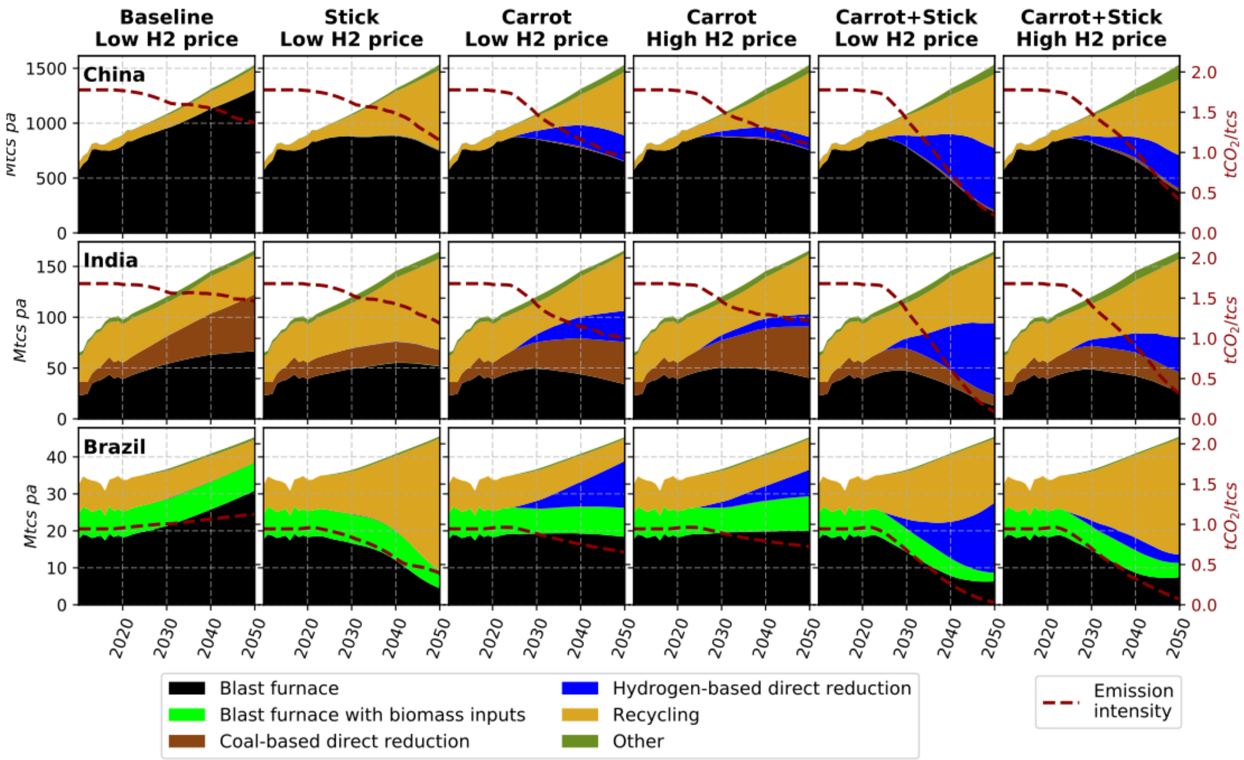

Figure 2: Steel production by distinct technology groups under different scenarios in China, India and Brazil. Numbers are in Mega tonnes of crude steel per annum (Mtcs pa) on the left axis. Average emission intensities of the whole steel sector in each region are depicted by the dashed line and relates to the right axis (in tCO2/tcs). The baseline shows likely projections of technology diffusion if current policies are continued unaltered. The 'stick' scenario shows how diffusion responds to a set of penalising policies (carbon tax and energy tax). The two 'carrot' scenarios show how diffusion responds to subsidies on low-carbon technologies and energy carriers under different hydrogen price assumptions. The latter two columns show projections of diffusion when the 'carrot' and 'stick' policies are combined, for two different hydrogen price assumptions. BF-BOF: Blast furnace coupled with basic oxygen furnace, includes several configurations (such as a CCS variant and top-gas recycling; BF-BOF (bio): A bio-based configuration that has been pulled out of the BF-BOF main group; DR-EAF (gas): gas-based direct reduction coupled with electric arc furnace; DR-EAF (coal): coal-based direct reduction; DR-EAF (H2): hydrogen-based direct reduction; SR-BOF: smelt reduction coupled with basic oxygen furnace; SR-BOF (adv): advanced form of the preceding; Recycling: scrap recycling in electric arc furnace; Other: Remaining technologies.

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EEIST

Economics of Energy Innovation and System Transition

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change. By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

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