Net Zero Steel

GLOBAL FACILITY LEVEL NET-ZERO STEEL PATHWAYS

TECHNICAL REPORT ON THE FIRST SCENARIOS 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 Energy 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.

The views expressed in this report do not necessarily reflect the views of any government or those of the institutions of the different authors.

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EXECUTIVE SUMMARY

Net-zero steel production by 2050 is possible by several different means, but we must act soon to make it possible. To provide practical visions of how this might happen, this project develops several spatially explicit, facility level pathways to net-zero global steel production by 2050. Its purpose is to understand the granular impacts on facilities and countries, including what infrastructure and policies are necessary.

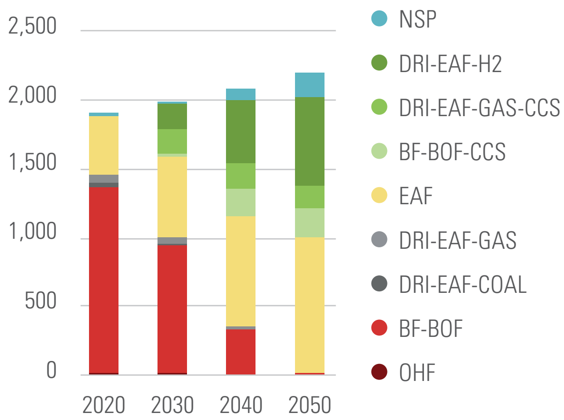
Our pathways start with a database of existing steel facilities worldwide, defined by location, technology, capacity, production, energy consumption and GHG emissions. The Global Energy Monitor (GEM) database, which identifies 622 facilities above 1 Mt per year capacity in 67 countries, is the starting 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 14% of global production that is not identified in GEM. While total global 2019 production is identified at 835 technology specific facilities in 94 countries, our scenario projections seed future production in an additional 39 countries based on scrap availability and national steel demand. The 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) that include indirect off-site heat and electricity purchases and scope 3 intermediate input emissions. A core assumption of our scenarios is there is also policy to drive utility electricity emissions to near zero. Future steel demand is driven by three scenarios where demand in all countries converge to 200, 250 and 300 kg per capita in 2080, based on current global average demand of 222 kg per capita (the US is 290 today, China 630, India 75, UK 150). Steel production is 1.9 Gt per year today, and 1.9, 2.2 and 2.5 Gt per year by 2050 in our scenarios. Scrap steel availability is based on global and regional forecasts, with scrap electric arc furnace (EAF) production increasing from 0.42 in 2019 to ~1.0 Gt in 2050.

To simulate pathways the model tracks furnace relining dates and replaces the core reduction and smelting processes with clean options based on geographic feasibility and political preferences. At 25 years a furnace relining is required, and the model is presented with several geographically and political preference-based options. The model meets the demand forecast in the following order: 1) add scrap EAF if there is incremental scrap available; 2) retrofit coal blast furnaces (BF-BOFs) and direct reduced iron EAF facilities within prescribed distances to CO_2 reservoirs for post combustion carbon capture – scenarios with access to 100km , 200km and 300km of CO_2 pipelines or other transport are considered; 3) consider whether there is low cost clean electricity to make electrolytic hydrogen for hydrogen DRI-EAF, and 4) if none of the previous options apply either a new non-spatially allocated facility is built or green iron or steel is imported. The central scenario (medium demand, <=200 km pipeline CCS) forecasts that by 2050 46% of production is from scrap EAF, 29% from DRI-EAF-H_2, 17% uses CCS and 8% from NSP. Emissions decline from 3.0 $GtCO_2e$ to 0.3. Most facilities can be retrofitted with low carbon processes, but about 200 Mt of new clean facilities must be built. Only one 90% mitigation primary steel technology is currently commercial (methane DRI EAF with CCS), and intensive commericialization is needed to bring hydrogen DRI (11 EU investments planned at time of writing), BF-BOFs with CCS, or alternatives to market by the very early 2030s. Costs for all primary steel decarbonization options, initially passed through to end-users using constructed public and private lead markets, are assessed to be close enough that they are not material compared to each other. Country level analysis identifies major shifts in capital investment from existing producers (e.g., China, South Korea) to new facilities in Africa and India in all scenarios. The modelling suggests CCS has limited global application without at least 200km of CO_2 transport, highlighting the need for transport infrastructure.

This project has several implications for global and national climate policy for steel use and demand:

- **Our low & medium demand and recyclable scrap forecasts require material efficiency building code, design & recyclability policies.** 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 BF-BOFs without 90% CCS can be built past 2025, and that they should be planning for near zero emissions alternatives.** 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 in the late 2020s requires a fast and effective global innovation process to commercialize green hydrogen direct reduced iron, which is underway in Europe and will likely meet the 2028 goal for several plants being operating, and BF-BOF CCS, which is arguably going too slowly to meet the 2030 goal.** This implies accelerated R&D and commercialization. Lead markets can be created with partners to build economies of scale using public and private green procurement, content regulation, supply chain branding, and limited but guaranteed pricing or output subsidies (e.g. through contracts for difference).
- If there are innovation blockages, e.g., lowering the cost of electrolyzers or getting post combustion CCS to work for BF-BOFs, **targeted innovation & early commercialization programs may be needed to identify and break commercialization blockages**, like the UK Offshore Wind Accelerator or the US ARPA-E.

Figure ES1. Medium Demand - 200 km CCS Pipeline



- Clean electricity requirements increase by 4-7 times under all 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, Canada).
- **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 are likely.**

Country data and all other products available at netzerosteel.org

INTRODUCTION

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. The Paris Agreement requires global, economy-wide emissions to fall to net-zero by 2050 –'70. Unfortunately, the history of treating steel as "hard to abate" or part of the "last 20% of emissions" has meant there is a lack of ambitious global steel decarbonization roadmaps or scenarios, and more generally a vision of how steel might be 1.5-2°C compliant without very substantial additive, verifiable, permanent and traceable natural or technological offsets which may not materialize in sufficient quantity at a reasonable cost. 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 one, are relatively spread out across an integrated facility, making CCS retrofits difficult and only maximum 50% capture possible on existing facilities (Fan and Friedmann, 2021).

The most ambitious and widely known Paris compliant scenario including iron & steel published to date is the IEA NZE scenario (International Energy Agency (IEA), 2021). It employs ~26% material efficiency gains, more secondary recycling (32% of production rising to 46%) and transformative hydrogen and CCS based production pathways to eliminate most emissions from the sector, leaving about 5% legacy unabated facilities (~150Mt) and about 70 Mt of residual post CCS emissions (the IEA NZE does not specify final 2050 emissions clearly). The IEA also does not publish national results nor detailed technological results for the NZE scenario. While there is a clear vision in the NZE of how the steel sector globally 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 near commercial low emissions steel making technologies (e.g., CCS or electrolytically based hydrogen DRI steel making) starting in the late 2020s, and no later than the early 2030s given the lifespan of steel plants. We need a detailed set of results to stimulate imagination and provoke debate, a necessary precursor for any change in policy, planning and investment.

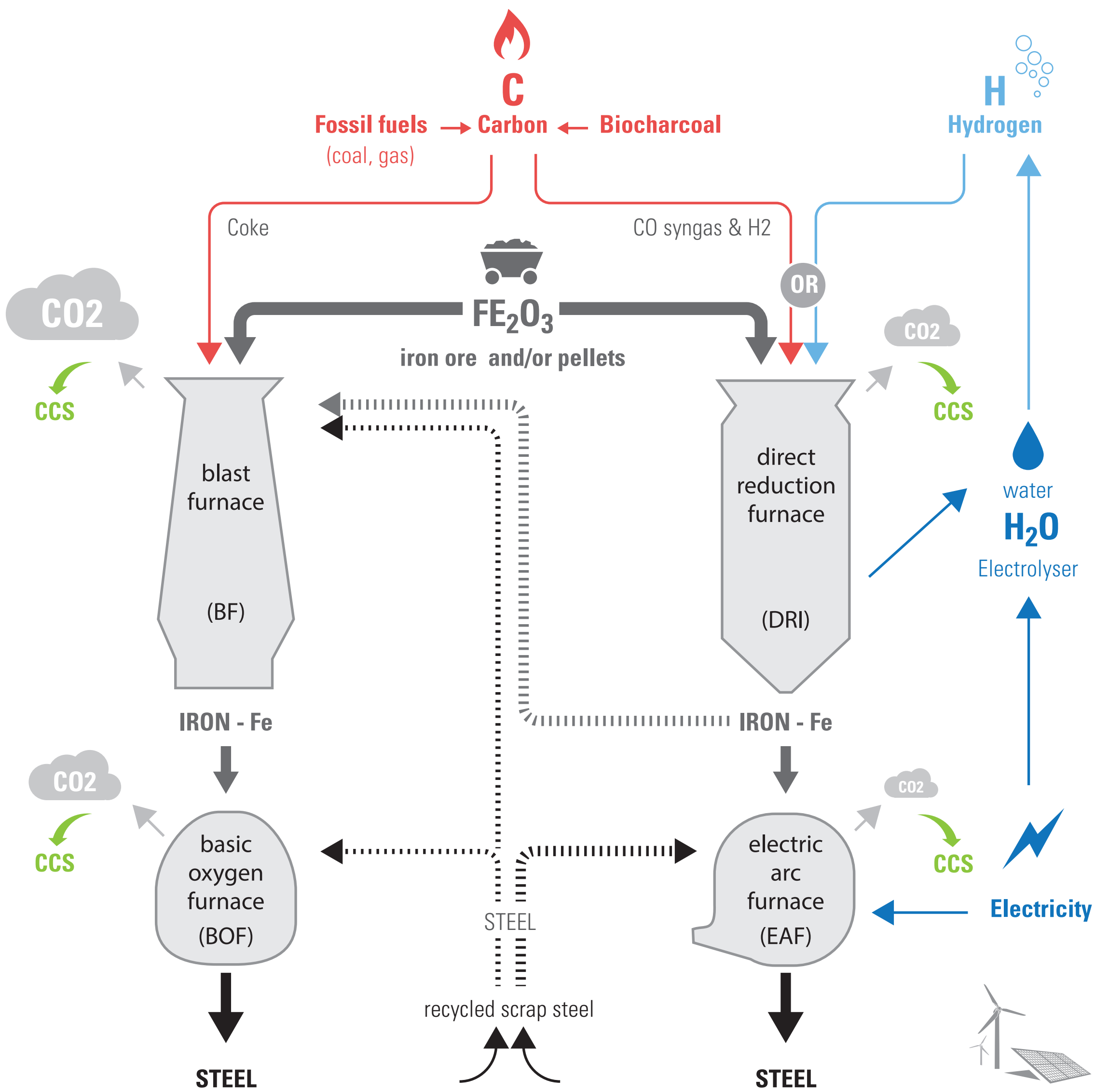
The objective of this project is to produce a simple and transparent facility level scenario (i.e., geographically explicit and based on real world steel production plants) of a global primary and secondary steel industry that goes to near zero emissions by 2050. It is meant to be highly transparent, 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. Ideally this scenario report will provide a launch vehicle for challenging the 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), 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 trauma can be minimized.

Ultimately the report and the facility level 1.5°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 encourage more ambition in their own proposals.

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 blown out using oxygen lancing and slagging agents) and mixed in the correct portions for a given end-use in a smelter. There are two main types of smelters; basic oxygen furnaces (BOFs) and electric arc furnaces (EAFs) **Figure 1**. 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

Figure 1. Carbon Pricing Groupings Operating in 2020: five programs exist, covering 78% of 2018 national emissions.



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 2**). Please note that **Figure 2** includes indirect electricity emissions, and 80% of steel finishing is electrified.

The global steel fleet of today

Most of the existing world steel production fleet is summarized in **Figure 3** and **Figure 4**. By far the largest portion of steel making is in east Asia, with 54% 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 relining in the 2020s.

Deep decarbonization options for iron and steel production

There is now a broad deep decarbonization literature on steel, including amongst others (Fan and Friedmann, 2021; Fischedick et al., 2014; IEA, 2020a, 2019a; Vogl et al., 2018a; Wang et al., 2021). At least seven main pathways having been identified, which we expand upon in short form in turn. Technology Readiness Levels (TRL), which were initially developed by NASA, have been provided. [1] TRL 9 represents a fully commercial technology ready for market uptake – 4-6 is the development, small to large prototype stage, while 7-9 is the deployment stage. The IEA uses an extended scale, where 10 is "Integration at scale needed", and 11 is "Mature, proof of stability reached".

Retrofit blast furnace basic oxygen furnace (BF-BOF) with up to 50% "end of pipe" carbon capture and storage (CCS) (TRL 5) (Fan and Friedmann, 2021). Research indicates that existing modern BF-BOFs could be retrofit for up to 50% capture.

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 cofired up to 20-30% for heat needs.

Lower demand, more 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 26% in the ETP 2020 and NZE 2021 (IEA, 2020b, 2019a; International Energy Agency (IEA), 2021).

New BF-BOFs can be built with up to 90%+ CCS, and can possibly use biomass as fuel and reductant (TRL 5) (Fan and Friedmann, 2021; IEA, 2020a). 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

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

Figure 2. Emissions by process step (Wang et al., 2021)

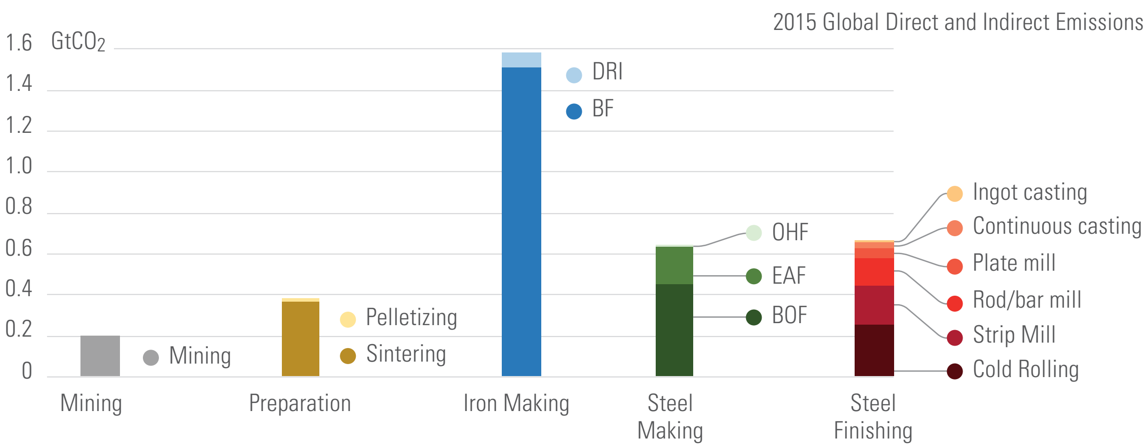


Figure 3. Global steel production by type and era of build in 2019 (GEMs Database)

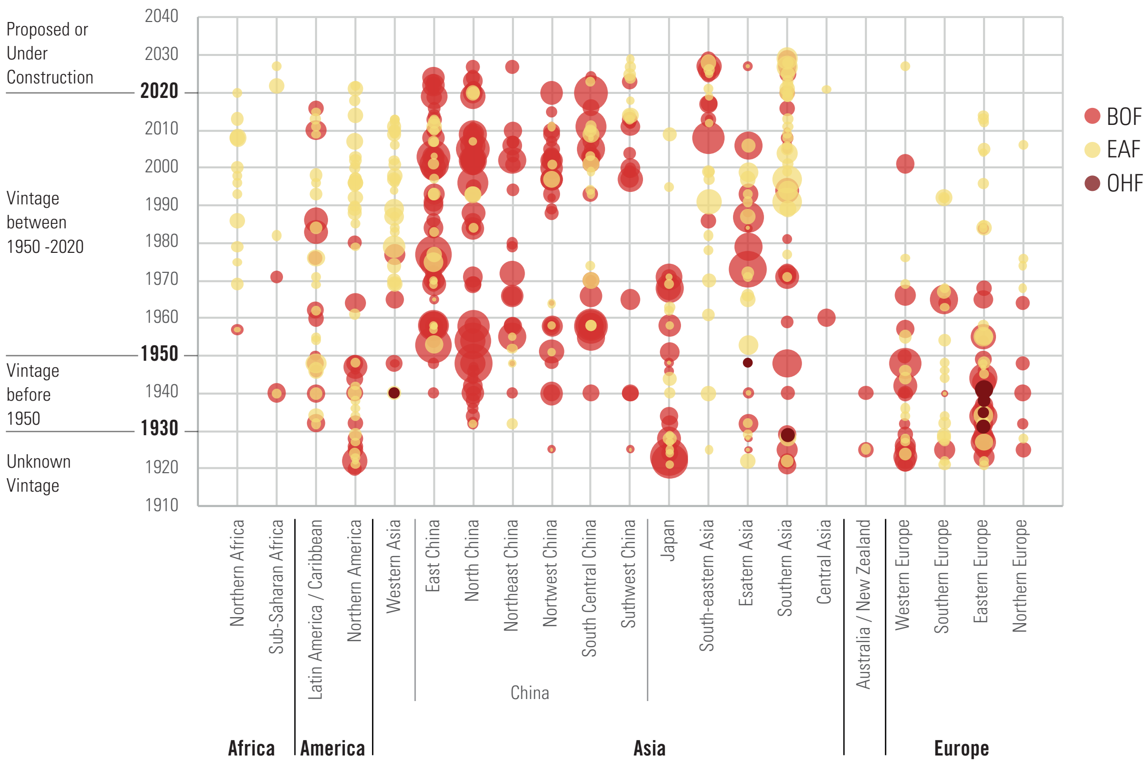
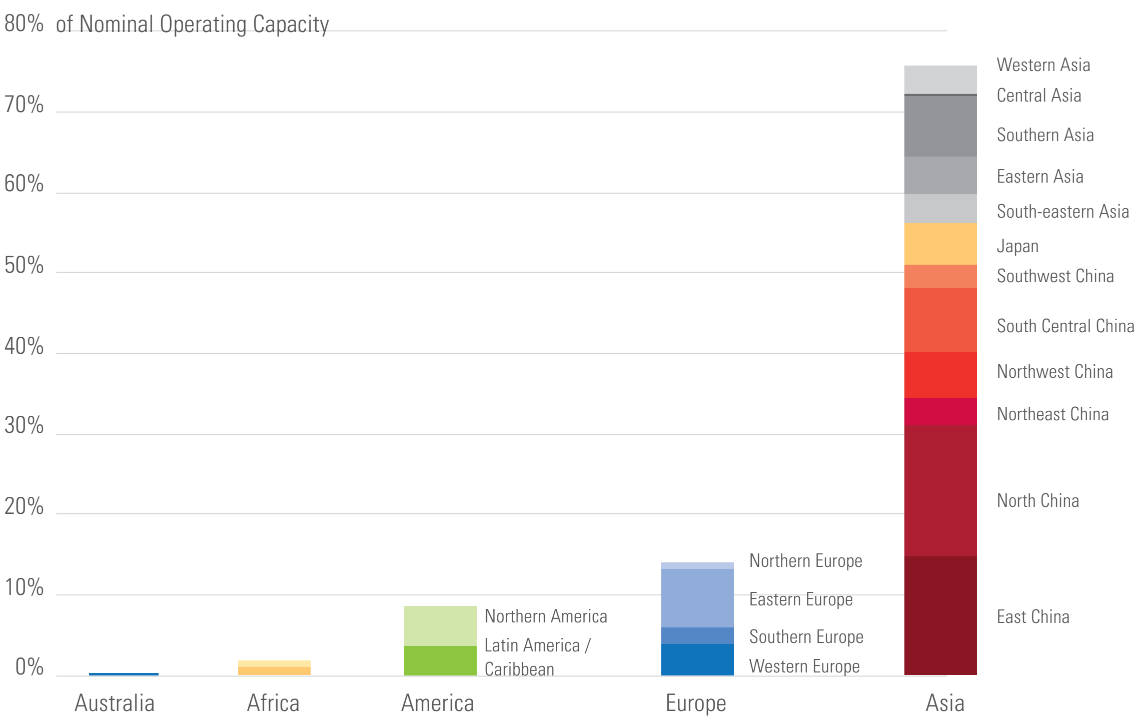


Figure 4. Where steel is produced in 2019 (GEMS Database)



atmospheric carbon in the soil (Hepburn et al., 2019) – there is a wide context dependent set of outcomes in between.

Syngas direct reduced iron DRI with CCS followed by 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 used as the reductant to strip oxygen form iron ore pellets. 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.

Green (electrolysis with clean electricity) hydrogen DRI followed by EAF (TRL 5-7+). Instead of a syngas of hydrogen and carbon monoxide, pure hydrogen is used as the reductant. A heat source is needed to drive the reaction, unlike in syngas DRIs. The reduced iron is then sent to an electric arc furnace for melting and smelting into 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 et al., 2021). The IEA previously provided a TRL of 5, but as progress is now moving very quickly in this area, we assign 7+ in our own assessment.

Aqueous/Molten oxide electrolysis (TRL 4).

Finally, a very promising but lower TRL technology is aqueous or molten oxide electrolysis. Electricity is directly used as the reductant, melting heat source, and smelter EAF.

While we suspect MOE or AOE may eventually become the most used method for making steel later this century (2060 onward), the TRL level was too low to include in our analysis. Besides the much lower TRL, there are several significant unresolved issues with this technology: three times higher peak power needs than hydrogen DRI despite better efficiency, and no reported breakthrough in anode survivability at the high temperatures MOE operates at.

Our research question

Given the existence of several possible technological pathways to very low emissions steel, but also the sector's current very high GHG intensity, what could a granular & transparent 1.5 C pathway for steel look like, given regional resource constraints and political preferences? Given the needs for net-zero emissions economy wide by 2050, and based on the general practice of assessing CCS at -90% mitigation, we set the threshold of permissible GHG intensity at a maximum 10% of current emissions. This removes a number of production pathways from further assessment. Retrofit BF-BOFs are disqualified because they are only likely to reach -50% capture, as is hydrogen co-firing of BF-BOFs, which similarly would not reduce emissions per tonne to >10% of current levels.

METHOD

Method summary

We summarize our scenario building process here; see the following methods sections for partial details. See the Methodology Appendixes for full details.

Starting with the 2019 steel production fleet we seek to answer the following questions:

1. What is projected demand through time including assumed material efficiency improvements?
2. What amount of production capacity is available before retrofitting and new build?
3. How much recyclable scrap is available? While BF-BOFs can be precharged with up to 30% scrap if available, in this analysis we denoted all new recycled steel production as passing through electric arc furnaces. We also presume that there are policies in place to drive grid electricity emissions to <50 grams CO_2 per kWh.[2]
4. Is there a preference for fully domestic production over imported reduced iron or steel? *We assume existing sites are explored first because of the presence of steel finishing, supply chains, transport infrastructure, customers, etc.*
5. What production method for needed new primary iron is to be used?
   a. Is CCS available?
      i. Is a saline aquifer or depleted oil & gas well available, and how far away? *100, 200 and 300 km distances to nearest known disposal sites were assessed*.
      ii. Are there political objections to CCS*? We assume no in all but a handful of countries (notably Germany, see Appendix), but these assumptions could be explored for specific regions at a later date.*
      iii. Has post combustion CCS been mastered for 90% capture for BF-BOFs?
         1. If no, then syngas DRI with CCS is used
         2. If yes, then BF-BOFs with CCS are used
      iv. Is excess biomass available to negative emissions? *We assume no, and this potential is not yet explored in our assessment*
   b. If CCS is unavailable, are plentiful renewables available at a reasonable cost to make electrolytic hydrogen? *We use geospatially detailed solar irradiation maps to determine this, assessed by taking sites that receive average levels above 3.5 kWh per m^2 per day. We also added a country-based assessment of excess hydropower being available, with Russia, Canada, Sweden, Brazil and Norway being initially selected.*
   c. If none of the above apply, then "Imported and/or Non-Spatially Allocated Production (Imports/NSP)") is employed. This could be new domestic or foreign new builds (as imports), or importation of green iron for use in EAFS.

Note that we have followed an a algorithmic technology section method to capture the effects of stated political preferences. Our estimates of costs show most options are roughly the same over time, with hydrogen DRI getting cheaper with falling electricity costs (from $0.06/kWh to $0.04/kWh) and BFBOFs with 90% capture CCS getting more expensive with carbon pricing. We could in the future work use a more cost based methodology if a stakeholder was interested.

Establishment of a baseline dataset of existing 2019 steel 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 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 1 Mt per year and up[3], and one from the Global Infrastructure Emissions Database (GIEDS) project[4]. We found the former clearer, more detailed, and more useful for our purpose, and GEM kindly provided us with a copy of their database (all errors of analysis remain ours). The

2 For reference, coal plants are 800-1000+ grams CO_2 per kWh, combined cycle gas plants 350-450, and single cycle gas plants 400-600.

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

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

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 methane with CCS for DRI production.

We found 2.0 Gt of crude steel capacity in 2019 in the GEM database, in 67 countries at 622 facilities. From this we estimated of 1.6 Gt of 2019 production, or 86% 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 14% of global production. In doing so we thereby found 27 additional countries (94 total) with reported production and/or capacity. We then estimated 213 additional 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 39 countries are also seeded in the model for future production based on scrap availability and national demand for steel.

Two other key databases were employed. The Oil & Gas Climate Initiative[5] was used to locate 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[6] to ascertain local solar insolation potential, as the basis for hydrogen DRI, based on research completed for (Trollip et al., 2021). We listed Brazil, Russia, Norway, Sweden, and Canada as having sufficient extra hydropower capacity to do hydrogen DRI with hydroelectricty power. Ideally in the future we will add wind availability to the assessment.

Deriving Facility Level Emissions and Production

Due to mismatches in primary data, we were unable to use the GIDS facility emissions data, and had to consider other sources. The most complete and up to date global picture of direct emissions available is from the IEA Iron and Steel Technology Roadmap (IEA, 2020a). The published emissions and emission factors for 2019 in the report 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 overall 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[7] also reports global direct emissions of 2.6 $GtCO_2e$.

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 5**). These include emissions associated with coke ovens and blast furnaces, on-site heat and electricity production, sintering and pelletization and direct reduction of iron, casting and hot and cold rolling processes. Upstream emissions are not included from the production of iron ore, processing of scrap steel off-site, and embodied emissions associated with the purchase of 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 5**). 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 5** compares different CO_2 emissions system boundaries adopted by WorldSteel, the IEA iron and steel roadmap and for the purposes of our study (direct emissions with no crediting). **Table 1** compares the total differences in energy and emissions between the system boundaries.

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

5 https://www.ogci.com/co2-storage-resource-catalogue/co2-data-download/

6 https://globalsolaratlas.info/map

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

Figure 5. Different System Boundaries for Emissions from Iron and Steel Facilities

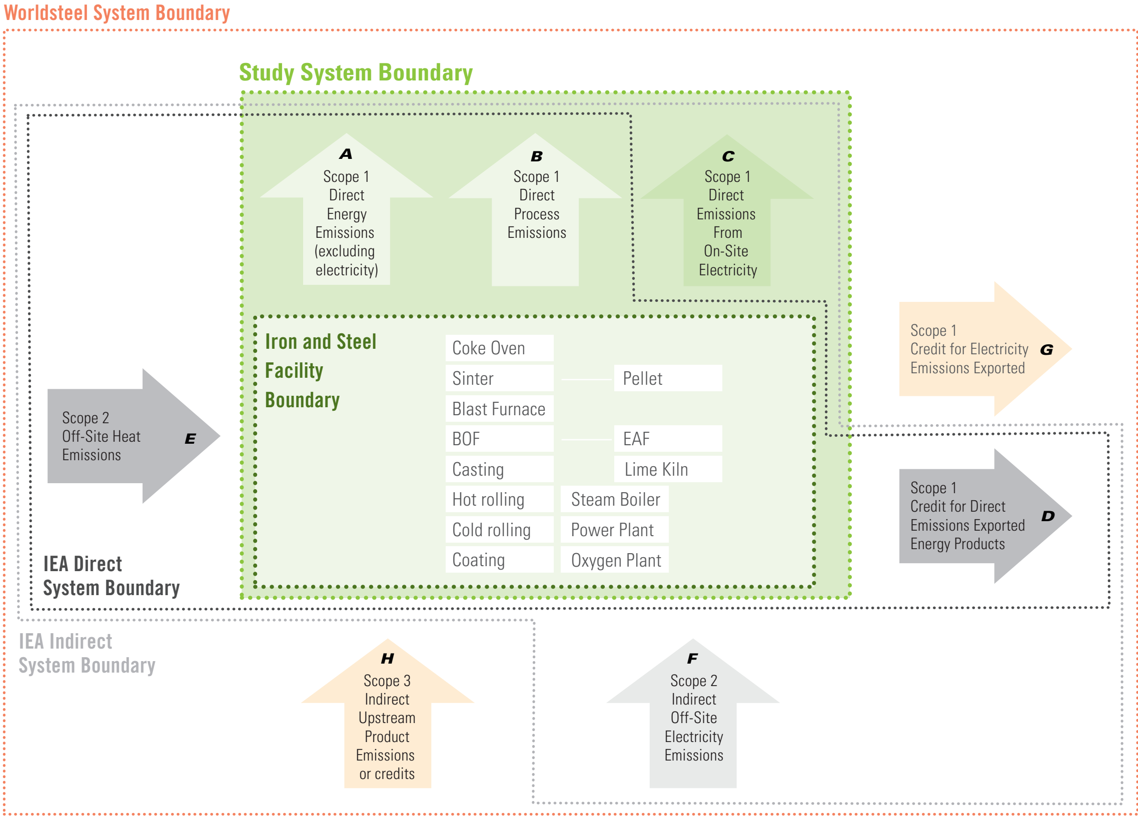


Table 1: Comparison of Energy and Emissions between IEA Roadmap, Worldsteel Association and Study System Boundaries

Source	Scope	Fuel / Process Type	Estimate of Energy Consumption (EJ)	Estimate of Emission Factor ($GtCO_2e/EJ$)	Estimate of Emissions ($GtCO_2e$)	Estimate of Emission Factor (tCO_2e/t crude steel)	Estimate of Energy Intensity (GJ/t crude steel)
IEA Roadmap	Direct	Coal	30.54	0.093	2.841	1.51	16.18
		Oil	0.45	0.0741	0.033	0.02	0.24
		Natural Gas	3.84	0.056	0.215	0.11	2.04
		Bio-energy	0.38	0	0	0	0.20
		Exported Energy	-4.94	0.093	-0.459	-0.24	-2.63
		Direct Process	-	-	-	0.10	-
		IEA Direct Sub-Total	30.28	-	2.630	1.40	16.11
	Indirect (Scope 2)	Imported Energy	0.61	0.093	0.06	0.030	0.32
		Electricity	4.50	0.139	0.62	0.333	2.39
		Indirect Energy Sub-Total	5.10	-	0.68	0.36	2.72
	Direct & Indirect (Scope 2)	TOTAL	35.39	-	3.31	1.76	18.83
Worldsteel Association	Direct	Sub-Total	-	-	2.63	1.40	-
	Indirect (Scope 2)	Sub-Total	-	-	0.62	0.33	-
	Indirect (Scope 3)	Sub-Total	-	-	0.19	0.10	-
	Direct & Indirect	TOTAL	-	-	3.44	1.83	-
Study Boundary	Direct (Including net exported energy and not including indirect emissions)	TOTAL	34.62	-	3.03	1.61	18.41

electricity is ultimately used on or off-site for industrial facilities. The selected study boundary allocates 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 blast furnace and coke oven gas has to be utilized even if there is a low carbon electricity alternative. If the electricity is exported and used in another sector, it may very well be replacing renewable electricity supply, especially given the net-zero targets of the electricity sector. Also, over time, if the BF-BOFs are replaced with DRI or molten oxide electrolysis units, there will be no off-gases available for electricity generation.

Facility energy and emission intensities are identified by considering global average emission intensities by process and technology and adjusting for the energy mix in different countries and processes indicated at the facility level in GEMs database.

Demand

We considered several different demand assessments from the established literature (Bataille, 2020), including the IEA's 2020 Energy Technology Perspectives (ETP) (IEA, 2020c) & World Energy Outlook (WEO) (IEA, 2020d), Sustainable Development Scenario (SDS) and NZE scenarios in reflection 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. Data availability for these demands on a per country basis is sparse and uncertain. Instead of adding these demands for each country in a highly uncertain way, we instead approached the problem from the perspective of long-term development convergence, at least for basic infrastructure and materials. According to WorldSteel, the current global apparent demand average is 222 kg per capita. The US & Russia are at about 300 kg per capita, and the UK at 160. We decided to set demand evolving from 2019 in convergence toward common global demands of 200, 250 and 300 kg per capita by 2080. 250 kg per capita puts our 2050 forecast on a schedule just a bit higher than the IEA NZE schedule,

Figure 6. Convergence of apparent demand 250 kg per capita in 2080

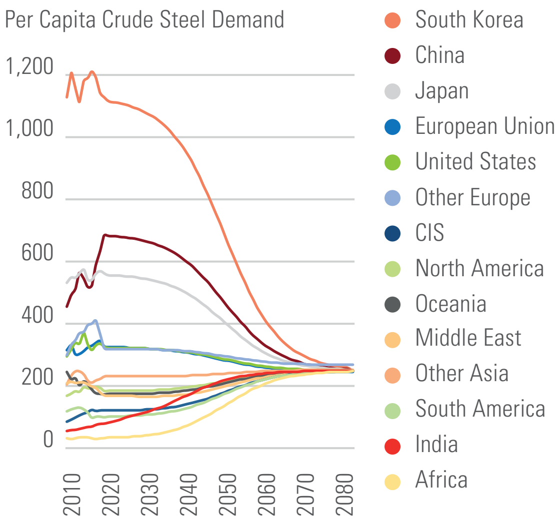


Table 2 Comparison of different Prompt and End-of-Life Scrap Steel Forecasts - forecasts may have different levels of production in 2050

Scenario	Prompt and EOL Scrap Recycled in Steel Production	2015	2020	2050
IEA Net Zero	Mt (Prompt and EOL)	-	608	1,012
	% of Crude Steel Production	-	32%	46%
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%

so we have bracketed the NZE forecast with our scenarios. A sigmoid "S" function was used to capture the fall in infrastructure demand in countries that have already built much of their energy, transport, water and sanitary infrastructure, and the rise in demand from countries still building it. The one country for which this generated surprising results was the UK, with just short of a doubling in demand occurring over the model time horizon, but this can be partially justified by the UK deep sea renewable energy buildout, which will require significant amounts of steel. 2050 has been marked with a dashed line; the larger market shares of South Korea, Japan and China are still evident.

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

Recycling Levels

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. 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 steel production (255 Mt in 2019) but is expected to fall as more efficient secondary manufacturing techniques are put in place to reduce prompt scrap. End of life scrap is today about 445 Mt, or about 24% of total steel production.

To determine the level of recycled scrap steel available for EAFs we track prompt and end-of-life scrap (700 Mt or 37% of total steel production in 2019). 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 630 Mt or 33% of crude steel production is estimated to be used in steel mill EAFs. This value is very close to the equivalent estimate of 32% that IEA NZE scenario uses for steel mill EAFs in 2020.

Global recycling rates are quite high, with approximately 85% of end-of-life steel collected for recycling, yet variable by type (high for appliances, vehicles, structural steel) and lower for packaging and rebar. 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[8].

For a country level perspective of recycled steel, the Bureau of International Recycling publishes some country stats. Regional forecasts are also available from Xylia et al. (Xylia et al., 2018) and Wang et al. (Wang et al., 2021). In the end we used an availability of 1.2 Gt by 2050, with 83% use, allocated by nation as per our sources.

A transparent, algorithmic turnover of steel facilities to low emissions

Based on estimates of facilities' functional age since last build or last retrofit, each facility is retrofit at the 25 year mark as resources and regional politics allow as per **Figure 7**. The basic presumption in this version of the model is that CCS (where available) is preferable due to perceived short term cost, and BF-BOFs with CCS are preferable to syngas DRI EAFS because of familiarity of the industry with the BF-BOF technology and its current ubiquity. Interestingly, our results show that despite this slanted preference order, hydrogen DRI EAFs always get built in significant quantities.

1. Is CCS available?
   a. Is a saline aquifer or depleted oil & gas well available, and how far away? *100, 200 and 30 km distances to nearest known disposal sites were assessed.*
   b. Are there political objections to CCS*? Are there political objections to CCS? We assume no in all but a handful of countries (notably Germany, see Appendix). Germany was set as likely to objecting to large-scale deployment of CCS technologies based on the political environment over the last decade, but this could change.*
   c. Is there a preference for retaining BF-BOFs, & has post combustion CCS been mastered for 90% capture on BF-BOFs? *We assume yes to preference for BF-BOFs based on deep knowledge of the technology, but if not, then syngas DRI EAFs with CCS are used. If yes, then BF-BOFs with CCS are used.*
   d. Is excess biomass available to negative emissions? *We assume no, and this is not yet explored in our assessment.*

8 https://corporate.arcelormittal.com/media/press-releases/arcelormittal-publishes-first-climate-action-report

2. If CCS is unavailable, are plentiful renewables available at a reasonable cost to make electrolytic hydrogen? We use geospatially detailed solar irradiation maps to determine this, assessed by taking sites that receive average levels above 3.5 kWh per m^2 per day. We also added a country-based assessment of excess hydropower being available, with Russia, Canada, Sweden, Brazil and Norway being initially selected.
3. If none of the above apply, then Imported and/or "Non spatially allocated production" (NSP) is employed. This could be new domestic builds at unknown sites, foreign new builds as imports, or importation of green iron, perhaps made in Australia, South Africa, Brazil or other iron ore bearing region with strong solar insolation for electrolytic hydrogen for use in EAFs (Trollip et al., 2021).

From a short term cumulative emissions point of view, BF-BOF scrap loads could be maximized with up to 30% green iron as it became available (e.g., in 2030-'35), and up to 25% hydrogen co-fired if available[9], but because this could lead to emissions lock-in we have not included these options.

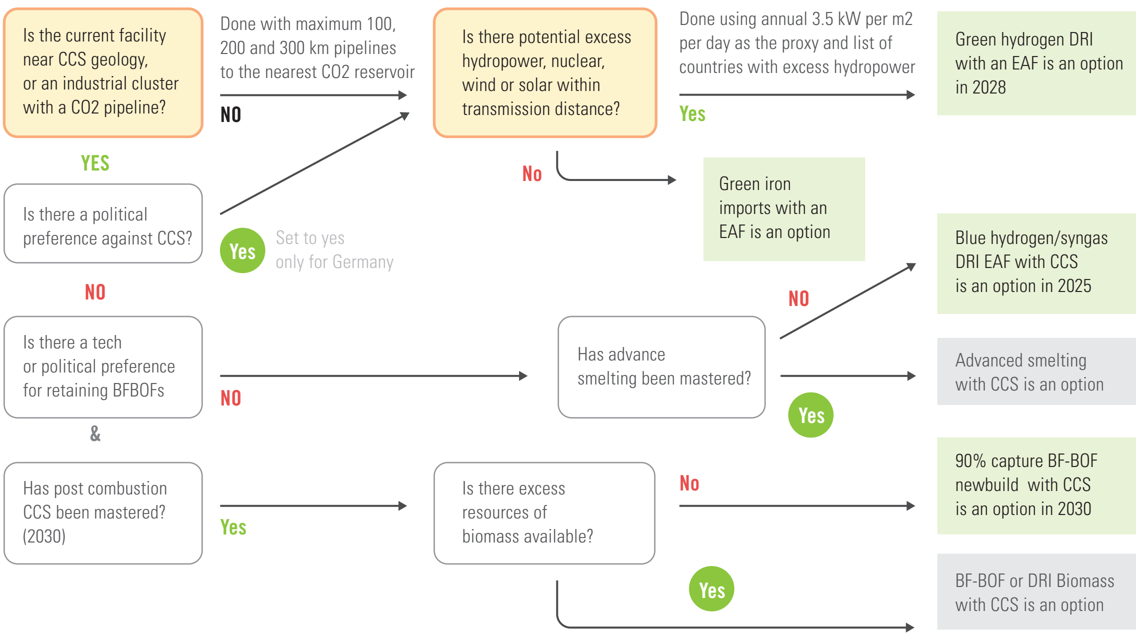
9 Thyssen Krupp is running tests to see by how much they can replace coal with hydrogen in a blast furnace run. There are physical limits based on the integrity of the iron ore and coke stack. Up to 40% co-firing for heat & reduction has been postulated by TK.

Production and Investment Cost Projections

For each scenario, the model projects the capacity installed and production of existing and new iron and steel facilities from 2020 to 2050. This projection of annual production and installed capacity for different iron and steel technologies can be linked to unit production OPEX costs and CAPEX costs related to capacity. In order to develop CAPEX and OPEX costs, a broad literature search was conducted. Fischedick et al (2014), Mayer et al. (2018) and Vogl et al. (2018) provide a detailed analysis of the near zero emission iron and steel technologies, particularly the DRI-EAF-H_2 route that is prominent in our model. Production costs of the main existing technologies (i.e., BF-BOF, EAF and DRI-EAF-NG) are summarized by (Medarac, H., Moya, J.A. and Somers, 2020; Van Ruijven et al., 2016) for large producing countries and on a global scale by the IEA in their Iron and Steel Roadmap (IEA, 2020a). Additional cost information for CCS retrofit of existing plants was gathered from a European Parliamentary research study (European Parliamentary Research Service, 2021).

While our costing analysis considers how technology costs may evolve for new low carbon technologies,

Figure 7. Process allocation mechanism

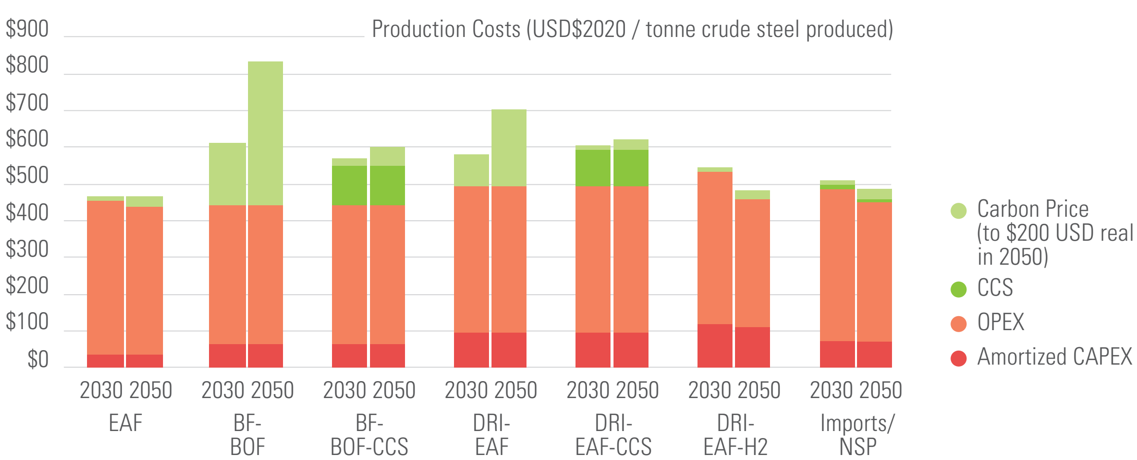


the analysis does not consider how market prices for OPEX costs (e.g., energy, raw materials, labour) are likely to change in time. The modelling also does not have the ability to consider feedback effects such as substitution since demand, production and many input prices are fixed in the model. Regional and national market price differences are also not considered in the model, but could be considered in future analysis.

The large exception to not considering changes in OPEX costs is electricity costs. Electricity is a large input cost for both EAF and DRI-EAF-H_2 (green). In this case we consider both declining grid electricity costs and on-site electricity production costs for green H_2 production. The global assumption is hydrogen electrolyser CAPEX costs fall by 2% per year (47% reduction by 2050), while the cost of electricity supply for for H_2 productionbased on dedicated on-site or directly wheeled generation facilities, fall linearly from an average of $60/MWh to $15/MWh in 2050 (75% reduction by 2050).

The average global unit production costs in 2030 and 2050 for the different technologies in the model are summarized in **Figure 8**. The costs are expressed in constant USD$2020 for every tonne of steel produced. Costs are divided between CAPEX, OPEX, CCS retrofit costs (both CAPEX and OPEX). A carbon price cost, which can be representative of a wide range of regulatory costs & constraints, is also added to each technology based on the fleet average direct facility emissions in the given year. The carbon price is assumed to rise linearly from $20 2020 USD in 2019 to $200 in 2050, the middle of the range at which DAC CCS is assumed to be a cost competitive offset. DRI with CCS is made available in 2025 – it's commercial today, and it takes several years to plan and build a steel plant. Post-combustion CCS for BF-BOFs is assumed to be available in 2030 after a period of intense piloting and commercialization. Technology CAPEX and OPEX costs in time are fixed and are representative of expected mature technology costs in 2030. While some improvement in average costs may be expected between 2030 and 2050 this cost trajectory is uncertain especially since siting of new CCS facilities may involve additional cost adders related to the increased distance to reservoirs. Typically, the largest unmodelled or unmodellable costs (costs that you know exist but cannot often find useful data to base them on) are: 1) land prices or the costs of obtaining easement waivers to build the infrastructure, and 2) variation in engineering costs due to things associated with drilling and blasting through terrain like differences in geology or topography. NSP represents non-spatially allocated and non-technology specified low carbon production. NSP could represent any combination of green DRI & EAF, BF-BOF-CCS, DRI-EAF-CCS, DRI-EAF-H_2 or another un-modelled low carbon production technology. For the purposes of estimating costs we assume a cost profile that relates to 50% EAF, 40% DRI-EAF-H_2, 5% BF-BOF-CCS and 5% DRI-EAF-CCS technologies, generally representative of the mix in low carbon technologies in 2050 in our modelling scenarios.

Figure 8. Illustration of GHG emission level



RESULTS & DISCUSSION

Our first result, key to all others, is that convergence to 200, 250 and 300 kg per capita steel us in 2080 and a global population of 9.7 billion by 2050 leads to 1.9, 2.2 and 2.5 Gt of steel being produced in 2050. In other words, steel production is likely to be stable or rise. Within this context, we use **Figure 9**, which compares the medium demand scenario with 100, 200 and 300km of CO_2 transport being available, to illustrate several important results.

A doubling of recycled steel making underlays all scenarios

Recycled steel making more than doubles in size in all cases, capturing at least half the global market, compared to 26% today, and possibly more (see later discussion on "Imports and/or Non spatially allocated Low Carbon Production" (Imports/NSP). Most recycling is done using electric arc furnaces with some fossil fuel preheating to save currently more expensive electricity. If the electricity source is decarbonized and the preheaters are electrified or removed the recycled steel can easily have emissions less than 100 kg per tonne steel, one twentieth the emissions of blast furnaces.

Recycled steel requires scrap, however, and the speed with which it can grow, and what it can be used for, is determined by the quantity and quality of scrap available. Our results are predicated on about 1.2 Gt a year of total scrap being made available by 2050, 1.0 Gt of that being usable for steel products. This requires establishing a collection network, and that the decommissioning of buildings, infrastructure, machinery and vehicles is performed in a manner that maximizes the extraction of recyclable steel. If contaminants, and especially copper from electrical wiring, rise to a sufficient point in the scrap supply, then thin sheet metal and eventually steel flats can no longer be made from the scrap. In the worst cases, a recycled steel mix with a high proportion of contaminants can only be used for reinforcement bar in concrete. To dilute the copper levels and generally control the contamination level in recycled steel, direct reduced iron is already being added in the US to make premium steel products (Tolomeo et al., 2019).

Access to CO_2 pipelines or other transport is critical to CCS market share

One of the key outcomes of the project is the criticality of CO_2 transport for CCS uptake. If infrastructure is limited to a maximum distance of only 100km from the existing steel sites, then very little is built globally. Many existing facilities, their supply chains and markets are simply not located where the geological disposal potential is. If 200 or 300 km of transport is allowed, ideally by pipeline for cost per tonne moved and reliability, then initially CCS takes most new market share, and then about 50-65% by 2050.

While pipelines are the by far the cheapest and most robust means to transport CO_2, they require right-of-way, which may not be forthcoming. Rail cars, trucks or shipping could also be used to move CO_2, but the sustainability of this depends highly on the means of transport and its leakage security.

The furnace relining schedule for plants is critical – with a 25 year cycle net zero by 2050 is possible, with 40 it isn't

Based on the IEA Net Zero Scenario (2021) and IEA ETP (2020) we have used 25 years as the time between furnace relinings. Based on combining information from the GEM database, World Steel, and OECD on facility lives and the 25 year cycle, many Asian facilities are coming to their furnace relining dates in the 2025-, medium

Figure 10. Medium demand and 200km of CO2 pipeline with a 40 year furnace relining cycle

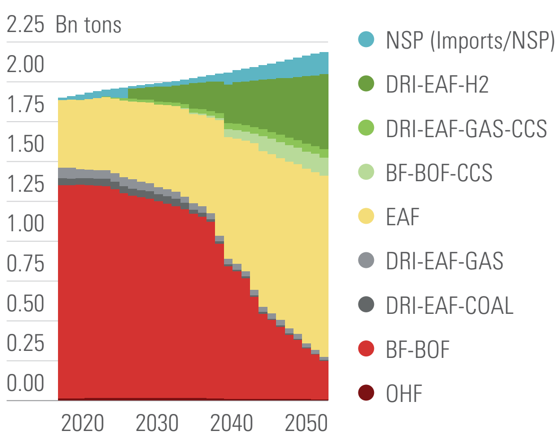
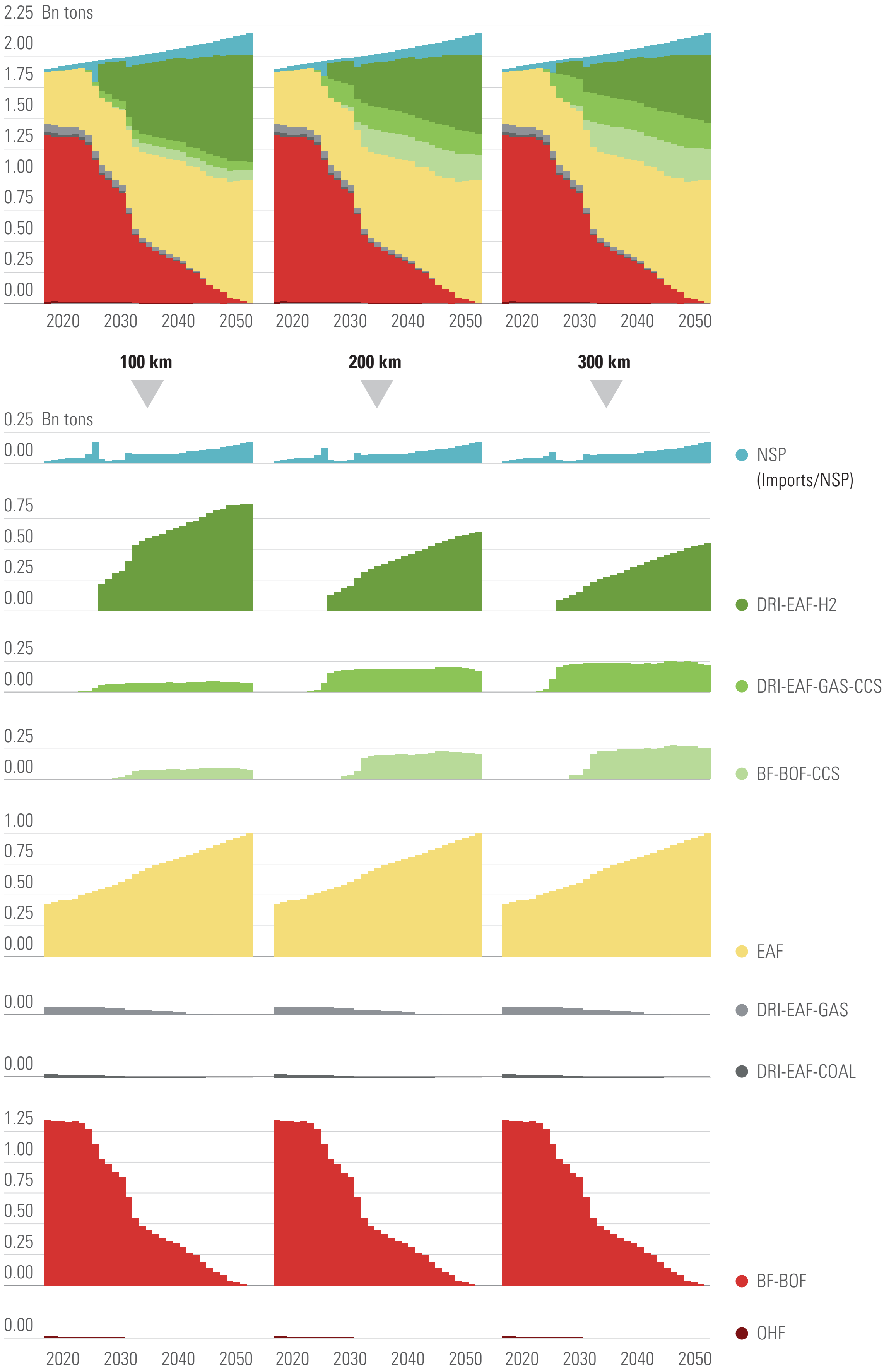


Figure 9. Comparison of global results at 100, 200 and 200 km of CO2 pipelines being available

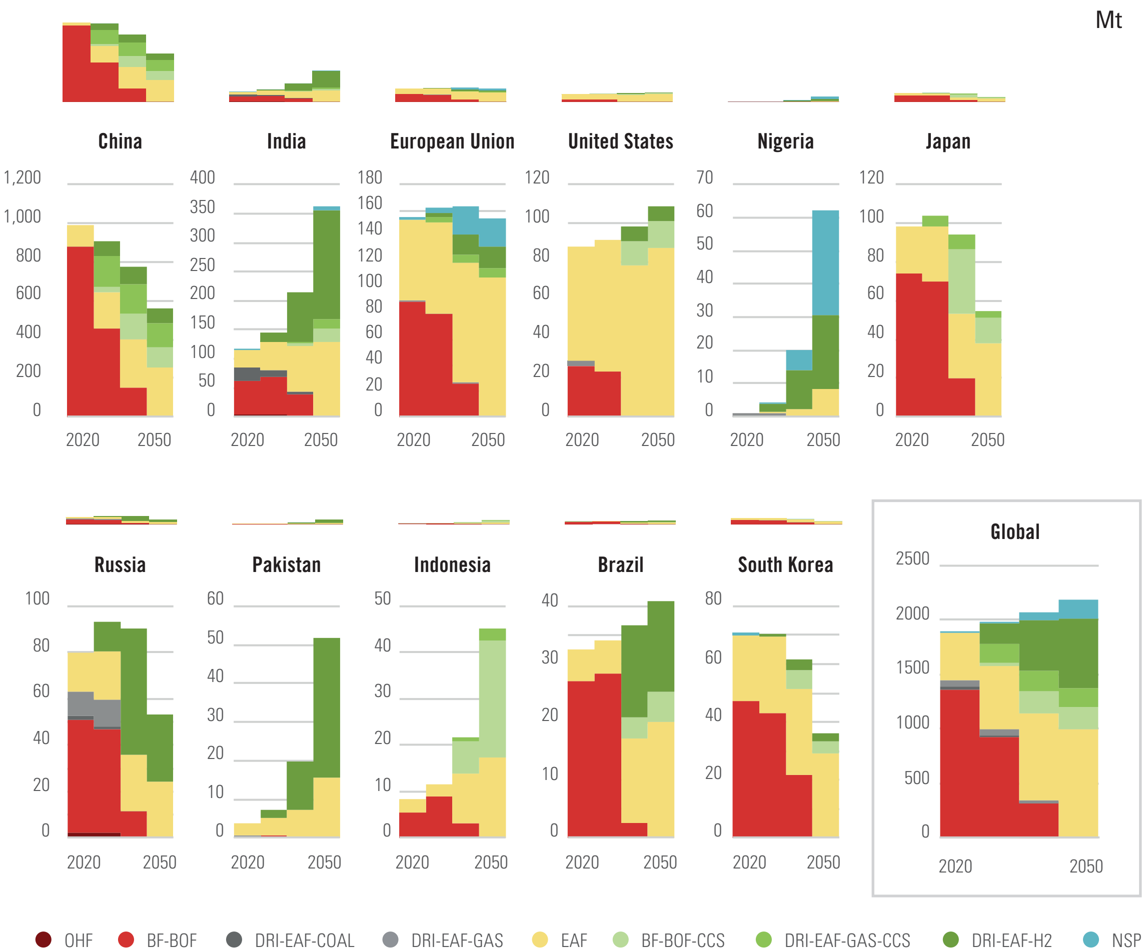


demand2035 period, when the core process equipment must be essentially torn down and rebuilt, and this is a critical opportunity for substituting in low emitting iron reduction and smelting. The IEA contrasted 25 and 40 year cycles in their ETP analysis. We ran 25, 32 and 40 years as a sensitivity analysis, and the difference is critical to reaching net zero by 2050 – with the 40 year cycle 10% of BFBOFs are still operating. Arguably, while well built and maintained furnaces can run beyond 25 years, if climate policy is important to countries something like a mandatory rebuild lifetime corresponding to the 2050 net date or earlier may be required.

The trade implications of "Imports and/or New non-spatially allocated production facilities (Imports/NSP)"

At the global level a substantial amount of demand (around 5%) cannot be met at existing sites with CCS or green hydrogen DRI. This is the wedge marked "Imports/NSP", or non-spatially allocated production. This is new iron and or steel production that must be sited in appropriate geographies for CCS or renewables-based hydrogen production. This has implications for different regions, starting with the next set of national and regional results shown (**Figure 11**). These could be built domestically at new sites, or imported from new sites in other countries. We currently normally make primary iron and steel in BF-BOFs near coal and iron ore and move it where it's needed. With hydrogen DRI, for one, we can make it near iron ore, cheap clean electricity for electrolysis or cheap methane and CCS, and move the low carbon reduced iron where it is needed for processing in EAFs, which can stay where they are, near markets and supply chains (Trollip et al., 2021). Eventually all primary steel could be run through DRI and EAFs, with iron being reduced and traded globally.

Figure 11. Global production by country for medium demand, 200 km of CO_2 pipeline



Looking at **Figure 11**, several regions could be net exporters on top of their specified production: China, the US, Japan, Russia, Pakistan, Indonesia, Brazil or South Korea. Many of them could import reduced iron ore from Australia (Gielen et al., 2020), Brazil, South Africa (Trollip et al., 2021), Russia or Canada for resale as steel. The EU, Nigeria and possibly India are notable as places that may need to import iron ore or reduced iron ore due to lack of capacity to expand their production, or by reason of having tight & expensive markets for clean electricity.

Figure 12 shows total production costs by technology, while **Figure 13** provide total CAPEX. The value of green iron and steel exports to be filled is somewhere between $50 & $100 billion per year.

Global energy use implications – coal way down, offsite electricity way up

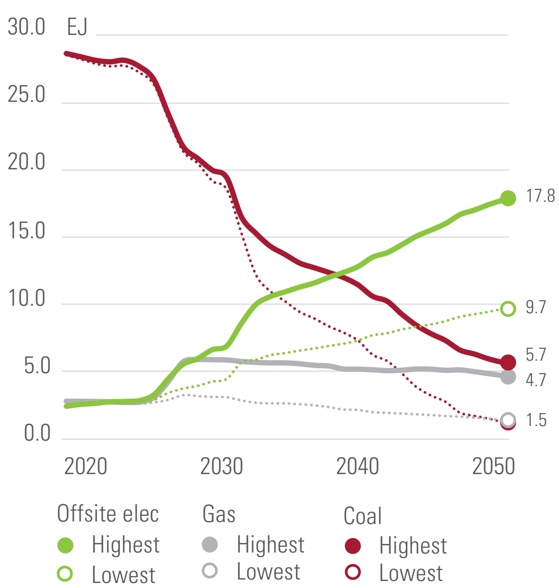
Steel production consumed 28.67 EJ of coal, 2.76 EJ of gas, and 2.45 EJ (669 TWh) of offsite electricity in 2019. Fuel use varies dramatically in all 25 year retrofit cycle scenarios, but coal use drops universally, from 28.67 in 2020 to 1.18 EJ in the low demand, 100km (with little CCS) case and 5.66 in the high demand, 300km case with the most CCS. Electricity demand grows by 4-7 times in our scenario. In our low demand, 300km of pipeline case (which offers more CCS) it rises to 2680 TWh, and in the high demand, low CCS 100km case 4931 TWh. For comparison the US consumed just over 4000 TWh in 2020.

We offer the highest and lowest coal, gas and offsite electricity use for our scenarios in **Figure 14** Coal, gas and offsite electricity use (EJ) for low demand, low CCS & highest electrification, and high demand, high CCS & lowest electrification cases contrasted.

Figure 12. Production costs by technology

Figure 13. CAPEX costs by technology

Figure 14. Coal, gas and offsite electricity use (EJ) for low demand, low CCS & highest electrification, and high demand, high CCS & lowest electrification cases contrasted



Results available for download by country

For each country and a number of aggregations (Global, European Union, G20, G7), for the medium 200km scenario, the following data are available on the website:

- Production by technology
- Capacity by technology
- Energy use by fuel delivered
- Emissions intensity per tonne of all steel, primary and secondary steel
- National emissions
- Facility scale production and transformations

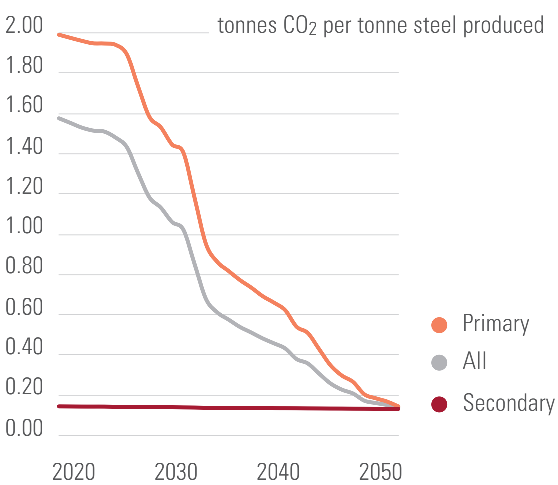
WHAT DOES THIS MEANFOR GLOBAL POLICYMAKERS & STEEL FIRMS?

Global intensity benchmarks for all, primary and secondary steel

Figure 15 provides a reference set of benchmarks for global steel production intensity for comparison. They show a steep fall starting in 2025 with the renovation cycle of the east Asian steel fleet, and then leveling out in the mid 2030s. While a slightly later steep fall would also achieve net zero, there is a serious danger of locking in unabated BF-BOF emissions in many markets if we wait until the mid 2030s.

Our secondary emissions, attributable to preheating and graphite anode decay in electric arc furnaces, could also fall but we focussed on primary emissions reduction in this project. The preheating emissions could be eliminated with electric preheating. An inert anode technology is nearly commercialized for aluminum, but ones for steel (which would have to operate at higher temperature) are likely some time away.

Figure 15. Global emissions intensity benchmarks for all, primary and secondary steel for the medium demand, 200km scenario



Policy implications

This modelling exercise has several direct implications for global climate policy with regards to steel makers.

- Our medium demand forecast assumes the material efficiency levels in the IEA NZE scenario (-25% by 2050), and our recyclable scrap forecast requires a much stronger network to gather and sort recyclable scrap. Vehicles, buildings, and infrastructure need to be designed to be taken apart at end of life in a way that allows high quality, low contamination recycling. This implies stronger building code, design & recyclability policies to encourage material efficiency and more high quality recycling (Bataille, 2020; IEA, 2020a, 2019b).
- Our results require a clear communication to steel makers that no more BF-BOFs without 90% CCS can be built past 2025, and that they should be planning for near zero emissions alternatives. This requires a multi-level policy commitment to transition to net-zero GHG industry, and eventually some form of competitiveness protections to protect low GHG investments, e.g. border GHG standards or border carbon adjustments. This in turn requires a transition pathway planning process including all key stakeholders to assess strategic & tech options, competitive advantages, and uncertainties.
- Starting the process of clean replacement in the late 2020s requires a fast and effective global innovation process to commercialize green hydrogen DRI, which is partially underway in Europe and will likely meet the 2028 goal for several plants being operating, and BF-BOF CCS, which is arguably going too slowly to meet the 2030 goal. This implies accelerated R&D and commercialization - lead markets can be created with partners to build economies of scale with public and private green procurement, content regs, supply chain branding, guaranteed pricing & output subsidies (e.g. contracts for difference).

- If there are innovation blockages, e.g. lowering the cost of electrolyzers or getting post combustion CCS to work for BF-BOFs, targeted innovation and early commercialization programs may be needed to identify and break commercialization blockages, e.g., the UK Offshore Wind Accelerator or the US ARPA-E.
- Syngas DRI CCS is already commercial, indicating some level of CCS could occur. For existing facilities not sitting right on top of CCS geology, this requires spatial planning and investment to get the necessary rights-of-ways in place for the necessary CO_2 pipelines or other transport.
- Even with a substantial commitment to CCS, some amount of green hydrogen DRI investment is likely to take place, requiring needed investment in solar, wind or other clean electricity generation, on top of the already considerable build out necessary for transport and building electrification. Overnight hydrogen storage will be required as well.
- A systemic innovation and market uptake approach is needed, that includes technology development, needed CO_2 & electricity transmission, and market design that values electricity system energy, capacity and demand response co-benefits in the business model.
- Improved local air quality and reduced wate use benefits should be assessed as part of the transition.
- If it takes too long to commercialize low emissions technologies or to mandate their use, and high intensities facilities are built in their place into the 2030s, early retirements may be necessary.

APPENDIX

BASELINE YEAR DATASET OF EXISTING FACILITIES

This appendix gives a description of the method used to develop the 2019 baseline year dataset for existing facilities that is used as input in the modelling projections.

The GEMs database identifies 2.0 Gt of crude steel capacity in 2019, in 67 countries at 622 facilities with specified geospatial coordinates. Cross referencing the GEMs database with GIEDS database, country level production identified by the Worldsteel Association (World Steel Association, 2020), and the OECD national capacity database, it was identified that 14% of global production capacity was missing from the database. To make up for the missing global production identified in each country and for each technology, production for average sized facilities by technology were allocated to the same geospatial locations based on the existing distribution of capacity within the country. Additional sites were also seeded in 32 countries that currently have no existing production but have demand and scrap steel availability. A summary of the sites by technology, production and number of countries is indicated in **Table 2**.

The project identifies within the global iron and steel boundary, 3.0 $GtCO_2e$ of emissions and energy consumption of 31,600 PJ in 2019. However, facility energy and emission intensities (i.e., energy or emissions per tonne of crude steel production) are not reported in a single consistent database. The GIEDS database provides some indication of facility level energy and emission intensity, but when these are mapped to GEMs facilities, too many inconsistencies were noted to reliably calculate facility level energy and emission intensities. In order to map global energy and emissions data to facilities the following method was developed to account for the expected variations in energy and emissions intensity between facilities and technologies:

1. A global perspective of average emission and energy intensities at facilities was developed from the comprehensive study by Wang et al (Wang et al., 2021). This work identified global emission and energy intensities by major technology and process.
2. Regional characteristics that account for differences between countries and regions was developed to adjust the global emission intensities of pro-

Table 3: Summary of Sites by Technology, Total Production and Number of Countries included in Model

	Metric	BF-BOF	EAF	DRI-EAF-GAS	DRI-EAF-COAL	OHF
Operating 2019 Sites included in GEM	#	352	224	32	14	7
	2019 Production (MT)	1,261,872	276,645	50,996	27,004	11,449
	Countries	40	38	16	5	3
Additional Sites added to make up for missing global production	#	24	134	9	8	0
	2019 production (MT)	69,468	140,186	14,873	14,537	0
	Countries	12	30	4	2	0
Seeded Sites for future production	#	0	32	0	0	0
	Countries	0	32	0	0	0

duction by technology for different countries and regions. These adjustments were derived from different benchmarking studies in the literature (Hasanbeigi et al., 2016; Hasanbeigi and Springer, 2019). Country adjustments were made for fifteen countries, including; China, India, Japan, Russia, South Korea, Brazil, Germany, Turkey, France, Canada, Mexico, Poland, Italy and Spain, that account for 90% of global production.

3. Adjustments were made to account for technology and process differences at integrated iron and steel facilities that are recorded in the GEMs database. The available data from GEMS was used to differentiate energy and emission intensity for different preparation process of iron ore (e.g., pelletization versus sintering), proprietary reduction processes (e.g., COREX, MIDREX), casting processes (e.g., flat or long products), and the overall age of the facility. These differences were associated with relative differences in energy and emission intensity derived from the literature (Holappa, 2020; Vogl et al., 2018b; Wang et al., 2021).

To develop projections of future production, the model maintains energy and emission intensities of existing facilities until they are scheduled for retrofit or are retired. All new production, is based on the energy and emission intensities of production summarized in Section 8.5. Production sites and corresponding geospatial coordinates are fixed in the model, so that all new production and new built facilities are also built in the future at the same sites. While this is not likely, since some new production capacity will be built at entirely new coordinates, it is an acceptable assumption for modelling purposes given that in producer countries production will likely correspond to existing supply chains and sites within the country.

MODEL DOCUMENTATION

Overview

This appendix gives a description of the key features 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 600 real world facilities that together comprise more than 86% of global production, with the remaining 14% inferred from a separate top-down analysis (described in detail in Section 4). The Steelpath model aims to enhance the policy relevance of the discourse surrounding the decarbonisation pathway for global steel production by making the location, size, ownership, and national origin of real-world steel production facilities clear in its projections.

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 constraint for Steelpath is system memory due to the use of high-resolution geographical information data and the requirement for hardware accelerated graphics to produce the model outputs. The current version of Steelpath is run on a process node with 64 GB of system RAM and a GPU with 10 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. notably, transformations in power generation to produce low carbon electricity) that have been outlined previously (see Section 4).

Although the model features detailed spatially located steel manufacturing plants that can be linked to real world actors (country governments, manufacturing firms in the steel supply chain etc.) the model does not represent the activity of decision makers as discrete individual agents in a bottom-up fashion. Rather, a single top-down decision-making process is employed to ensure that all steel production facilities undergo a deterministic transformation to net zero production in the period 2020-2050, with the intention being that the implications for individual real-world actors (market dynamics, investment planning etc.) are then inferred from demonstrating a successful pathway to net zero production in an *ex post* fashion. In simple terms, the model is intended to show a few possible pathways for the decarbonisation of the sector as a jumping off point for discussions amongst real-world actors as to how this can be achieved. The implications for steel manufacturers, government etc. are intended to be uncovered in this discussion rather than captured in the model. As the model is explicitly designed to show a technologically feasible transition to net zero emissions, other pathways that do not achieve net zero emissions within the steel production sector itself (for example, allowing moderate residual emissions from the steel industry and then using negative emissions sequestration technologies to offset this) are not considered in the current model version.

Key Model Inputs

Steel Production

The model version used in this report is based on the February 2021 release of The Global Steel Plant Tracker database compiled by Global Energy Monitor (https://globalenergymonitor.org/projects/global-steel-plant-tracker/). This contains 623 facilities across 67 countries and territories[10], and provides a snapshot of global steel production in 2019 for facilities above 1 million tonnes (Mt) in size.

Steel Demand

For base year calibration the model version used in this report employs historical demand use statistics from the 2020 release of the World Steel Association Steel Statistical Yearbook, which provides demand for 131 named countries and territories and 8 regions that do not correspond to distinct and identifiable political entities (these regions are “Other Africa”, “Other Asia”, “Other C.I.S.”, “Other Europe”, “Other Middle East”, “Other North America”, “Other Oceania”, and “Other South America”).

Scrap Steel Availability

Total global availability of recyclable steel and its allocation amongst various countries and regions is carried out as described in detail in Section 4.1.

Carbon Capture and Storage Potential

The potential for carbon capture and storage to play a role in decbarbonising steel production is assessed using geographically explicit data from the 2021 edition of the CO_2 Storage Resource Catalogue produced by the Oil and Gas Climate Initiative (https://www.ogci.com/co2-storage-resource-catalogue/co2-data-download/). 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). In this study we assess 100km, 200km, and 300km as maximum distances. We do not explicitly

10 The authors have used the country names and geographical segmentation contained in the original GEM Steel Plant Tracker database and have no position regarding the possession, administration or de facto status of any disputed regions or territories regardless of their status under national or international law and regardless of official recognition or otherwise by the United Nations and/or other international geopolitical organizations.

take into account real world constraints that may be present in individual cases that may make the construction of CO_2 pipeline infrastructure more or less feasible. These include but are not limited to 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.).

Global Solar Irradiation

The potential for local, low-cost green hydrogen production from electrolysers supplied by renewable electricity is assessed using global solar irradiation data (global horizontal irradiance, GHI) from the Global Solar Atlas, a project developed by Solargis r.s.o. for the World Bank (https://globalsolaratlas.info/map). In addition, a number of countries (Russia, Canada, Sweden, Brazil and Norway) are assessed as having a high likelihood of developing future low carbon power markets with excess electricity from hydropower sources.

User Defined Inputs

Several user defined inputs are essentially key assumptions that drive model behaviour. The default settings that are employed in the model runs used to produce this report are as follows.

Technical Parameters

- Maximum Distance Used to Infer CCS Viability (km): scenario dependent, testing 100km, 200km, 300km
- Minimum Solar Radiation Threshold Used to Infer Low Cost H_2 Production Potential (kWh/m^2): 3.5
- Retrofit Cycle Used to Determine Plant Retirements (Years): 25
- Last Year for Unabated BF-BOF Deployment: 2025
- First Available Year for DRI-EAF-GAS-CCS: 2025
- First Available Year for DRI-EAF-H_2: 2028
- First Available Year for BF-BOF-CCS: 2030
- Maximum Possible Capacity Factor: 0.9
- Maximum Scrap Fraction Permitted in Production: 80%
- Maximum Single Site Production Capacity (thousand tonnes): 25,000

Political Preference Parameters

- We assume that Germany does not deploy new CCS facilities - *based on the policy direction shown over the last decade successive administrations have shown a reluctance to include CCS in national decarbonisation pathways due at least in part to strong public opposition.*
- We assume that Sweden does not deploy new CCS facilities based on policy announcements and investments in DRI-EAF-H_2, i.e. the SSAB/LKAB/Vattenfal HBYRIT project.
- We assume that Canada does not deploy new CCS facilities – *this decision is mainly due to a lack of clarity in the CO_2 storage database used to assess CCS potential as to whether the sequestration sites identified for Canada that correspond to existing BF-BOF sites in Ontario extend fully into Canada or if they are mainly located on the other side of the US border increasing complexity and costs of implementation*
- We assume that Canada moves away from legacy BF-BOF technologies, based on recent government expenditures to aid steel makers in replacing older BFBOFs with EAFs.
- We assume that the UK moves away from legacy BF-BOF technologies, including BF-BOFs with CCS *–successive UK governments over many decades have consistently prioritised the use of alternative resources to coal in the energy mix and we judge it unlikely that a resurgent British steel industry would be one that is strongly dependent on imported coal.*

Technologies

Table 4 Overview of available technologies and characteristics used in the current model version

Technology	Full Name	Investment Cycle (years)	Emissions Intensity (tCO_2e/t)	Energy Intensity (GJ/t)	Notes
EAF	Electric Arc Furnace	25	0.115	0.22	Current technology
OHF	Open Hearth Furnace	25	Assessed on per facility basis	Assessed on per facility basis	Legacy technology, no new like-for-like replacements
BF-BOF	Blast Furnace-Basic Oxygen Furnace	25	1.783	18.49	Current technology, like-for-like replacement only permitted up until model year 2024
BF-BOF-CCS	Blast Furnace-Basic Oxygen Furnace with CCS	25	0.250	20.34	Future technology, available starting in model year 2030
DRI-EAF-COAL	Direct Reduced Iron-Electric Arc Furnace using Coal	25	1.200	15.54	Current technology
DRI-EAF-GAS	Direct Reduced Iron-Electric Arc Furnace using Natural Gas	25	0.992	14.76	Current technology
DRI-EAF-GAS-CCS	Direct Reduced Iron-Electric Arc Furnace using Natural Gas with CCS	25	0.139	16.24	Future technology, available starting in model year 2025 (existing facilities already exist in United Arab Emirates)
DRI-EAF-H_2	Direct Reduced Iron-Electric Arc Furnace using Green Hydrogen	25	0.115	0.22	Future technology, available starting in model year 2027
Imports/NSP	Imported and/or Non Spatially Allocated Production	NA	0.120	2.02	Emission and Energy Intensity based on share of production of low carbon technologies (EAF,DRI-EAF-H_2, BF-BOF-CCS, DRI-EAF-GAS-CCS) in medium demand 200 km pipeline scenario.

Method

The model operates in three distinct phases:

- Importing baseline year data for 2019
- Projecting forward the transition from 2020-2050
- Visualising the transformation of the global steel sector by producing geospatial graphics and time-series animations

Importing baseline year data for 2019

This phase constructs the base year data, a global snapshot of steel production and demand in 2019. The process is as follows:

a. The 623 production sites in Global Energy Monitor's Steel Plant Tracker Database are disaggregated into 711 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).

b. The February 2021 edition of Global Energy Monitor's Steel Plant Tracker Database does not include facilities that are under 1 Mt in size. As noted previously in Section 4.4, the authors were able to cross reference between OECD data, data from WorldSteel Association, and the GIEDS database to locate information on around 40 facilities in 27 countries but did not have a specific georeferenced location for these plants. The approach taken to spatially locate these additional facilities is to position them at national capitals in each country.

c. An additional 213 additional archetype facilities (mostly smaller electric arc furnaces) are added to the base model database to ensure that demand and emissions are consistent with overall global estimates of total demand and emissions.

d. The 133 countries in WorldSteel Association data are compared against the 63 countries in Global Energy Monitor's Steel Plant Tracker Database and the 27 countries where the authors have information on additional production through cross referencing 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 positioned in the national capital for each country. This step results in 39 additional facilities being added.

e. Following the data import phases detailed above, the model starts with a 2019 baseline dataset of 957 facilities and sub-facilities.
f. 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 and replacement lifecycles.
g. All facilities in the model are assessed to understand their proximity to subsurface geology suitable for long-term storage of captured CO_2 underground. This is used later to understand whether or not various facilities can be transformed to employ carbon capture and storage technology.
h. All facilities in the model are assessed to understand their potential for low cost hydrogen production using electrolysis with renewable electricity. In our work here, we assume a solar irradiance threshold of 3.5 kWh/m^2 is a useful indicator for whether or not a steel plant is likely to be in an area in future with low-cost renewable electricity available.

Projecting forward the transition from 2020-2050

This phase projects global steel production, emissions and technological change for each of the 957 baseline facilities across the 30-year time horizon from 2020-2050. The step-by-step process can be described as follows:

a. In each intertemporal period the model identifies the age of all steel production plants in the database. Facilities that have exceeded their investment lifecycle (see the description of technologies, above) are marked as being available for retrofit/new investment within the current intertemporal period (i.e. 2020, 2021, 2022, etc). All other plants are assumed to be capable of production.
b. For each country the model assesses projected demand for the current intertemporal period against possible production, accounting for flexibility in the existing manufacturing stock. Plants are assumed to be able to ramp production from zero up to a maximum theoretical capacity factor (in this report we assume a maximum possible capacity factor of 90%). Additionally, electric arc furnaces (EAFs) are also constrained by the amount of scrap available to each country in each intertemporal period, and by a nominal ceiling on the percentage of total steel demand that can come from scrap. For this report, we have assumed 80% for the latter figure.
c. If production from existing plants can cover demand, the model adjusts capacity factors for each country so that production is equal to demand. If existing plants cannot cover demand, then the model constructs additional plants.
d. Shortfalls in production capacity are handled by:
   i. First constructing additional electric arc furnaces (EAFs) to maximise utilisation of scrap steel within the model constraints described above, the assumption being that this is the cheapest possible manufacturing pathway to meet demand.
   ii. If additional EAFs cannot close the production gap, the second action taken is to expand capacity at facilities that have reached the end of their investment lifecycle in the current intertemporal period (i.e. to continue unbroken production at existing sites).
   iii. If expanding capacity at facilities that are at the end of their investment lifecycle does not close the production gap, then the model expands capacity at other facilities regardless of their age.
e. The spatial distribution of additional production capacity is carried out as follows:
   i. Production sites in each country are ranked by size. New capacity additions are added sequentially starting at the largest plant and cascading down the list until the production gap is either closed or the model runs out of sites to allo-

cate new production to. In the latter case the model will loop around and cascade down the list again from the largest site onwards.

ii. All production sites, whether those are the 623 original sets of coordinates from the GEM Steel Plant Tracker database or additional facilities located at country capitals, have their total capacity tracked. The maximum permitted capacity at any individual site is a user defined variable. For this report we have used 25 Mt. For context, the largest steel manufacturing facility in the world at the time of writing is the POSCO facility at Gwangyang in South Korea, which is the size of a small city. Sites that have had their maximum capacity reached do not have additional capacity allocated to them unless any of their sub-facilities are retired due to their age (in which case they become available for locating new capacity again).

iii. When production gaps are closed in any individual intertemporal period (i.e. the sum total of existing plants and newly added plants is able to cover demand) the model will re-evaluate the capacity factors used a second time, so that production is equal to demand.

f. The model changes production equipment used in each sub-facility according to a deterministic set of rules designed to achieve zero carbon steel production by 2050:

i. EAF facilities are assumed to be replaced on a like for like basis.

ii. BF-BOF facilities can be replaced like for like up until a user defined cut off year (unless per country assumptions on political preferences preclude this). For the model runs used in this report, this is 2025. BF-BOF facilities have several options beyond the cut off year for like for like replacement.

- If post combustion carbon capture and storage (CCS) is available (user defined variable, current report assumes 2030), if political preferences do not preclude CCS technology, and a suitable storage location is within a user defined range (we tested 100km, 200km, and 300km) the BF-BOF converts to a BF-BOF with CCS.
- If post combustion carbon capture and storage is not technologically mature but a suitable storage location is available the model will convert the BF-BOF plant to a DRI-EAF plant with CCS. This option is already technologically mature at the time of writing.
- If neither of the above options is viable (i.e. no CCS) the model will check whether or not the site is in a region with the potential for local, low-cost green hydrogen production from electrolysers supplied by renewable electricity. Technological maturity for this technology being available is also a user defined variable (currently set to 2028). If yes, the model converts the BF-BOF plant to a DRI-EAF plant fed by green hydrogen.

iii. DRI-EAF facilities that are fossil fuelled (coal or natural gas) have several options for replacement:

- If a suitable carbon storage location is available within the user defined range, the model will convert the DRI-EAF plant to a DRI-EAF plant with CCS.
- If CCS is not an option the model will check if the site is in a region that has been assessed as suitable for low-cost green hydrogen production. If yes, the model converts the DRI-EAF plant to a DRI-EAF plant using green hydrogen (DRI-EAF-H_2).

iv. Any facilities that cannot be converted are labelled as "Imported and/or nonspatially allocated production" (Imports/NSP). Nonspatial production is low carbon production that would need to be located at production locations beyond the 623 original sites that are found in the GEM Steel Tracker Database. Options for nonspatial production include building new facilities in locations that are close to suitable CCS injection sites, using green hydrogen produced at suitable locations beyond the immediate vicinity of the steel manufacturing facility, or using imported green iron with EAFs. Additional information on interpreting Imports/NSP can be found in the main body of the report in Section 5.4.

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
- Delivered fuel by end use over time
- Share of delivered fuel by end use over time
- Geospatial distribution of steel production over time
- Geospatial distribution of emissions over time

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