Decarbonisation in the global steel sector: tracking the progress

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Executive Summary

This report presents a comprehensive assessment of progress status of the global iron and steel industry toward long-term decarbonisation. The report is comprised of three components:

1. Synthesis of the findings of recent literature on key areas where progress needs to be closely monitored to ensure long term decarbonisation of the global steel sector and overview of international initiatives in the global steel sector,

2. Identification and evaluation of progress of key indicators that can continually be monitored, beyond the conventional energy and emission indicators, in those priority areas.

3. Assessment of corporate climate action in the steel sector, and to what extent the existing emission reduction targets and their implementation plans are aligned with the identified key priority areas.

The research presented here is based on various publicly available databases and recent literature from academics, think tanks and key international cooperative partnerships. This report focuses on supply-side decarbonisation strategies.

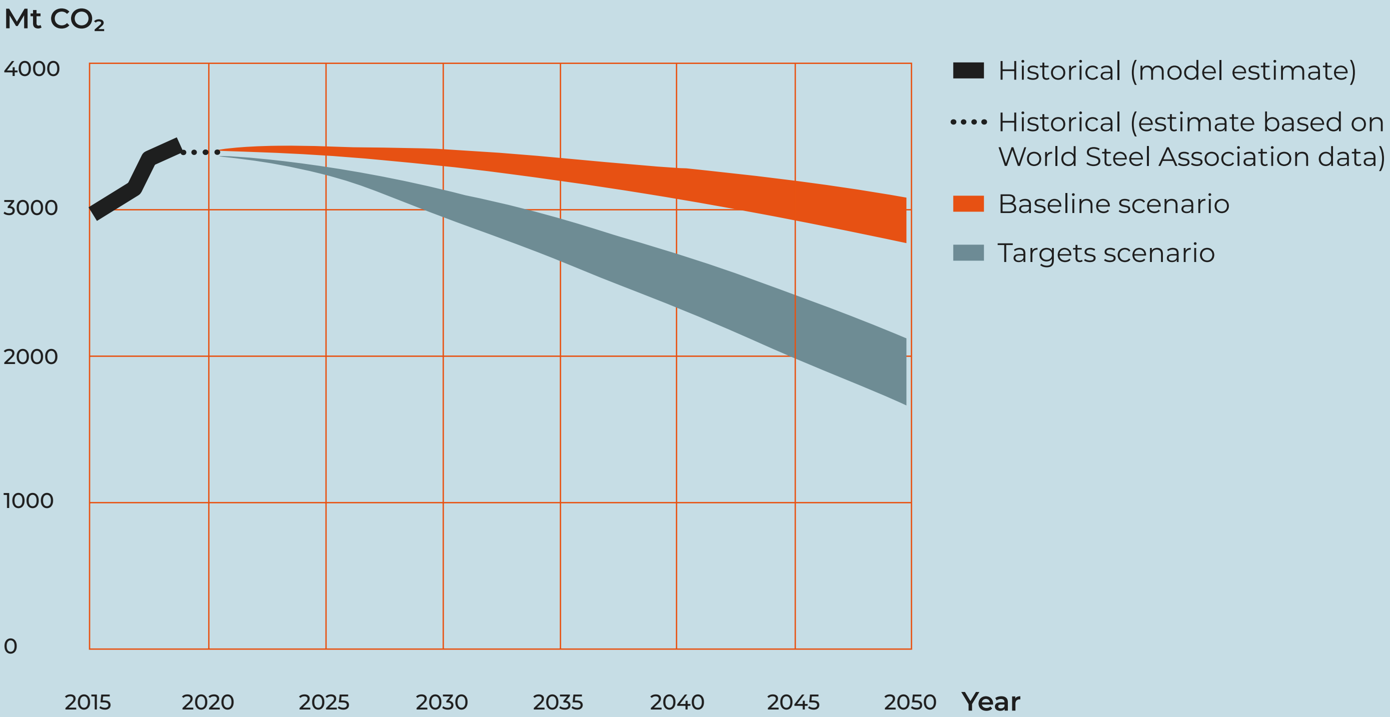
Main findings

We find that the global steel sector is making progress towards reducing its CO_2 emissions but is not yet on track to half CO_2 emissions by 2030 or fully decarbonise by 2050, which supports other studies. **We estimate that the global steel sector could potentially reduce CO_2 emissions between 8-11% in 2030 and 31-41% in 2050, when compared to the baseline scenario, through full implementation of existing GHG reduction targets in steel producing companies[1]. This is equivalent to a reduction from 2019 levels between 7-13% in 2030 and 37-51% in 2050 (Figure ES - 1).**

1 Our analysis includes the quantification of GHG emission reduction targets from top 60 steel producers, estimations of emissions mitigation potential of Chinese state-owned companies in the top 60 (with no other target) and an extrapolation of GHG emission reduction targets to the rest of the world based on the findings of the top 60 steel producers. See de Villafranca Casas et al. (2022) for more details on the methodology.

Figure ES - 1

CO_2 emissions reduction potential from GHG emission reduction targets worldwide (based on extrapolation from top 60 steel producing companies) compared to a baseline scenario.



Source: de Villafranca Casas et al. (2022)

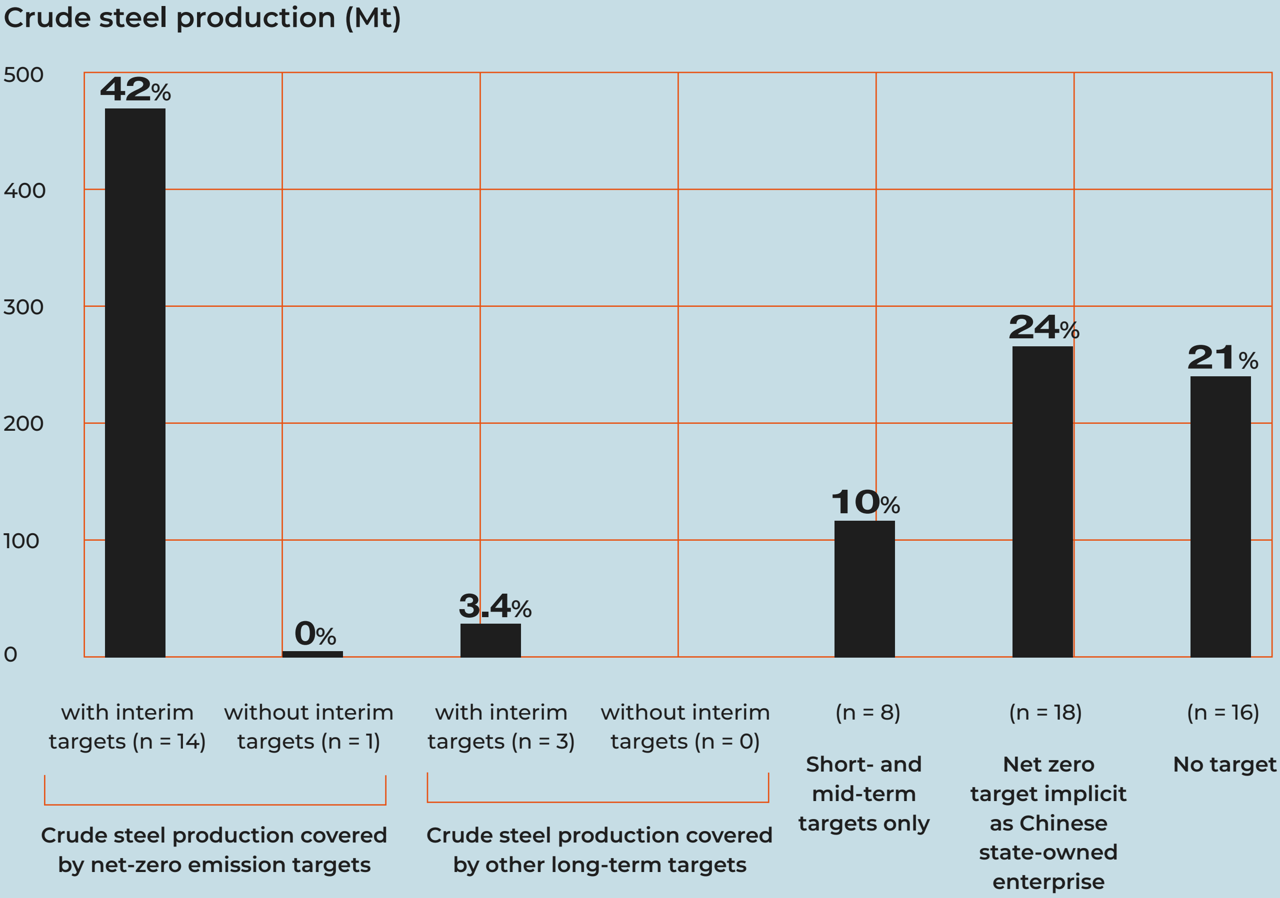
The achievement of the targets is highly uncertain as a clear plan on how to reach the targets are missing from most of the pledges. Our analysis of GHG reduction targets of the top 60 steel producers – collectively responsible for over 60% of global steel production and 65% or global CO_2 emissions from steel production – shows that 26 of them had one or more targets (Figure ES - 2).

From the 26 companies with one or more GHG emission reduction targets, we found that only 8 provide details on the measures and timeline to achieve them. Six companies provide limited information, while 12 do not provide any information on how they intend to achieve their targets. Not providing details about how companies plan to achieve net-zero emission and other types of GHG emission reduction targets leads to a lack of transparency and sets the global steel sector further away from a 1.5°C trajectory.

From those companies with information on their emission reduction plans, our analysis found that these companies are considering a wide variety of technological options – with varying levels of emission reduction potential,

Figure ES - 2

Overview of long, mid- and short-term GHG emission reduction targets by 60 largest steel makers.



% represents share of top 60 global steel makers in 2019. Source: de Villafranca Casas et al. (2022)

and at different levels of development – to achieve their climate-related targets. Most companies are considering more than one measure in their emission reduction plans.

The majority of the measures considered in company emission reduction plans are short-term actions with limited emission mitigation potential such as increased use of best available technologies (BATs), energy efficiency, and renewable energy. While implementation of these actions is a crucial step towards reducing emissions in the steel sector, our analysis supports other studies findings that without additional investment in moderate and deep emission reduction technologies, the steel sector will not be able to decarbonise by 2050. Focusing solely in short-term improvement may create a technology lock-in and could potentially create an investment barrier to the realisation of the steelmakers' long-term GHG emission reduction targets.

We also found two measures with moderate and deep emission reduction potential that companies are planning to implement to achieve their emission reduction plans: CCU/S and hydrogen-based DRI. While these have the potential to significantly reduce emissions from primary steel making in the longer term, our analysis of the indicators in the key supply-side priority show that additional resources are needed to fully commercialise these technologies in a timely manner.

We estimate that the global steel sector could potentially reduce the emission intensity of steel production between 18-23% in 2030 and between 54-63% in 2050 from 2019 levels if all GHG reduction targets are implemented. In contrast, 1.5°C compatible benchmarks from literature concur that the emission intensity from steelmaking needs to gradually decline by more than 90% and up to 100% from 2019 levels by 2050. To achieve this, we have identified three key supply-side priorities for the global steel sector: (1) Cease new investments in blast furnaces unless built with technologies suitable for deep emission reductions, (2) Innovate and commercialise deep reduction technologies for primary steel production in a timely manner, and (3) Enhance the recycling of scrap steel.

We analysed a set of indicators for each of these priority areas and found both positive and negative signs of transformation to 1.5°C Paris Agreement compatible scenarios:

- **Cease new investments in blast furnaces unless built with technologies suitable for deep emission reductions.**
  - Planned steel production capacities and capacities already under construction are dominated by the BF-BOF route – the most emissions intensive route. Achieving deep emission reduction in the BF-BOF route will require the use of CCU/S. However, there are currently only five CCU/S projects under development which operation at desired efficiencies remain to be proven. Simple retrofit of BF-BOF with CCU/S (without additional measures) can only deliver moderate emission reductions, while more advanced rebuilding of the BF plant is required to achieve deep emission reductions.
  - There is a window of opportunity to invest in low-carbon technologies (with deep mitigation potential) and avoid technological lock-ins – as almost half (45%) of the current BF-BOF stock is nearing its end of life.
- **Innovate and commercialise deep reduction technologies for primary steel production in a timely manner.**
  - There is an increasing number of low-carbon steel plant projects over the last years, indicating the start of a potential exponential trend. Over half of these projects are still in the pilot or demonstration phase, and crucial steps are being taken towards large-scale deployment and commercialisation in the years to come.

- While the number of new low-carbon steel projects is increasing rapidly, projects planned to be put in operation by 2030 are still far off what is needed according to Paris-compatible benchmarks (3.5 times more full-scale plants are needed compared to what is in the pipeline).
- Among announced low-carbon steel projects, hydrogen-based DRI is the dominating technology. But despite the strong interest for that technology, DRI only plays a minor role among planned steel capacities globally.

Enhance the recycling of scrap steel.

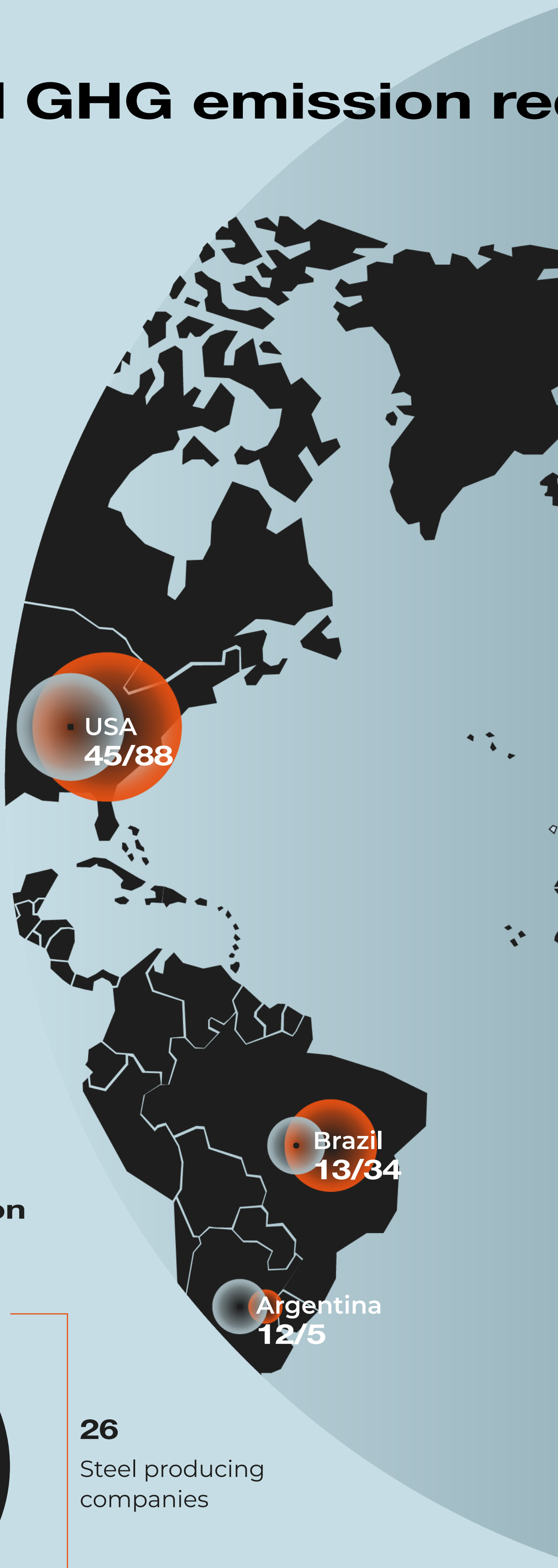
- Secondary steel production will play a key role in achieving the required emission reductions in a Paris compatible scenario, but the supply of scrap steel is currently one of the main barriers.
- The supply of steel scrap needs to increase in terms of volume and improve in terms of quality for the sector to achieve a 1.5°C-compatible trajectory, we found insufficient data to track advancements in those areas.

When analysing publicly available emission reduction plans of companies, we found that barely any steelmaker mentions the required transformation in the global steel sector. Some steelmakers highlight how challenging this will be for the company, but none acknowledge the challenge for the global steel sector.

The climate-related targets and potential GHG emission reductions associated with those, are not only driven by individual companies, but also by international cooperative initiatives (ICIs) or national-level initiatives. There is a range of ICIs operating in the global steel sector focusing on both the supply and demand of low-carbon steel (we present an overview in Section 5).

While the UNFCC process is focused on national governments and cannot set sector-specific reduction targets, having agreements such as the Glasgow Breakthrough during COP26 between national governments could further facilitate the development of needed economies of scale and aid towards sector decarbonisation. Monitoring the development of these commitments and company-specific targets is crucial to track sectoral progress.

Overview of global steel GHG emission re & mitigation potential



26

steel producing companies (from 60 companies that we assessed) have a GHG emission reduction target, equivalent to 34% of global crude steel production.

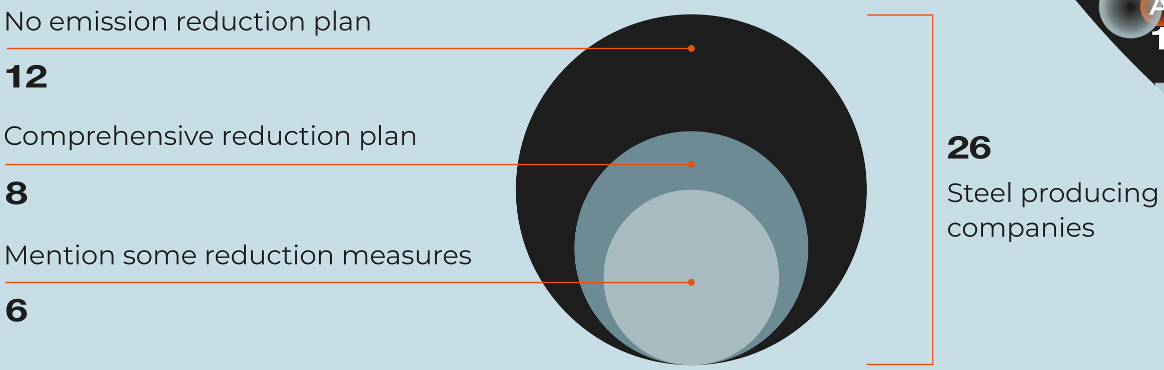
up to 13 %

of global CO_2 from steel production could be avoided **in 2030** if all* GHG emission reduction targets are fully implemented, in comparison to 2019.

up to 51 %

of global CO_2 from steel production could be avoided **in 2050** if all* GHG emission reduction targets are fully implemented, in comparison to 2019.

Target coverage of 2019 crude steel production of top 60 global steelmakers



* This assumes full implementation of GHG emission reduction targets in 60 steel companies analysed, extrapolation of these targets to the rest of steel companies world-wide, and achievement of Chinese national targets for state-owned companies in the top 60 that have no target. See (de Villafranca Casas et al., 2022) for further details on methodology.

** Countries shown are based on steel companies headquarters and do not necessarily reflect where steel is produced.

...duction targets

Size of orange circle = Steel production in 2019, size of gray circle = Steel production in 2019, covered by targets (Mt crude steel)

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Abbreviations

AIE	Alkaline iron electrolysis
BAT	Best available technology
BF	Blast furnace
BOF	Basic oxygen furnace
°C	Degree Centigrade
CAT	Climate Action Tracker
CIS	Commonwealth of Independent States
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCU/S	Carbon capture utilization and/or storage
CDP	Carbon Disclosure Project
CH_4	Methane
CO_2	Carbon dioxide
DRI	Direct reduced iron
EAF	Electric arc furnace
G	Giga, 10^9
GEM	Global Energy Monitor
GHG	Greenhouse gas
GST	Green steel tracker
H2	Hydrogen
H-DRI	Hydrogen-based direct reduced iron
IBRSR	Iron bath reactor smelting reduction
ICI	International cooperative initiative
IEA STEPS	International Energy Agency’s stated policies scenario
IPCC	Intergovernmental Panel on Climate Change
M	Mega, 10^6
MPP	Mission Possible Pathways
MOE	Molten oxide electrolysis
NASA	United States’ National Aeronautics and Space Administration
NG	Natural gas
RD&D	Research, development and deployment
R&D	Research and development
Scrap-EAF	Scrap steel to electric arc furnace
SOE	State-owned enterprise
t	Metric ton
tpa	Tons per annum
TRL	Technology readiness level
UK	United Kingdom
US	United States
USD	United States dollars

1

Introduction

Steel is a key building block of modern society. It is used for infrastructure, buildings, appliances, vehicles, packaging, and many other products. Its unique combination of durability, strength, and recyclability, make steel substitution challenging.It is also relatively low cost and abundant. Over the last fifty years its use has continuously risen; and as economies continue developing, steel demand is expected to increase by more than a third towards 2050 if no proactive and coordinated measures are taken globally to reduce consumption (IEA, 2020).

Due to the high dependence on energy and fossil raw materials, traditional steel production is an energy- and carbon-intensive product. In 2019, the steel sector was responsible for 8% of global final energy consumption, or 20% of industrial use (IEA, 2020). In 2020, the global steel sector was responsible for 11% of global CO_2 emissions and 7% of global energy use and process related greenhouse gas (GHG) emissions (Swalec and Shearer, 2021).

To achieve the Paris Agreement 1.5°C goal and avoid the most catastrophic impacts of climate change, carbon dioxide (CO_2) emissions should be halved by end of this decade and reach net-zero by 2050 – requiring immediate GHG emission reductions in all sectors (Calvin et al., 2018; IPCC, 2022). Having one of the most energy and emission intensive processes, the steel sector has a challenging road ahead towards decarbonisation. Studies have shown that existing solutions to reduce energy consumption and to replace fossil energy will not be sufficient to achieve the required mitigation, and that transformational changes – with technologies that are still under different stages of development are required (Davis et al., 2018; Boehm et al., 2021; Bashmakov et al., 2022).

Since the adoption of the Paris Agreement, there has been a substantial growth in climate-related targets in the global steel sector; such targets are set independently, or are part of a larger climate initiative (Hsu et al., 2019, 2020). Moreover, national-level pledges announced to date to achieve net-zero GHG or CO_2 emissions by 2050-2070 cover virtually the entire global steel production (World Steel Association, 2020a; Net Zero Tracker, 2022). As the momentum for long-term decarbonisation rises, we see an increasing number of studies and independent organisations assessing climate action in the steel sector. These include databases that track announcements of decarbonisation roadmaps and low-carbon steel projects. A few recent studies provided a comprehensive overview of the current technology stock, and capacity planned to be added (Swalec and Shearer, 2021; Swalec, 2022) while others developed decarbonisation pathways along with benchmarks for key indicators (IEA, 2021; Delasalle et al., 2022; IEA et al., 2022). Several other recent studies made specific recommendations on how to achieve the transition (Energy Transitions Commission, 2019; Climate Action Tracker, 2020; IEA, 2020, 2022; IRENA, 2020; Agora Industry et al., 2021; Bataille et al., 2021; Yu et al., 2021; Teske, 2022).

This study first synthesises the findings of recent literature on key areas where progress needs to be closely monitored to ensure long term decarbonisation of the global steel sector, identifies key indicators that can continually be monitored, beyond the conventional energy and emission indicators, in those priority areas, and assesses them. Then we investigate progress of corporate climate action in the steel sector, and to what extent the existing emission reduction targets and their implementation plans are aligned with the identified key priority areas. The research presented here is based on various publicly available databases and recent literature from academics, think tanks and key international cooperative partnerships.

This report is structured as follows: **First**, in Section 2, we provide an overview of the steel sector's climate action status—where it is and where it needs to be to be compatible with the Paris Agreement 1.5°C goal—through the lens of available steel production technologies and new developments. We then present three key supply-side priority areas for the steel sector decarbonisation and key indicators (in Section 3) to track the sector's progress. **Second**, in Section 4, we present an overview of the existing GHG emission reduction targets and plans between 2020 and 2050 of the top steel makers and quantify the aggregate CO_2 reduction potential of the sector as a whole. This section presents the main findings of the report. **And third**, in Section 5, we provide an overview of existing international cooperative initiatives – multi-stakeholder arrangements of a variety of non-state and subnational actors which may also cooperate with national governments – active in the steel sector and driving climate action through knowledge sharing, technical implementation, development of standards and/or through campaigning for policy changes. **Finally**, conclusions are drawn in Section 6.

This report does not discuss decarbonisation roadmaps and actions proposed at national levels, some of which are compiled in e.g. Johnson et al. (2022). Moreover, this report focuses on supply-side decarbonisation strategies by the steel companies. Whilst demand-side interventions such as the reduction of steel demand in end-use sectors through better design and higher energy and material efficiency are very important for reducing GHG emissions in the global iron and steel sector (Bataille et al., 2018; Rissman et al., 2020; Fennell et al., 2022). On the emission analysis, this report focuses on CO_2, the most dominant GHG from the sector and covers both direct and the large majority of indirect emission (see Box 1 for details).

Box 1

System boundaries on GHG emission estimates presented in this report.

GHG emissions from the steelmaking process can be categorized into scope 1, 2 and 3 emissions (see Table 1 below for a detailed explanation). Scope 1 emissions include those generated directly from the steel company: process emissions and emissions from fuel combustion. Scope 2 emissions are indirect emissions that are caused by the activity of the steel company, but the generator of the emissions is owned and operated by another entity. Those mainly include emissions from electricity consumption and emissions from coke production (if done off site). Scope 3 emissions are upstream (activities related to production of raw materials used in the crude steel making process) and downstream (activities related to further processing of crude steel, transportation, and use of final products) indirect emissions which take place along the steel company's value chain and include all emissions which do not fall under scopes 1 and 2 (e.g., from coal mining to production and handling of end-use products).

Due to data availability limitations, the emission reduction calculations in this report covers scope 1 and 2 emissions but excludes scope 3 emissions. The importance of scope 2 emissions is further strengthened by the expected increase in direct and indirect electrification of steel production in a 1.5°C compatible scenario. Scope 3 emissions are limited (IEA, 2020).

Table 1

Description of direct and indirect GHG emissions in steel production.

Direct	Indirect	
Scope 1	Scope 2	Scope 3
Generated directly by the steel company. Examples: • *Process emissions* • *Fuel combustion*	Caused from the activities of the steel company, but generation of emissions are owned and operated by another entity. Examples: • *Coke production* • *Purchased electricity & heat consumption*	Emissions taking place at the value chain of the steel company but outside of the steel production company. This refers to upstream and downstream. **Upstream**: activities related to extraction and process of raw materials used in the steel making company. **Downstream**: activities related to further processing of crude steel into products and use of final products). Examples: • *Emissions generated from iron mining, coal mining (including methane leakage from coal mines), transport of raw materials and finished products, commodity production, and final product use commodity production & use*

2

Steel sector status and the required actions under 1.5 °C emission pathways

In this section we present the status quo of the global iron and steel industry and the different technological options available for its alignment with the 1.5°C Paris Agreement temperature goal, based on the latest available literature.

2.1 Status of global iron and steel production

Global steel production continues to rise steadily, mainly driven by Asia and in particular China, which was responsible for 53% of global production in 2021 compared to about 18% in 2001 (International Iron and Steel Institute (IISI), 2002; World Steel Association, 2020b) (Figure 1). Other Asian countries, Japan and India, are the next global producers after China responsible for 6% and 5% of global production in 2021, respectively (Swalec and Shearer, 2021). Global demand for steel is expected to continue to grow, particularly in developing and emerging economies (excluding China where demand is expected to stagnate) (Energy Transitions Commission, 2019; IEA, 2020). India's steel production, for instance, is expected to grow by four-fold by 2050 from 2019 levels (IEA, 2020).

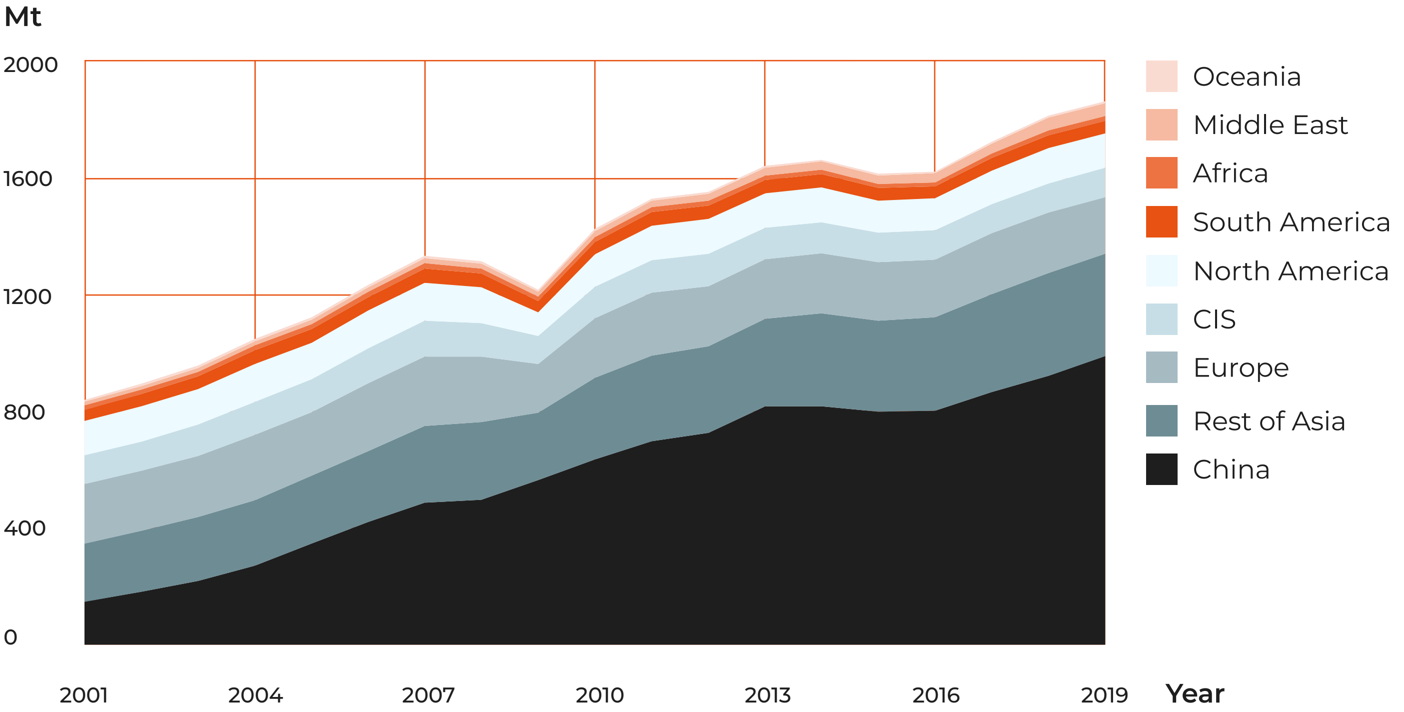
Global steel production today is mainly achieved through three different technology routes:

1. blast furnace to basic oxygen furnace (BF-BOF) route, (primary steel production);
2. direct reduced iron to electric arc furnace (DRI-EAF) route (primary steel production); and
3. scrap steel to electric arc furnace (scrap-EAF) route (secondary steel production).

These three production routes have large differences in emission intensities, which are linked to the energy intensity and fuel types used. The two primary steel production routes traditionally rely on fossil fuels as reducing agent and to generate thermal energy to reduce the virgin iron ore into iron for further processing into steel. While the BF-BOF route is highly energy intensive and reliant on coked coal, the DRI-EAF route is fuelled by fossil gas or coal but requires less energy. The production of secondary steel in the scrap-EAF route only generates minimal process emissions from electrode

Figure 1

Global crude steel production by region



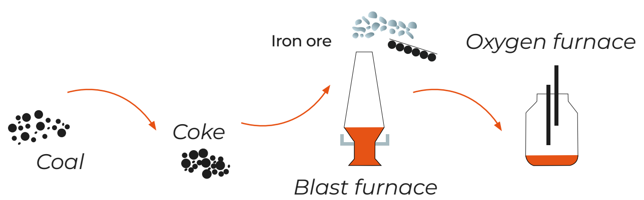
Source: (World Steel Association, 2020a). Produced by author.

Figure 2

Traditional steel making routes and share in total crude production in 2019

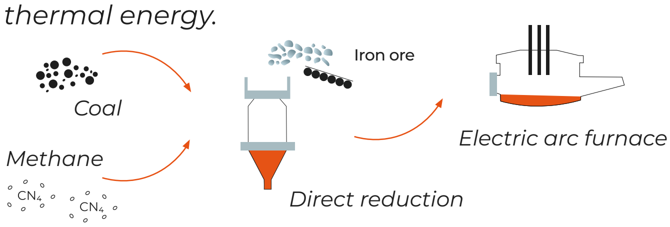
1. Blast furnace to basic oxygen furnace (BF-BOF) route

The Most common and emissions-intensive production route. Reliant on coked coal for thermal energy and as a reduction agent.



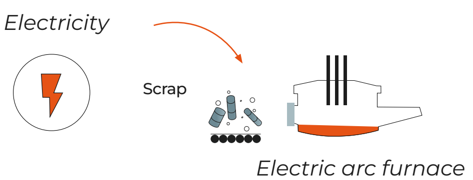
2. Direct reduced iron to electric arc furnace (DRI-EAF) route

The second most emissions-intensive production route currently practised. Reliant on methane or coal as a reduction agent, and electricity for thermal energy.

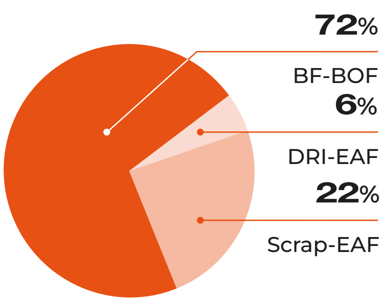


3. Scrap steel to electric arc furnace (scrap-EAF) route

The production does not generate any process emissions and is fully reliant on electricity.



Frequency of use in 2019



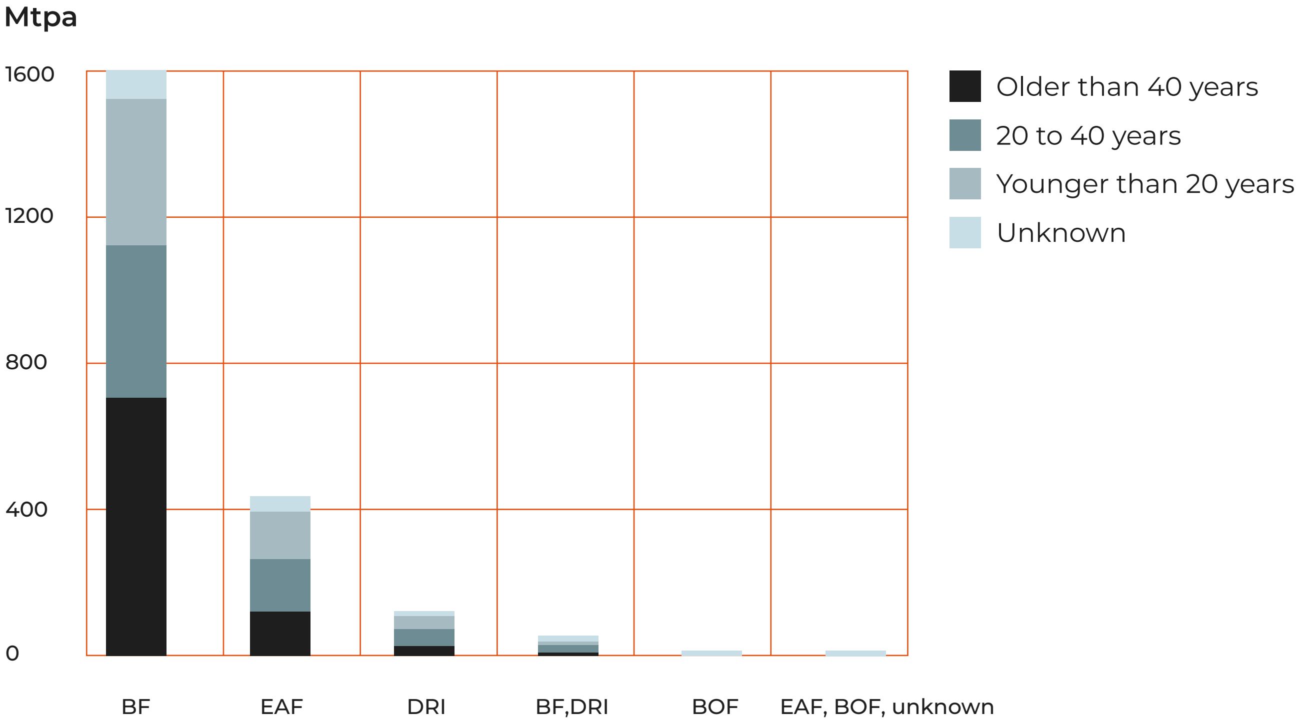
Source: (World Steel Association, 2020a). Produced by author.

degradation and is fully reliant on electricity (Bataille et al., 2021; Mission Possible Partnership and Net-zero Steel Initiative, 2021).

The BF-BOF route is the most common (72% of global production in 2019), while the two other routes make up the remainder of the production capacity (6% and 22% of production from DRI-EAF and scrapEAF, respectively) (World Steel Association, 2020a). In China, the largest steel producing country, the BF-BOF route accounted for 90% of national total steel production in 2019 (Oda, 2022).

Steelmaking facilities have an average lifetime of 40 years with an investment cycle of 15-20 years (Swalec and Shearer, 2021). An overview of the age distribution of steel plants globally (see Figure 3) indicates that a large proportion of the fleet will enter new investment cycles within the near-term.

Figure 3
The age distribution of existing steel plants globally.



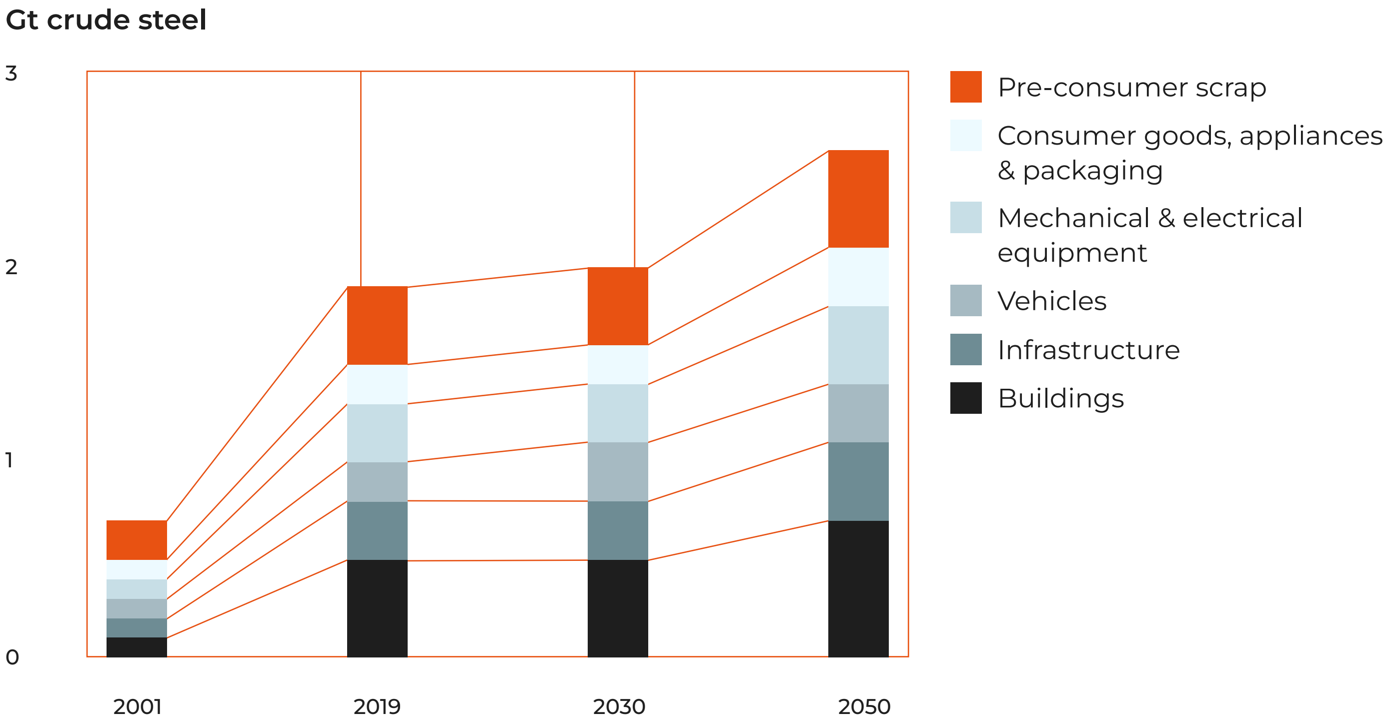
Note: Author's calculations based on data from the Global Steel Plant Tracker (Global Energy Monitor, 2022). Includes all steel plants globally with at least one million tons of crude steel annually. The dataset is from March 2022. BF refers to blast furnace, EAF refers to electric arc furnace, and DRI refers to direct reduced iron. Produced by author.

2.2 1.5°C-compatible benchmarks for the global steel sector

Global steel demand is expected to continue growing until 2050 in the absence of demand reduction measures. The International Energy Agency (IEA), for example, projects in its baseline scenario (Stated Policies Scenario) that the crude steel demand would grow from 1.9 Gt in 2019 to over 2.5 Gt in 2050 across end-use sectors (IEA, 2020) (Figure 4).

For CO_2 emissions, IEA projects in its baseline scenario that direct and indirect CO_2 emissions from global steel production would increase slightly

Figure 4
Historical and projected steel demand per end-use sector based on projections under IEA (IEA, 2020) stated policies scenario (STEPS).



Source: IEA stated policies scenario (STEPS). Produced by author.

from 3.7 $GtCO_2$/year in 2019 to 3.9 $GtCO_2$/year in 2050 (IEA, 2020). Following an increased scrap recovery rate, the emission intensity of global steel production is expected to decrease, offsetting much of the global growth in demand from end-use sectors as shown in Figure 4. There are studies that project lower baseline scenario emissions in 2050 (Delasalle et al., 2022), but there is a general agreement in the literature that a substantial amount of annual CO_2 emissions in the order of 2 to 3 $GtCO_2$ will remain unless significant effort is made to reduce them.

To lead the emissions trajectory onto a path compatible with the 1.5°C goal of the Paris Agreement, a portfolio of various different technologies will be required, taking into consideration local and regional aspects related to resource availability and policy environment.

To gain a better understanding around what will be required from the steel industry's supply-side, we have analysed existing 1.5°C compatible benchmarks from the literature. The Energy Transitions Commission (Delasalle et al., 2022) and the Climate Action Tracker (2020) have developed 1.5°C-compatible benchmarks for 2030 and 2050 on the carbon intensity of steel production (see Figure 5). As a reference, steel production under the IEA's Stated Policies Scenario (IEA, 2020) would lead to minimal carbon intensity reduction mainly due to implementation of existing measures such as energy efficiency and best available technologies (BAT).

These benchmarks show a relatively high level of agreement in both the medium (2030-2039)- and long-term (2040 and after), suggesting a decline between 25% to 44% in 2030 compared to the emission intensity in 2020, and between 93% and 100% in 2050. The most significant difference between benchmarks in the medium term (2030) is mainly a result of uncertainties related to technological development and commercialisation of near-zero emissions technologies, and different assumptions regarding carbon pricing. In the long term, there is an agreement that all steel production must be produced using technologies with deep reduction potential in 2050, only allowing residual emissions resulting from plants equipped with carbon capture and usage or storage (CCU/S) that does not achieve 100% capture rates, and emissions from electrode degradation in EAFs.

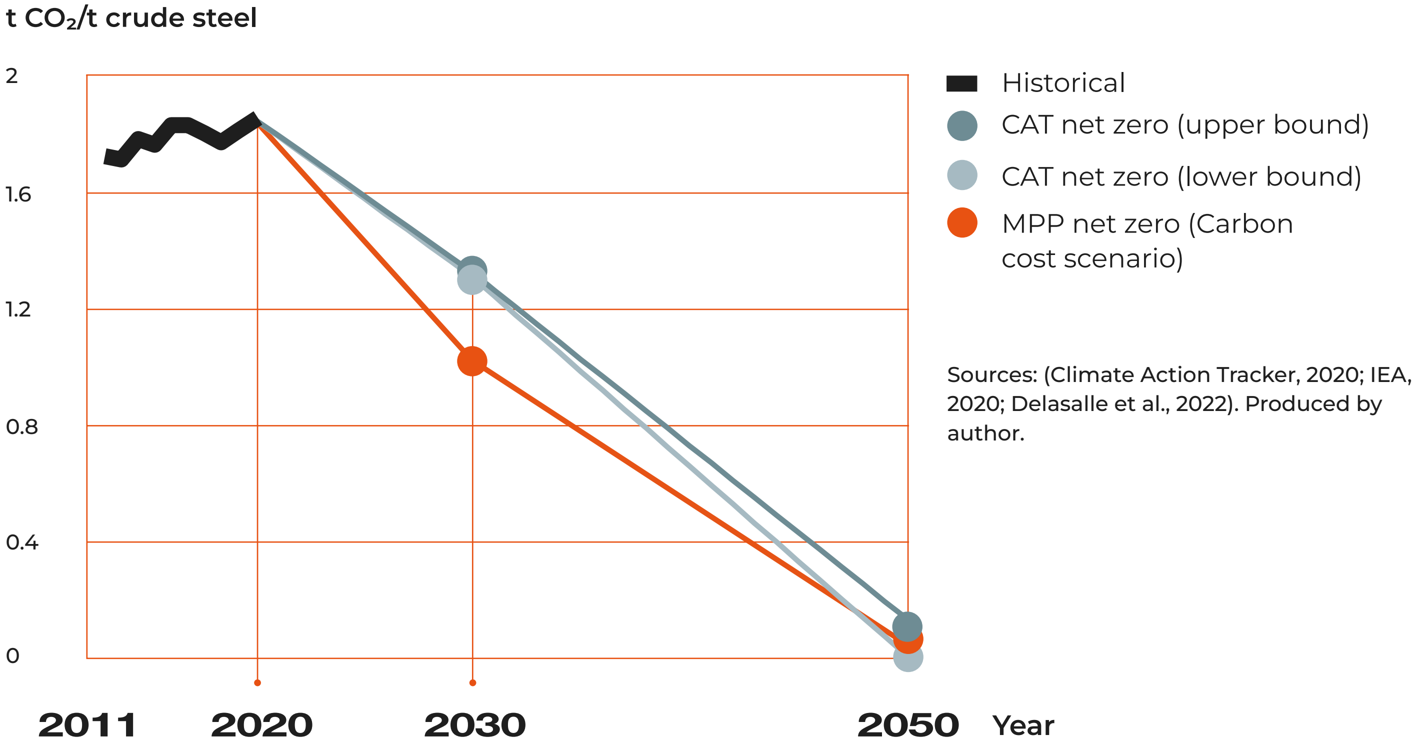
Even though the average rates of decline between 2020-2030 and 2030-2050 are similar across the analysed benchmark scenarios, the efforts behind those changes are rather different. In the near- to medium-term, emission reductions are expected to mainly be led by improved energy efficiency and the increased rate of recycled scrap steel, while near-zero emissions technologies play a smaller role. After 2030, a rapid deployment of near-zero emissions technologies is expected. That, however, requires increased efforts and investments in technology development already in this decade.

Noteworthy points from the benchmarking studies include:

- Achieving the required reductions by 2050 will require significant effort in developing and commercialising near-zero emission steelmaking technologies in this decade. This would enable near-decarbonisation of steel production by 2050 while also avoiding the creation of stranded assets

Figure 5

Global historical steel emission intensity and 1.5°C compatible benchmarks collected from literature.



Sources: (Climate Action Tracker, 2020; IEA, 2020; Delasalle et al., 2022). Produced by author.

- New investments in BF-BOF would increase emissions in the near- to medium-term and make long term decarbonisation significantly more challenging. Substantial changes to conventional BF-BOF plants will be required
- Carbon capture technology will be required to achieve near-zero emissions by 2050 and will require increased efforts in technological and infrastructure development in the near-term
- Green hydrogen-based steel will play a vital role in the decarbonisation of global steel production, but its price competitiveness will be highly reliant on the cost-competitiveness of green hydrogen. Early investments in green hydrogen-based steel can increase its demand and drive down the cost
- Increasing the rate of recycled scrap steel offers a commercially available option to significantly reduce emissions in the near-term, but the production potential will vary significantly across regions and increased efforts in reducing scrap steel contamination are needed. However, global available scrap supply will not suffice to satisfy all demand and primary steel production cannot be eliminated for the foreseeable future, particularly not in developing and emerging economies.

Based on this backdrop, steelmakers need to develop individual decarbonisation roadmaps taking context-specific aspects into account. More specifically, we identified three key supply-side priorities:

Cease – new investments in blast furnaces unless built with technologies suitable for deep emission reductions

In the designing of company and/or region-specific decarbonisation roadmaps, companies need to consider the type and status of their current technology stock, and which would be the most suitable technologies to be in line with a 1.5°C compatible trajectory. For instance, depending on the age of existing BF-BOFs, their early retirement and retrofitting with DRI technology may be a suitable option for older facilities.

Because of the long lifetime of BF-BOF facilities and the technical challenges in achieving deep emission reductions for that technology, building out new capacities will either risk achieving the climate targets, or will generate stranded assets (Vogl et al., 2021; Delasalle et al., 2022; IEA et al., 2022; Swalec, 2022). Investments in new blast furnace capacity should therefore be avoided, or only take place under the condition that they are built with appropriate technology for deep emission reductions, as well as including plans for developing required infrastructure. Deep emission reductions in the blast furnace route essentially means the use of carbon capture and usage or storage (CCU/S). But considering the various downsides and uncertainties around CCU/S (see section 2.3.1) that technology should be seen as a potential way out for young (below 20 years) BF-BOF capacities but does not necessarily justify the development of new BF-BOF capacity.

Nevertheless, the majority of planned and proposed new steel capacity is blast furnace based. This is further discussed in section 2.3.1.

Innovate – and commercialise deep reduction technologies for primary steel production in a timely manner

To enable the phase out of blast furnace capacity, breakthrough technologies which allows for near-zero steel production must be developed and tested at scale ahead of the new investment cycles of existing plants. Most breakthrough technologies are expected to reach commercialisation within the next one or two decades, while many existing steel facilities are approaching a new investment cycle around 2030 (Swalec and Shearer, 2021). Ensuring the timely roll-out of breakthrough technologies will require increased and active participation from steelmakers in technology development and the increased cooperation between steel companies could be beneficial for all parties. International cooperation is particularly important to ensure that technology availability does not become a barrier in developing and emerging economies where most of the demand growth for primary steel is expected (IEA et al., 2022).

By engaging in early investments in commercial-scale near-zero plants, companies can build experience and advance learning curves to further speed up the transition. Further, to manage investment risks, steel companies can seek partnerships with downstream steel consumers seeking to reduce their scope 3 emissions such as in the automotive industry and public entities (Mission Possible Partnership and Net-zero Steel Initiative, 2021).

The Energy Transition Commission estimates that, to meet growing steel demand and maintain existing plants, about USD 47 billion in investments are required annually over the next 30 years (Delasalle et al., 2022). For the transition to a net-zero emissions technology stock, additional annual investments of about USD 9 billion are needed, translating to an abatement cost as low as USD 7/tCO_2 in terms of capital expenditures (Delasalle et al., 2022). That translates to USD 1.7 trillion over the next 30 years. Another estimate by Wood Mackenzie is at a similar level of USD 1.4 trillion (Wu et al., 2022). However, investment needs in auxiliary processes and infrastructure development such as for the production, transportation and storage of green hydrogen, captured CO_2 and electricity infrastructure will add to those figures. The timely and coordinated development of necessary infrastructure for low-carbon technologies will be vital in enabling the deployment of required technologies at the scale and pace required (Löfgren and Rootzén, 2021). Comparing to the value of the global steel market in 2020 at USD 1092 billion (Visiongain, 2022), the required investments would be around 5-6% annually.

Enhance - the recycling of scrap steel

Secondary steel production is almost ten times more energy efficient than the BF-BOF route and could thus bring significant energy and emissions savings. Since secondary steel production is an already commercialised technology, increasing its production could offer a way to reduce emissions already in the short term, independent of the development in moderate mitigation technologies and deep emission reduction technologies. As the secondary production route is not reliant on coal, it can also contribute to a strengthened energy security (Nicholas and Basirat, 2021).

IEA's Net Zero by 2050 scenario (NZE) suggests that global secondary steelmaking needs to increase drastically, and to make up almost half of the market (46%) by 2050 (IEA, 2021). In (Bataille et al., 2021), similar modelling results are presented, requiring secondary steel production to make up at least half of the global market in 2050, requiring about 1 Gt of steel scrap supply globally, compared to 0.63 Gt in 2020. In (Wang et al., 2021), it is estimated that the global scrap supply could increase 3.5 fold (about 2.2 Gt) between 2020 and 2050, while the World Steel Association projects a scrap availability of about 0.9 Gt in 2050 (World Steel Association, 2021).

A key driver in increasing the secondary steel production is thus increasing the supply of scrap steel that is usable for secondary steelmaking (OECD, 2018). Creating demand for low carbon steel, which could stimulate more scrap recovery, could be a key trigger for that (Kuramochi, 2016). But other barriers such as reducing the contamination of scrap steel and improving sorting and collection systems also need to be overcome (Energy Transitions Commission, 2019).

Although some regions already have high steel recycling rates (including the US and Europe), other regions, particularly Asia, has great potential to increase their recycling rates (Xylia et al., 2018). The majority of the increase in global steel production over the last 20 years has been driven by large emerging economies such as China and India and used in infrastructure development. With an average lifetime of about 70 years, those steel products are expected to reach end of life within the next 30-50 years, leading to a rise in scrap supply in those countries (Wang et al., 2021).

As steel scrap is traded internationally, increased recovery rates in certain regions could incentivise secondary steel production domestically as well as internationally by increasing the global scrap supply. But in order to match regional scrap supply and demand, obstacles such as trade barriers and the timely development of required infrastructure must be overcome (Kuramochi, 2016).

2.3 Decarbonisation options for primary steelmaking

In this section, we describe the key mitigation options for each steelmaking technology route in more detail. Because most decarbonisation technologies for steel production are still being developed, we refer to their stage of development using NASA's technology readiness level (TRL) scale as classified in the various cited literature (see Table 2) (NASA, 2012). Table 3 gives an overview of the different technological mitigation options for the primary steel production routes (BF-BOF and DRI-EAF).

We categorise these into three groups depending on their GHG emissions mitigation potential when compared to the emissions intensity of traditional BF-BOF:

- limited mitigation potential (10-30% reduction compared to BF-BOF),
- moderate mitigation potential (~ 65% reduction compared to BF-BOF), and
- deep emission reduction technologies (~ 95% reduction compared to BF-BOF).

Table 2

NASA's technology readiness level (TRL) scale and definitions (NASA, 2012).

TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of enabling technologies)
TRL 6	Technology demonstrated in relevant environment
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualifie
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

Table 3

Overview and definition of steel-making technologies.

Technology readiness level (TRL) scale refers to 1: basic principles observed to 9: proven and operation technology. The emission reduction potential is defined with reference to the emission intensity of steel produced with a conventional BF-BOF. These ranges were collected from the following sources: (Material Economics, 2019; IEA, 2020; Bataille et al., 2021; Draxler et al., 2021; Swalec and Shearer, 2021; Wang et al., 2021).

	Production route & Technology	CO_2 reduction potential (compared to BF-BOF)	Technology Readiness Level	Mitigation potential
DRI-EAF	Green hydrogen based DRI	95-100%	5-8	Deep (~95% reduction)
DRI-EAF	Direct electrification	95-100%	2-6	Deep (~95% reduction)
DRI-EAF	Fossil fuel based DRI + CCU/S*	80-190%	9	Deep (~95% reduction)
BF-BOF	Smelting reduction (HIsarna) + CCU/S*	80-90%	6-7	Deep (~95% reduction)
BF-BOF	Top gas recycling + CCU/S*	65%	5-6	Moderate (~65% reduction)
BF-BOF	CCU/S* retrofit	50-63%	7-8	Moderate (~65% reduction)
BF-BOF	Biomass substitution	25-30%	2-9	Limited (10-30% reduction)
BF-BOF	Increased scrap usage	Not available	9	Limited (10-30% reduction)
BF-BOF	Smelting reduction (HIsarna)	20%	4-6	Limited (10-30% reduction)
BF-BOF	Top gas recycling	15-25%	5-9	Limited (10-30% reduction)
BF-BOF	Process efficiency improvement	15%	9	Limited (10-30% reduction)
BF-BOF	Hydrogen-based gas injection	20%	5-8	Limited (10-30% reduction)
BF-BOF	Hydrogen co-firing	10%	5-7	Limited (10-30% reduction)

* CCU/S results in a range of residual emissions and is still largely under-development (see section 2.3.1)

2.3.1 Blast furnace to basic oxygen furnace

Due to the persistent need for coke as a reducing agent in the blast furnace, which generates process emissions, efficiency measures to the blast furnace route can only achieve limited emission reduction of about 15-20% (Table 3). Indeed, parts of the coke in the blast furnace could be substituted by biomass, but due to various challenges regarding the supply of sustainable biomass, significant contributions from that mitigation option are not expected (see Box 2 on biomass). Therefore, CCU/S remains the key option to achieve deep emission reductions, even though it comes with a number of key barriers, as discussed in the next section.

Carbon Capture Utilisation or Storage (CCU/S)

There are several carbon capture technologies suitable for steel making plants (Kuramochi et al., 2012). While it is evident that CCU/S will be needed to decarbonise the steel sector and achieve the 1.5°C goal of the Paris Agreement, it is important to acknowledge that the use of CCU/S in steel making will result in a range of residual CO_2 emissions depending on the production route. The level of captured emissions ranges between 50-90% depending on the process; we explain each of them in turn.

There are several key challenges of fitting CCU/S to conventional steel plants. One challenge is the low CO_2 concentration in the exhaust gas of the blast furnace, which makes the capturing of the CO_2 more challenging and expensive in comparison to other processes such as coal to chemicals (Baylin-Stern and Berghout, 2021). Another challenge is that existing blast furnace facilities have several point sources of CO_2 emissions (such as from the blast furnace and the basic oxygen furnace) which requires instalments of multiple capture entities and CO_2 infrastructure in the process (Bataille et al., 2021). Fitting carbon capture technology to a conventional BF-BOF plant could therefore only achieve moderate capture rates of about 50%.

From the global sectoral perspective, this means that, to achieve the 1.5°C temperature target, existing BF-BOFs and all new planned blast furnace capacity would need to be rebuilt to specifically integrate CCU/S plus include other technologies that allow for the CO_2 concentration to be higher. Doing so could achieve higher capture rates, but still not above 90% (Bataille et al., 2021).

Iron bath reactor smelting reduction (also referred to as HIsarna), which eliminates the need for a blast furnace by producing liquid hot metal directly from raw materials, generates a pure CO_2 flue gas which makes it suitable for CCU/S. The technology is still reliant on coal, meaning that methane emissions from coal mining are not reduced and will continue to contribute significant scope 3 emissions (Swalec and Shearer, 2021). Without CCU/S, the technology could achieve 20% emission reduction, and 80% with CCU/S. Even though existing BF-BOF facilities could be retrofitted with this technology, it would require significant changes to an existing plant. It is currently at a TRL level 6 (Draxler et al., 2021).

Another near-zero emission technology which involves gas injection into the blast furnace, requires less changes to the existing plant. Hydrogen-based gas injections which could include coke oven gas, biomass, wastes or pure hydrogen, substitutes fossil energy carriers and could achieve 20% emission reductions, and about 65% emission reductions with CCU/S. The current TRL lies within the range of 5-8, but due to the low achievable CO_2 capture rates, investments in this technology could lead to lock-in effects. As for the TRL of the actual post-combustion CCU/S technology, this is currently at a level of 5-6 (Draxler et al., 2021).

Even though CCU/S is likely to play an important role in the decarbonisation of the iron and steel sector – particularly for relatively young BF-BOF plants – there are several barriers to its deployment which should be considered and may limit its role (UNFCCC, 2021). First and foremost, the principal idea of fitting CCU/S technology to a plant is to reduce its CO_2 emissions to make it compatible with a 1.5°C emissions pathway. Doing so requires the sector reaching carbon-neutrality by mid-century. The available carbon capture technologies, however, have moderate mitigation potential, meaning that carbon-neutrality cannot be fully achieved.

Another issue could be the geological storage potential and permanence for CO_2 storage, which is yet unproven. Although various studies indicate that there should be sufficient storage potential on the global scale, regional storage availabilities may vary (Budinis et al., 2018). Several ongoing projects are investigating the risks of leakage and security of storing CO_2, which also must be socially and politically accepted. Indeed, limiting the need for carbon storage through the application of CCU/S could alleviate such challenges. However, companies and policymakers must take responsibility of how the captured carbon is being used. To date, the majority of captured carbon has been used for enhanced oil recovery to extract oil that otherwise would have been kept in the ground. This is the case for the single so far commercially operational CCU plant in the iron and steel sector (Global CCS Institute, 2022).

The widespread deployment of CCU/S could result in increased pressure on other vital resources. Capturing carbon leads to an increased thermal and electrical energy consumption which could further challenge the decarbonisation of the energy sector. Further, depending on the type, some CCU/S technologies consume large amounts of water which could lead to regional water scarcity should CCU/S be widely deployed (Rosa et al., 2020, 2021). The usefulness of CCU/S must therefore be carefully studied within the energy-water-climate nexus.

The widespread deployment and the number of companies concentrating on CCU/S as a decarbonisation solution would continue to incentivise the extraction of fossil fuels while directing research and development efforts away from renewable energy-based technologies. This could risk slowing down the commercialisation of such technologies which will be vital in the low-carbon transformation, while the reliance on fossil fuels with volatile prices could lead to increasing operational costs and weakened energy security (Grant et al., 2021). Further, even if blast furnaces are equipped with CCU/S to reduce scope 1 and 2 emissions, the continued dependence on coke results in significant methane emissions from coal mining (Dawidowski et al., 2019).

Box 2
The role of sustainable biomass in a decarbonised steel sector.

Biomass in the form of bio-charcoal and bio-methane can be used in steelmaking: Bio-charcoal for thermal energy and as a reduction agent in the BF-BOF route, and bio-methane as a reducing agent in the DRI route. Replacing coke with bio-charcoal is already practiced at a commercial scale in Brazil (Energy Transitions Commission, 2019).

But even though biomass can be sustainably produced, there are several aspects which significantly limits its production capacity. For biomass to be considered sustainable, emissions from its full life cycle must be taken into account, including from collection and transformation, land use change, and carbon absorption that would have occurred if the biomass were not harvested. Its production also competes with limited land availability and risks competing with food production or driving deforestation. Further, even though the use of sustainable biomass could reduce CO_2 emissions, the combustion of biomass still generates other air pollutants, worsening the local air quality (Energy Transitions Commission, 2021)

Emissions from steelmaking through both the BF-BOF route and the DRI route can be reduced using sustainable biomass. But limited production potential of sustainable biomass in a 1.5°Ccompatible world may mean that its use needs to be prioritised for sectors where other decarbonisation options are not available.

Indeed, the adoption of biomass-based fuels could be a near-term mitigation option in regions with abundant supplies of biomass and thus the possibility to generate sufficient supplies of it sustainably (Nwachukwu et al., 2021). But since there are decarbonisation options available for steel production which are not dependent on the use of biomass (e.g. using green hydrogen and clean electricity) sustainable biomass should in general not be prioritised for the decarbonisation of the steel industry (Mission Possible Partnership and Net-zero Steel Initiative, 2021). Even though the use of sustainable biomass could be used to reduce emissions in steelmaking in the short term, it risks delaying the development and roll-out of other vital decarbonisation technologies such as green hydrogen-based DRI and direct electrolysis.

Based on this, there are reasons to remain critical with regard to the potential of CCU/S in the decarbonisation of the iron and steel industry. Nevertheless, it is evident that CCU/S will be needed to achieve the 1.5°C goal of the Paris Agreement (see section 2.3.1). When considering CCU/S as a decarbonisation option, companies should prioritise technologies with higher capture rates such as iron bath reactor smelting to avoid carbon lock-in effects and minimise residual emissions. Further, companies considering mitigation through CCU must take responsibility of how the captured carbon is being used and make sure it is not leading to additional emissions.

2.3.2 Direct reduced iron to electric arc furnace (DRI-EAF)

Since the energy demand in the DRI-EAF route is already electrified by using the EAF to produce steel, this route can achieve deep emission reductions by decarbonising the reducing agent (for which methane is traditionally used) and the electric power supply (Mission Possible Partnership and Net-zero Steel Initiative, 2021). The reduction step can be decarbonised in various ways. One of the most technologically advanced way is hydrogen-based direct reduction, where emissions can be mitigated by using low-carbon hydrogen (see Box 3 on hydrogen) instead of methane which is commonly used today. Hydrogen-based DRI steel production has developed rapidly in the last few years and is expected to reach a TRL level of 7-9 by 2030 (Draxler et al., 2021). The first industrialscale hydrogen DRI plant was planned to be put in operation in China in 2022, while the first one in Europe is planned to be put in operation in 2024 (Agora Industry et al., 2021). However, scaling this production route faces several potential barriers such as the timely deployment of clean electricity supply, hydrogen storage, and water supply for electrolysis (Beswick et al., 2021; Löfgren and Rootzen, 2021). Also, the iron ore required for DRI is of a higher grade compared to that required for blast furnaces and providing a sufficient supply of highgrade iron ore for DRI could become a barrier to large scale deployment. Potential solutions to overcome that are discussed in (Nicholas and Basirat, 2022b, 2022c).

In addition to hydrogen-based DRI, other, more innovative production routes which are less developed could also play an important role in the mid-to long term future (Fischedick et al., 2014). One of those is molten oxide electrolysis (MOE) which reduced the iron ore directly with electricity and thus does not require any hydrogen feedstock. Compared to the BF-BOF route, MOE uses about 40% less energy, and 20% less energy than the DRI hydrogenbased route (Chan et al., 2019). MOE is already practised at commercial scale in the aluminium, zinc and nickel industries, while commercialisation in the iron and steel industry is expected around 2040 (Denis-Ryan et al., 2016).

Box 3

The different shades of hydrogen.

Hydrogen has been produced and used as a fuel since the beginning of the 20th century, predominantly produced from methane. Due to the high significant volume of emissions that the conventional production process generates, various ways of producing hydrogen with less emissions are under development. Different production methods for hydrogen are categorised using a set of shades. The only fully climate neutral process of doing so is through water electrolysis driven by electricity generated from renewable resources – green hydrogen. Other processes can reduce emissions to various extents. The most common shades of hydrogen are presented below.

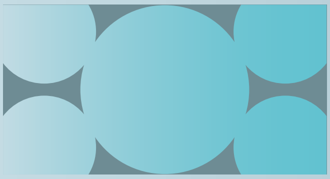
In 2020, almost all global hydrogen supply was generated from fossil fuels with blue hydrogen representing 0.7% and only 0.03% of the supply generated via electrolysis (IEA, 2021). Low-emissions technologies are still being developed and need to be proven at scale. Green hydrogen production has been accelerating in the last few years, indicating the start of an exponential growth even though starting from very low levels. Nevertheless, the acceleration of global green hydrogen production is not moving fast enough to be in line with a 1.5°C-compatible scenario (Boehm et al., 2022).

Grey H2

Produced with fossil fuels, typically using natural gas through methane steam reforming, or with coal using coal gasification. Generates CO_2 emissions.

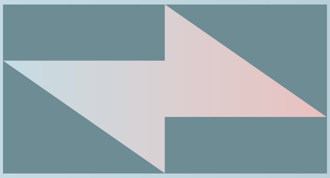
Blue H2

Grey hydrogen produced using carbon capture and storage (CCS). CO_2 emissions are reduced, but not eliminated.



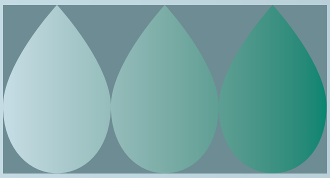
Turquoise H2

Produces hydrogen and solid carbon based on methane pyrolysis. If the thermal energy is generated from renewable sources, and the carbon is permanently stored, the process does not emit CO_2 to the atmosphere.



Pink H2

Hydrogen made through water electrolysis powered by electricity generated from nuclear power.



Green H2

Hydrogen made through water electrolysis powered by electricity generated from renewable resources. No CO_2 emissions are generated.

3

Tracking indicators of steel sector decarbonisation

Key takeways

There are several technological options – in different levels of development – for decarbonisation of the primary steelmaking routes (BF-BOF and DRI-EAF). Some have **limited mitigation potential** (**10-30%** reduction compared to BF-BOF) like improving energy efficiency, or switching to best available technologies; some have **moderate mitigation potential** (up to **65%** reduction compared to BF-BOF) such as retrofitting carbon capture utilization and/or storage (CCU/S) without additional improvements or biomass substitution; and others will result in **deep emissions reductions** (up to **95%** reduction compared to BF-BOF) such as green hydrogen based direct reduced iron (DRI), direct electrolysis or a combination of various measures with limited and moderate mitigation potential (e.g. gas injection to blast furnace + CCU/S).

Because the secondary steel production route (scrap-EAF) generates marginal process emissions from electrode degradation, its decarbonisation is almost fully dependent on the decarbonisation of the energy supply.

We have identified three **key supply-side priorities** for the global steel sector to be aligned with the Paris Agreement temperature goal, which steel makers should consider:

1. Cease – new investments in blast furnaces unless built with technologies suitable for deep emission reduction

2. Innovate - and commercialise deep reduction technologies for primary steel production in a timely manner; and

3. Enhance - the recycling of scrap steel

We analysed a set of drivers for each of these key supply-side priority areas and found both positive and negative signs of the global steel sector's transformation to 1.5°C Paris Agreement compatible scenarios.

- Despite the large amount of planned and capacity under construction for additional BF-BOF route – which would result in high demand for CCU/S and efficiency measures for its decarbonisation – only five CCU/S projects are currently under development.
- There is a rapidly rising number of announced low-carbon steel plant projects, indicating the potential start of an exponential trend over the last three years. The majority of which are expected to become operational within the next few years. Even though most of them (57%) are in the research, pilot or demonstration phase, it is an essential step towards commercialisation and large-scale deployment in the longer-term.
- Hydrogen based steel production makes the majority (65%) of low-carbon steel projects.
- Despite the strong interest in green hydrogen-based steel production among companies engaging in low-carbon steel projects, that interest is not well reflected in the overall steel project pipeline as DRI only plays a minor role among planned steel capacity additions (roughly 5% of planned capacity and capacity in construction).
- The supply of steel scrap needs to increase in terms of volume and improve in terms of quality in order for the sector to achieve a 1.5°C-compatible trajectory. However, insufficient data makes it challenging to track advancements in those areas.

3.1 Drivers of transformation

As presented in the State of Climate Action report (Boehm et al., 2022), evaluating the progress of transformation needed to achieve international climate goals in different sectors is critical for informing where best to focus attention and change the future course of action.

In the case of the global steel sector, there has been little observed change historically in the emission intensity of production (see Figure 5). Nevertheless, progress towards decarbonisation could still be taking place. To find out if this is the case for the steel sector, we look at early signs of sector transformation. We do so by tracking indicators driving the process of transformation rather than the outcome of that transformation (e.g. emissions intensity or absolute emissions) (Höhne et al., 2021).

The selection of the driver indicators is informed by 1.5°C-compatible pathway analyses. More specifically, we derive them from the three key supply-side priority areas defined in section 3: (1) Cease new investments in blast furnaces unless built with technologies suitable for deep emission reduction, (2) Innovate and commercialise deep reduction technologies for primary steel production in a timely manner, and (3) Enhance the recycling of scrap steel. For each of these priority areas, we identify driver indicators affecting those priority areas, as presented in Table 4. Although the list of indicators is not comprehensive due to data limiltations, they serve as a basis for the analysis of current progress and the identification of potential gaps or challenges.

Table 4
Overview of the selection of driver indicators.

Priority/transformation	Driver indicator
1. Cease – new investments in blast furnaces unless built with technologies suitable for deep emission reduction	New blast furnace capacities in the pipeline *(Data source: Global steel plant tracker (Global Energy Monitor, 2022), March 2022 edition)*
2. Innovate - and commercialise deep reduction technologies for primary steel production in a timely manner	Low-carbon steel projects in the pipeline or announced and the technologies behind them: 1. Number of CCU/S projects (operating and in the pipeline 2. Number of green/low-carbon hydrogen projects planned to go online/ announced & DRI capacity on the pipeline 3. Green hydrogen production (Data source: Green steel tracker (Vogl et al., 2022) and web search) 4. Annual investment on low-carbon technology RD&D (Data source: Not available)
3. Enhance - the recycling of scrap steel	1. Steel scrap recovery rate 2. R&D projects aiming to improve processes to remove contaminants from steel scrap and efficient sorting 3. Number of goverments with policies/regulations to improve sorting (Data source: Not available)

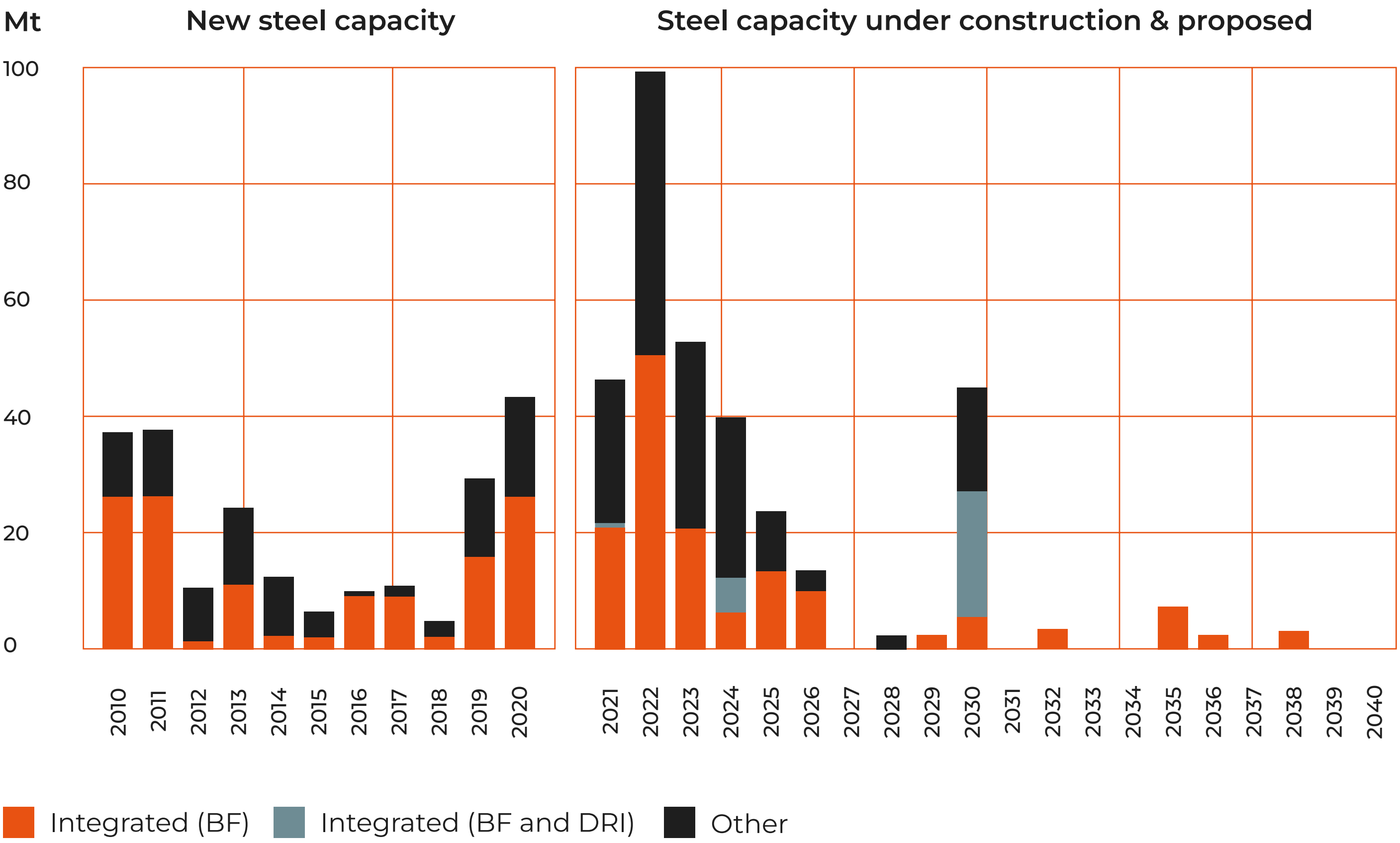
3.2 Cease – new investments in blast furnaces and develop decarbonisation strategies for them

As presented in Section 2.3, the BF-BOF route is the hardest to decarbonise. While existing efficiency measures led to a 15-20% process emissions reduction potential, near-zero emissions technologies – still in various stages of development – such as retrofitting with CCU/S, lead to a maximum process emissions reduction potential of 50-90% depending on the technologies used.

Furthermore, this route also features in recently added capacity, with 56% of new added steel capacity between 2010 and 2020[2] based on the BF ironmaking route (see Figure 6). Of planned capacity and capacity under construction between 2021 and 2040, at least 50% is based on the BF route. As presented in Figure 5, there is an expected spike in new capacities in 2030. That is largely the result of India's goal to almost double its steel production to 300 Mtpa by then compared to current levels (Hindustan Times, 2022). This means that, to stay in line with a 1.5°C-compatible trajectory, new added blast furnace plants will, at some point within its lifetime, either need to have efficiency measures and be equipped with CCU/S or become stranded assets. This implies a strong role for the CCU/S-based decarbonisation route, which would result in a range of residual emissions (see section on CCU/S), should this trend continue. If plans to expand blast furnace capacity are realized, it is important that companies invest in technologies which are easy to fit

2
Includes planned capacity and capacity under construction

Figure 6
Steel capacity additions until 2020 and capacity in the pipeline from 2021.



Authors' calculations based on data from the March 2022 edition of the Global Steel Plant Tracker (Global Energy Monitor, 2022). Proposed new steel capacity and capacity under construction indicates which year the capacity is expected to become operational.

CCU/S to as well as developing plans for the infrastructure development required for the processing of captured carbon.

The role of CCU/S for already existing blast furnace capacity appears less certain. Among existing blast furnace facilities, nearly half of the capacity (45%) is already far beyond or at the point of reaching its expected lifetime, while another 26% will reach the expected end of lifetime within 10-20 years (see Figure 3). This poses an important opportunity to steer away from the blast furnace route but also a risk to lock in a significant share of the technology stock to the that route, particularly as plants already beyond their expected lifetime could be renewed within the next few years. Using this situation as an opportunity and shifting away from blast furnace-based ironmaking would require planning and preparation in the near term. Another relatively large part (26% of existing blast furnace-based capacity) is younger than 20 years and thus facing a new investment cycle within the next five to ten years. That creates a window of opportunity to change the direction and invest in near-zero emissions technologies such as the DRI route.

The required investments in a blast furnace in the new investment cycle, of around 15-20 years (see section 2.1), typically amounts to a third to half of the initial investment cost of about USD 280-300 million (Vogl et al., 2021). That is a relatively high cost and could therefore provide an opportunity for steelmakers to reconsider its production route as the new investment cycle approaches. Vogl, Olsson and Nykvist (2021) found this to be the most logical time for a steelmaker to shift to another, near-zero emissions technology, given the substantial investment needs for each new investment cycle, and considering lost revenues in the required pause in production[3] between investment cycles. Should all steelmakers choose to do so, starting in 2022, all existing blast furnace capacity could be phased out by 2037/2038. Should such a decision, however, be delayed by 5 or 10 years, the phase out year gets closer to 2050 and could put the climate target at risk by contributing to significant additional cumulative emissions.

3 In a new investment cycle of a blast furnace steel plant, operations need to be paused for a couple of months in order to make the necessary technological updates.

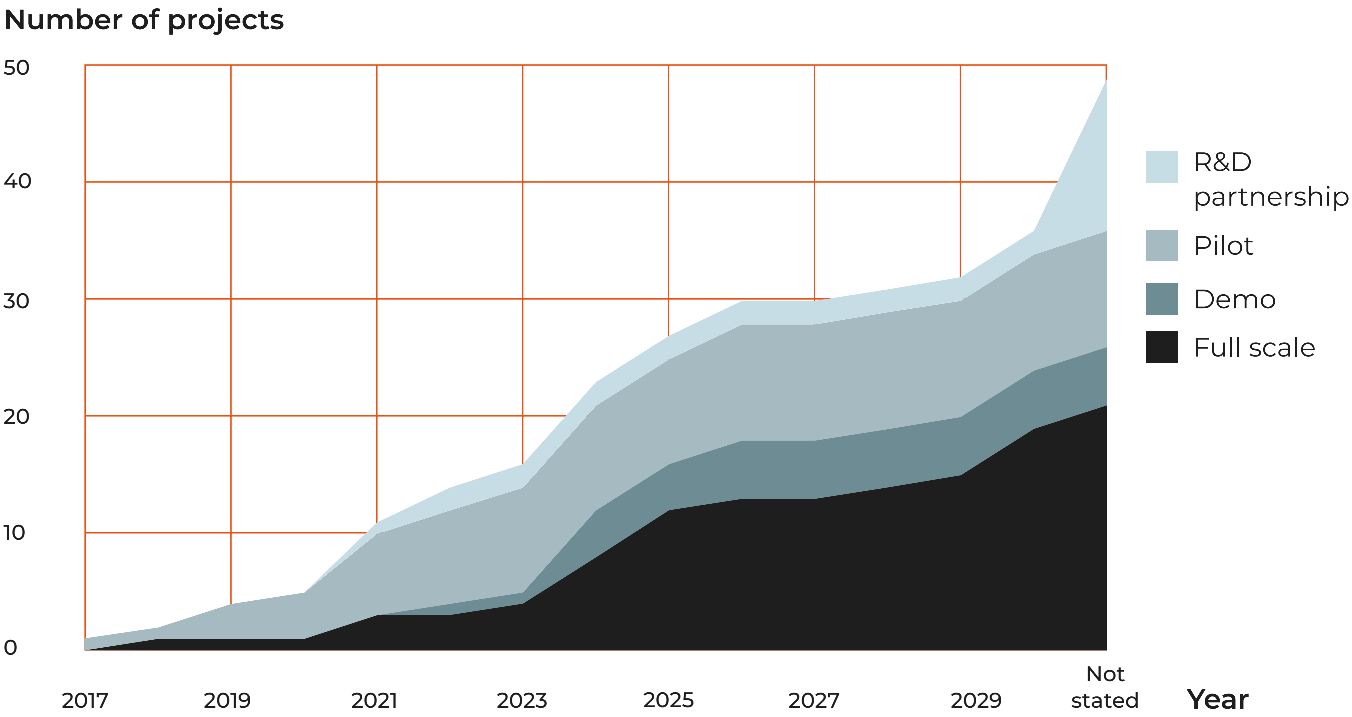
A steel company's decision to shift from blast furnace to a near-zero emissions technology in the end of an investment cycle will evidently also be influenced by the technological readiness and cost of alternative technologies. An increased focus on the rapid and timely demonstration and commercialisation of near-zero emissions technologies is therefore of high importance.

3.3 Innovate – and commercialise deep reduction technologies in a timely manner

Even though the wide range of near-zero carbon steelmaking technologies together could reduce emissions in the steel sector to the extent that is needed, developing and deploying them in a timely manner is imperative (Wang et al., 2021). While steel companies continue to invest in coal-reliant blast furnaces, data from the Green Steel Tracker (Vogl et al., 2022) suggests

Figure 7

Number of low-carbon steel projects globally according to when they are being planned to become operational.

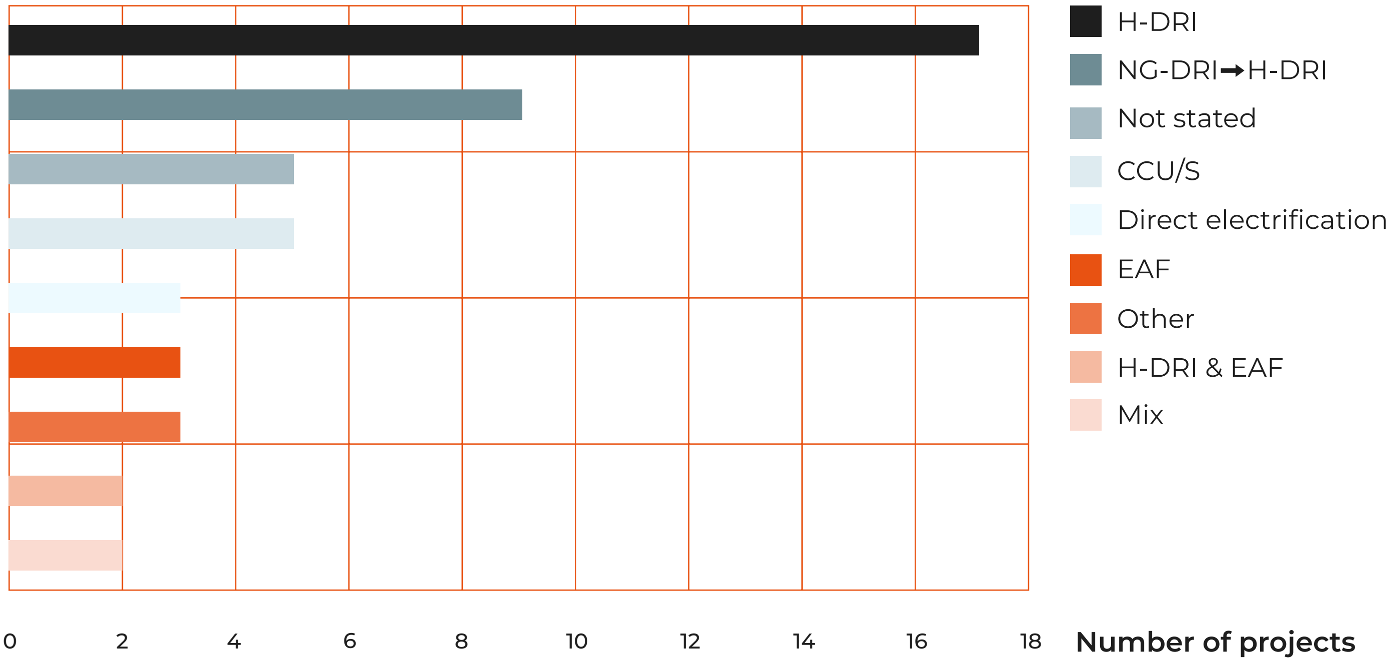


Authors' calculations based on data from the Green Steel Tracker (Vogl et al., 2022). The data was updated in March 2022 .

that there is a rapidly rising number of announced low-carbon steel plant projects, indicating the potential start of an exponential trend over the last three years albeit starting from a low reference point (Figure 7). However, comparing to 1.5 - compatible benchmarks available in the literature, the current pipeline is not in line with what will be required by 2030. In the Energy Transitions Commission's (Delasalle et al., 2022) 1.5 - compatible scenario (Carbon Cost scenario), 71 low-carbon primary steel plants need to be in operation by 2030 (Figure 7). That is more than 3.5 times more than the currently full-scale plants expected to be in operation by then. The IEA/IRENA (IEA et al., 2022) estimates wider range of 40-200 low-carbon steel plants in operation by 2030. The majority of the announced projects are expected to become operational within the next few years, and even though most of them (57%) are in the research, pilot or demonstration phase, meaning that they might not have a notable direct influence on the carbon intensity of global steel production, it is an essential step towards commercialisation and large-scale deployment.

The technologies that are being considered under these projects provide insights regarding what companies currently view as the most promising decarbonisation options. An overview of these technologies is shown in Figure 8. Of the announced lowcarbon steel projects, hydrogen-related projects make up the clear majority, about 65% of all projects (excluding projects where the technology is not specified).

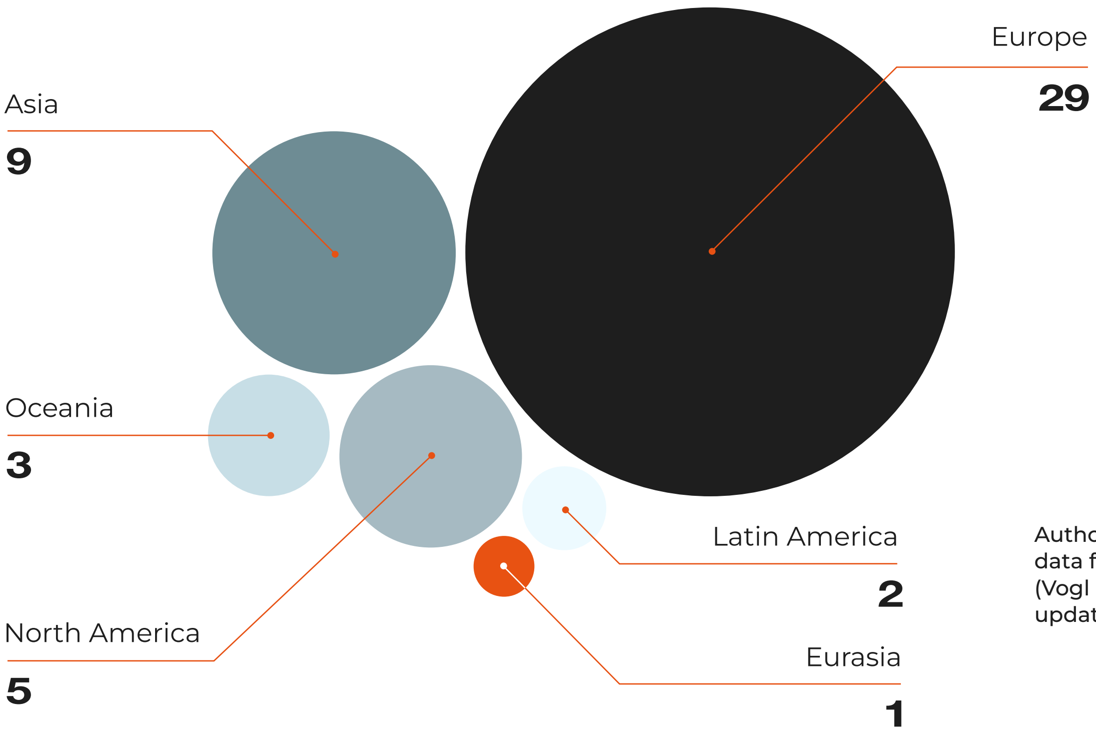
Figure 8
Number of announced low-carbon steel projects globally by technology type.



Authors' calculations based on data from the Green Steel Tracker (Leadership Group for Industry Transition, 2021). The data was updated in November 2021. H-DRI refers to green hydrogen-based direct reduced iron, NG-DRI ➞ H-DRI refers to projects using natural gas-based direct reduced iron but plan to switch to green hydrogen in the near/medium-term future, CCU/S refers to carbon capture and usage or storage, and EAF refers to scrap steel to electric arc furnace.

But looking at the regional distribution of low-carbon steel projects, there seem to be a mismatch in terms of innovation and expected future capacity expansion. Most of the future demand growth is expected to take place in the developing world, while Europe is currently leading innovation (see Figure 9). This indicates a strong need for technology transfer and sharing of experience.

Figure 9
Number of low carbon projects by region.



Authors' calculations based on data from the Green Steel Tracker (Vogl et al., 2022). The data was updated in March 2022.

3.3.1 Number of CCU/S projects at steel production sites (operating and in the pipeline)

Despite being one of the sectors in which CCU/S will be most needed to achieve net-zero emissions, it is one of the sectors with least activity in terms of planned projects (Biermann, 2022). An analysis of the number of CCU/S-related projects in the current pipeline suggests significantly less activity compared to that of the DRI-based route. Only five projects, representing 11% of low-carbon projects (excluding projects where the technology is not specified) are focusing on the development of CCU/S (Figure 8). According to data from the Green Steel Tracker and complimentary web search by the authors, one new CCU/S project was announced each year between 2018 and 2021. In order to speed up the development of CCU/S in the steel sector, increased R&D, pilot, and demonstration efforts are needed.

Carbon capture technologies are costly. The technology itself, as well as the transport and storage of captured CO_2 lead to increased energy demand, which translates into additional costs. Therefore, CCU/S will only make economic sense in an environment where there is a cost to releasing CO_2 into the atmosphere, i.e. with some form of carbon pricing, or if the captured

CO_2 can be reused in climateneutral manner (i.e. as feedstock for materials that will store the carbon rather than in processes that emit it back to the atmosphere). However, carbon pricing mechanisms do not exist globally, and where they exist, the carbon price tend to increase slowly and gradually. This incentivises the adoption of cheaper and already commercialised mitigation measures such as energy efficiency. Nevertheless, once carbon prices increase to such levels where CCU/S start to make sense from an economic perspective, it is important that the technology is available. Therefore, applying other mechanisms in the short term will be important to promote the development of the technology. Examples of such mechanisms include private-public partnerships and contracts for cost difference.

3.3.2 Number of green/low-carbon hydrogen projects planned to go online/announced and DRI capacity in the pipeline

The interest in hydrogenbased steel production emerged strongly in the last two years, representing the vast majority of announced lowcarbon steel projects in years 2020 and 2021 (Vogl et al., 2022).

Despite the strong interest it is not well reflected in the overall steel project pipeline. DRI only plays a minor role in the current steel pipeline (roughly 5% of planned capacity and capacity in construction). The DRI technology, if it is fed by natural gas to begin with, could be switched to hydrogen at a later stage, which would make it a more attractive option for companies to reduce emissions and prepare for full decarbonisation, as well as avoid ending up with stranded assets.

The indicated preference for hydrogen-based steel production suggested by the data presented in this report can also be strengthened through concrete examples: Tata Steel's CCS Athos project in the Netherlands was cancelled in late 2021 as the company decided to opt for green hydrogen-based steel production instead. Despite a successful feasibility study on the potential of transporting and storing captured CO_2 in the North Sea Canal Area, the company expects that the increasing availability of green hydrogen and resulting falling costs of the gas will make green hydrogenbased steel cost competitive (Burgess, 2021).

Almost a third of the announced hydrogen-related low-carbon steel projects are primarily based on natural gas for the time being and aiming to shift to green or low-carbon hydrogen in the future. That shift will be highly reliant on the advancements in the green hydrogen sector and its cost competitiveness relative to natural gas and other fossil fuels.

While the price of natural gas might mainly influence steelmakers which have already decided to go for the DRI route, the price of coking coal could have an accelerating influence on the green steel sector. As a result of a combination of factors including cyclones and floods damaging or destroying mining infrastructure, border closures during the Covid-19 pandemic and diplomatic tensions between countries, the global price of coking coal increased sharply in 2021 and peaked in October 2021. Coking coal was responsible for about half of the cost of the raw materials required to produce a ton of steel. The continuation of such incidents in combination with overall decreasing investments in coking coal mines suggest that the price may remain elevated (Clercq et al., 2022). Steel companies taking such a scenario into account could lead to an accelerated transition away from the blast furnace-based production route.

3.3.3 Green hydrogen production

As suggested by the growing interest for green hydrogen-based DRI, as well as by 1.5°C-compatible scenarios, green hydrogen-based ironmaking could scale significantly in the near- to mid-term future. Doing so, however, not only requires a shift in technology away from BF to DRI, but also in feedstocks and material supply chains. That, in turn, will be reliant on the development of appropriate infrastructure, including renewable energy-based electricity and hydrogen storage, but also ensuring sufficient water supply.

The price of electricity is a key cost contributor to green hydrogen production, and the cost of green hydrogen makes a strong influence on the economic viability of H-DRI ironmaking. Therefore, a steel company's access to rich renewable energy resources may influence its decision with regard to how to secure its green hydrogen supply (or whether to opt for that route to begin with) (Gielen et al., 2020; IRENA, 2020).

The scaling of green hydrogen-based ironmaking will require the deployment of renewablebased electricity generation and infrastructure. The increased share of variable renewable energies (i.e. wind and solar) is likely to lead to higher variations in electricity prices; fewer periods with moderate electricity prices and more periods with high or low electricity prices. Investing in larger hydrogen storage capacities could enable steel producers to take advantage of periods with low electricity prices and hence significantly reduce the costs for H-DRI steelmaking (Toktarova, 2021). At the same time, green steel production could help manage volatile energy prices and provide gridbalancing services.

Another outcome could be that the supply chains in the steel sector are shifted. Countries endowed with rich renewable and iron ore resources could start exporting "green" reduced iron ore instead of exporting iron ore directly. Examples of such countries are Australia and Brazil, which are the two biggest producers of iron ore globally (Garside, 2022). The rich renewable energy resources could enable those counties to produce green hydrogen at a comparatively low cost, and thus produce green iron at lower costs relative to in regions with higher costs of clean electricity. Doing so could create new revenue streams in those countries while contributing to the decarbonisation of steelmaking in the importing regions (Gielen et al., 2020; Toktarova et al., 2020).

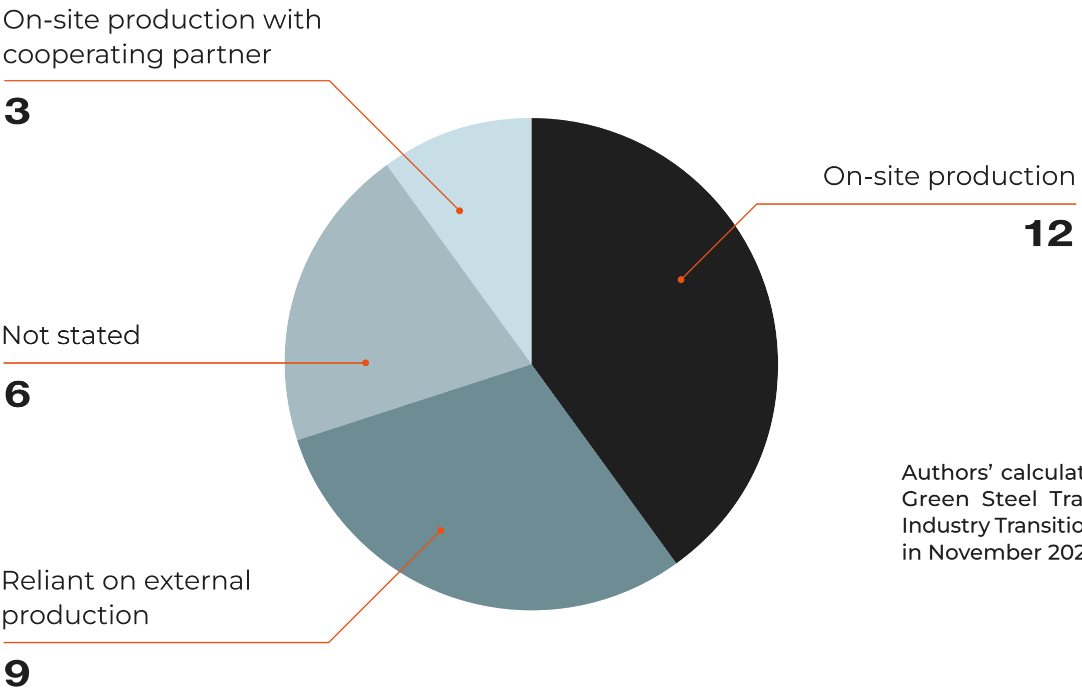
But scaling green hydrogen production also leads to increased consumption of water. Green hydrogen producing countries need to ensure that the rise in water consumption does not negatively impact the ecosystem or local communities (Kolodziejczyk, 2022).

Based on this, steel companies might be incentivised to develop green hydrogen production on-site to reduce operational costs and potentially also overall costs, but also to improve energy/feedstock security. While companies/projects reliant on external green hydrogen production could be exposed to higher operational costs, they would instead forego the initial investment for green hydrogen production. The most economically attractive option is likely to be highly reliant on local renewable energy-based electricity prices. On-site production could reduce the risk for a shortfall of supply. There are concerns that, despite the rapid acceleration of green hydrogen projects globally, there will be a shortfall in supply, and that some of the announced projects risk not being implemented due to lack of financing and governmental support (Por, 2020). In turn, an imbalance between supply and demand may lead to surging prices. Based on benchmarks developed for 1.5°C-compatible scenarios, the current rate of expansion of the global green hydrogen sector is well off track (Boehm et al., 2022).

4 10% of projects have not stated how they plan to acquire green hydrogen for their steel production.

Among green hydrogen DRI projects in the Green Steel Tracker database (Vogl et al., 2022; update March 2022), about half[4] of announced and ongoing projects are developing green hydrogen production on-site, while another 10% are also developing it internally but through cooperation with external partners (Figure 10). About 30% of projects are reliant on external production.

Figure 10
Number of announced low-carbon hydrogen projects in the steel sector categorized by ownership.

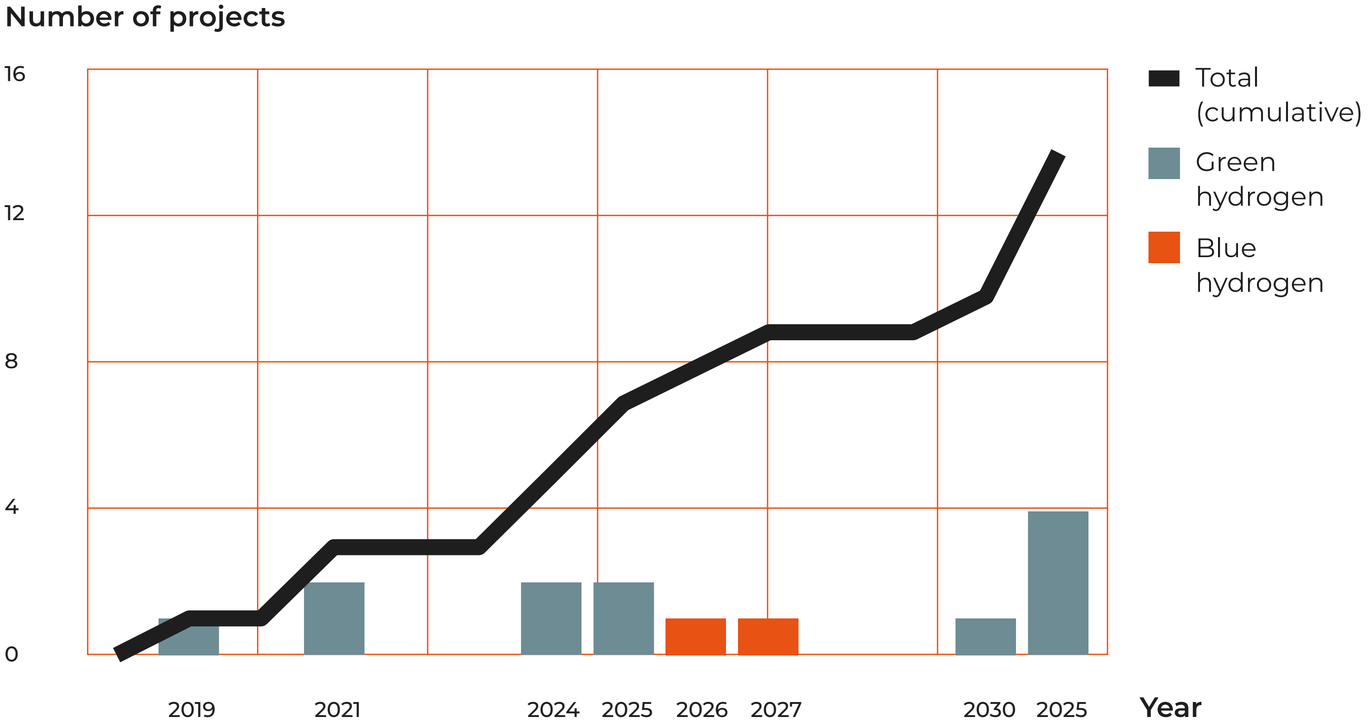


Authors' calculations based on data from the Green Steel Tracker (Leadership Group for Industry Transition, 2021). The data was updated in November 2021.

The number of green hydrogen production projects linked specifically to the steel sector is growing. If projects in the pipeline are realized as planned, 10 projects will be online by 2030 (Figure 11). Due to lack of data, however, the green hydrogen production capacity those would contribute to is yet unclear and it is therefore not possible to gauge whether that is in line with what would be needed in a 1.5°C-compatible scenario.

Figure 11

Number of low-carbon hydrogen production projects in the steel sector planned to become operational.



Authors' calculations based on data from the Green Steel Tracker (Vogl et al., 2022). The data was updated in March 2022.

Even if green hydrogen-based DRI production has a higher mitigation potential and is the focus of this section, some hydrogen companies (14%) also consider blue hydrogen as a low-carbon alternative. Nevertheless, judging from the current pipeline of low-carbon steel projects, the majority of those are planning on using natural gas as a transitioning fuel until green hydrogen becomes more cost competitive than natural gas.

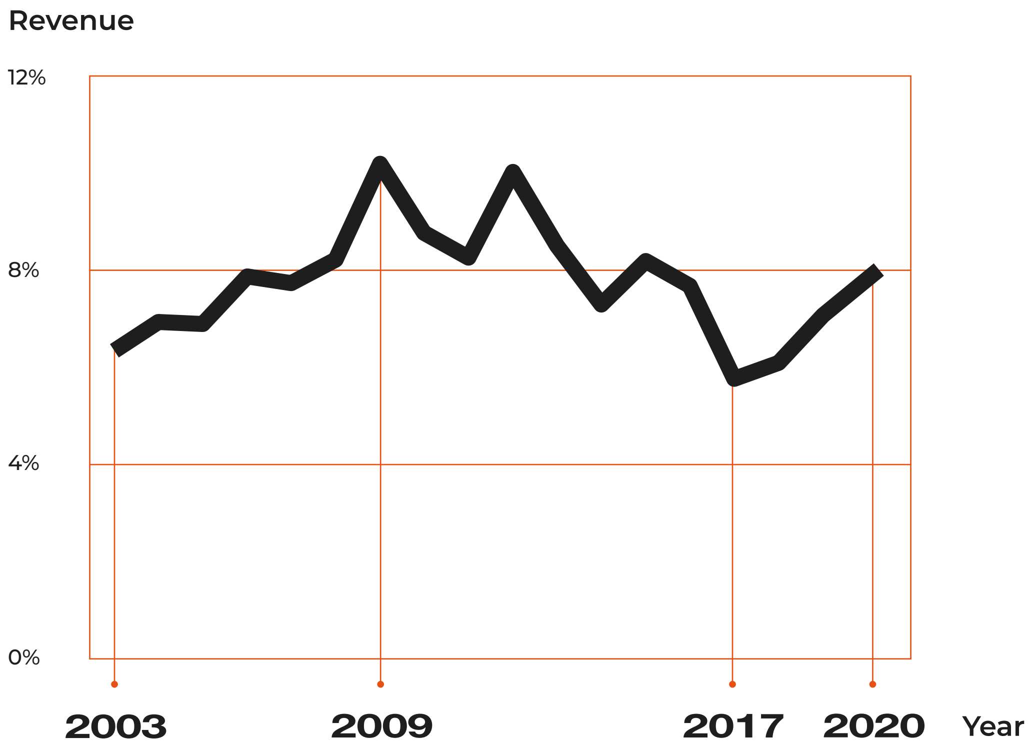
3.3.4 Annual investment in low-carbon technology RD&D

The share of steel companies' revenue invested in new processes and products, including capital expenditure and R&D, temporarily increased between 2003 and 2009, before declining again to reach below 2003 levels in 2017. In the last few years (2017-2020), the rate has picked up again, reaching 8% in 2020[5] (Figure 9). Even though this data suggests that current investments would be above what is needed for 1.5°C - alignment, the data does not necessarily cover investments in decarbonisation efforts solely. More granular data on investments is needed to identify the type of new processes and products those investments are directed toward which is not specified in the existing data. That means that, part of those investments could go towards optimising existing technologies and operations rather than to developing deep emission reduction technologies.

5
The rates are derived using data reported by a limited number of companies – from 23 in 2003 to 66 in 2020.

Figure 12

The share of revenue invested in new processes and products, including capital expenditure and R&D among World Steel Association member companies.



Source: (World Steel Association, 2021). Produced by author.

3.4 Enhance – the recycling of scrap steel

As more countries industrialise, the amount of scrap steel generated will increase over time. This provides an opportunity to mitigate emissions through increasing the secondary steel production.

On a global level, the scrap recovery rate lies around 70-85%, but it differs across regions as well as per type of steel (Bataille et al., 2021; Wang et al., 2021). Increasing the scrap recovery rate will require improved sorting systems and improved methods for maximising the extracted steel from buildings, infrastructure and other equipment containing steel at its end of life. Based on that, tracking R&D projects aiming to improve processes to remove contaminants from steel scrap and efficient sorting could enhance our understanding on progress towards this priority area.

In addition to improving the technical feasibility to enhance the recycling of scrap steel, policies and regulations supporting the increased recycling of scrap is another important driver, but comprehensive databases on such indicators are lacking. In general terms, the global policy support for metals recycling targets both primary and secondary production (OECD, 2018). That, in some cases, risks benefiting primary production disproportionately. This

Is the case, for example, for policies aiming to reduce the cost of energy as primary metal production has a higher energy intensity than secondary production. However, there are policies that might focus mostly on supporting secondary production of metals. An example of policy support that could specifically be directed towards secondary production of metals is public investment finance which has grown in the last few years following the increase in green bonds. Measures improving waste management such as landfill taxes and bans, and the public establishment of separated recycling collection can also indirectly benefit secondary production of metals. Countries with domestic mineral resources and emerging economies are more actively supporting primary production of metals while support for secondary production is more prevalent in advanced economies.

Even though these insights give us an idea of potential gaps, available data to track indicators and early signs of transformation under this priority area are insufficient. We therefore seek improved data collection on indicators such as scrap steel recovery rates, R&D and polices, both globally and regionally.

In terms of actual scrap use in key steel producing countries and regions, the rate has remained relatively steady in the past five years with small increases in China, the EU, Turkey, Japan, and Russia, and decreasing rates in the US and the Republic of Korea (Bureau of International Recycling, 2022). In 2021, Turkey, who is also the world leader in scrap imports, had the highest share of scrap use in crude steel production at 86%, followed by the US, the EU, Russia, and the Republic of Korea.

4

Climate action plans by the global top 60 steel companies

Key takeways

- **Of the 60 top steelmaker companies, 26 have a GHG emission reduction target.** These 26 companies produced over a third of global primary and secondary steel in 2019 – equivalent to 35% of CO_2 emissions from steel production globally.
- The majority of companies that have a climate target, have one or two interim targets in addition to longer term target (>2040). Four companies have only short-term targets (<2030).
- **15 companies (from the top 60) have carbon neutrality, or net-zero target emissions target,** including 7 of the largest steel producers.
- Overall - **we estimate an emissions reduction potential for the whole global steel sector between 7-11% in 2030 and 31-41% in 2050** assuming full achievement of GHG emission reduction targets in comparison to the baseline scenario.
- **Companies with GHG emission reduction targets consider a wide range of technologies and measures to fulfil them.** Most frequently mentioned technologies are hydrogen-based DRI, increased use of renewable energy and CCU/S. While hydrogen-based DRI has a deep emission reduction potential (~95% reduction compared to BF-BOF) and CCU/S moderate-deep emissions reduction potential (~50-90% when compare to BF-BOF), all other measures considered by companies have only limited emissions mitigation potential (~10-30% compared to BF-BOF).
- **The majority of companies do not have a clear roadmap for implementing these measures.** Of the 26 steel producers with targets, 12 do not provide an emissions reduction plan; 6 mention limited emissions reduction measures, and only 8 steelmakers have a comprehensive, detailed emissions reduction plan incl. timeline, targeted technologies and measures to achieve their targets and challenges toward implementation.
- **The vast majority of the 26 steelmakers do not explain how they will reduce emissions beyond short-term actions and measures with limited emissions reduction potential** such as increasing energy efficiency and the share of renewable energy. Without additional investments in deep emissions reduction technologies for the longer-term, short-term improvements may create a technology lock-in that could jeopardize the global steel sector decarbonisation.

4.1 Methods overview

In this section we present the key findings from our latest analysis on the mitigation targets of the top 60 steel companies to:

1. provide a comprehensive overview of commitments and plans of major steel companies, and

2. quantify those commitments and estimate the emissions mitigation potential of the global steel sector.

For our analysis, we selected the top 60 steel producing companies, based on the primary and secondary steel production in 2019 reported in World Steel Association (World Steel Association, 2020a). These 60 companies accounted for 61% of global total primary and secondary steel production.

Detailed description of the data and method applied in the analysis can be found in de Villafranca Casas et al. (2022). We have only considered publicly available information for our data collection (e.g. corporate sustainability reports and responses to CDP climate change questionnaires).

First, we systematically collected information on the GHG emission reduction targets, and the technologies or measures the companies consider for meeting their climate-related target: the emission reduction plans. We collected data on GHG emission reduction targets and emission reduction plans until July 2022.

Second, we estimated the potential reduction of the full implementation of GHG emission reduction targets compared to a baseline scenario. To obtain the global sector CO_2 emissions mitigation potential, we extrapolated the targets share of the top 60 companies to the rest of the companies.

Due to data availability limitations, the emission reduction calculations covers scope 1 and 2 emissions but excludes scope 3 emissions. The importance of scope 2 emissions is further strengthened by the expected increase in direct and indirect electrification of steel production in a 1.5°Ccompatible scenario. Scope 3 emissions are limited (IEA, 2020). More information on the boundaries in Box 1.

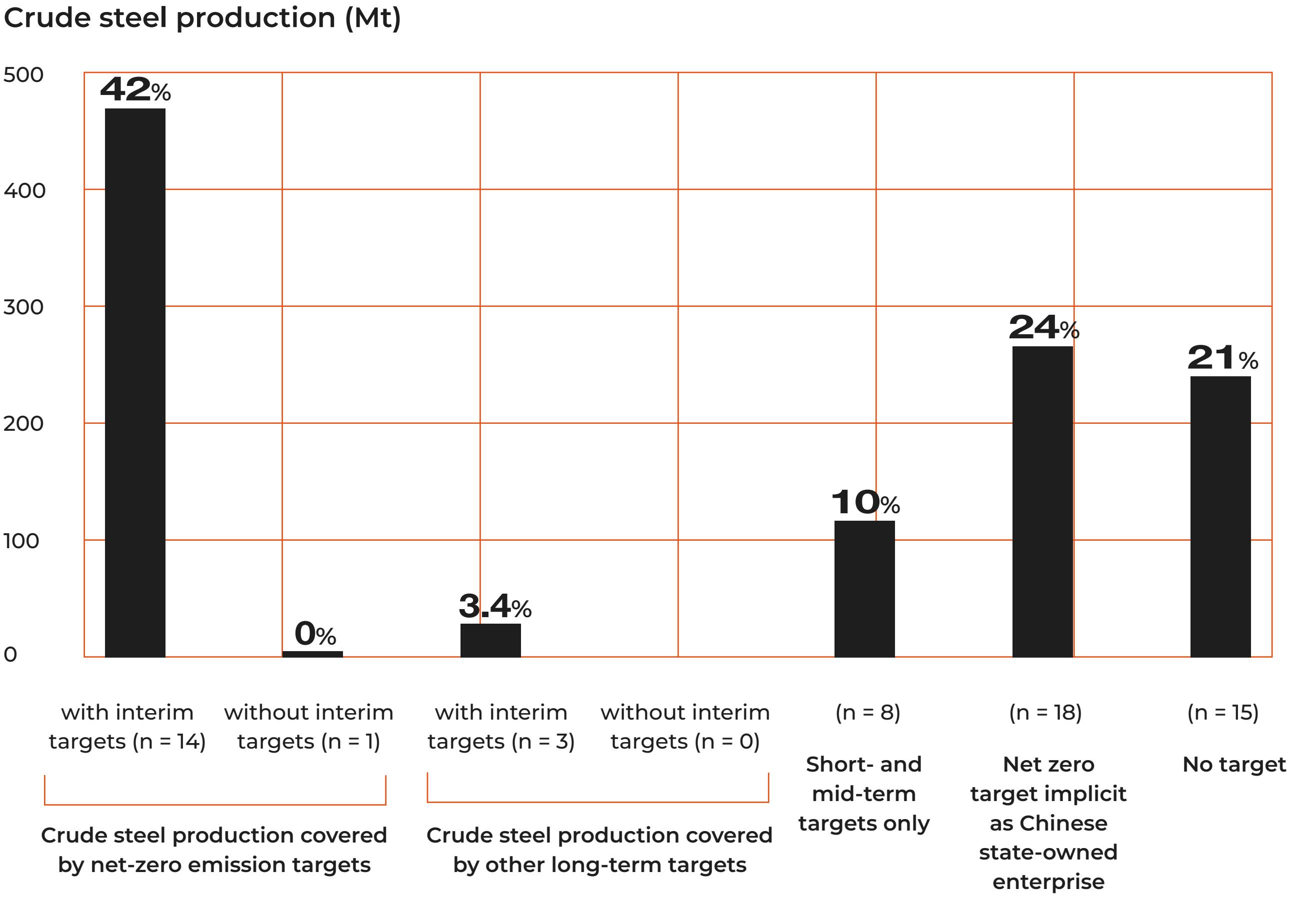
4.2 Overview of GHG mitigation targets

Of the top 60 crude steel producers, 26 have a GHG emission reduction target, 23 of which are from companies headquartered outside of China. When adding Chinese state-owned steelmakers (see Box 4 on Chinese SOEs), 43 of the 60 largest steelmakers have a GHG emission reduction target (Figure 13). The sum of the 26 companies' crude steel production equals 55% of the top 60's crude steel production in 2019 (Figure 13).

Of the top 60 steel producers, 15 have a net-zero emissions target. Seven of these companies are within the largest 15 steelmakers and therefore contribute substantially to the large coverage. Net-zero emissions targets translate to roughly 42% of the crude steel production by the top 60 producers (Figure 12), excluding Chinese SOEs.

Figure 13

Overview of short-term (2022-2029), mid-term (2030-2039) long-term (2040 and after) GHG emission reduction targets by 60 largest steelmakers.



% represents share of top 60 global steel makers in 2019. Source: de Villafranca Casas et al. (2022)

The majority of companies that have a GHG emission reduction target, have one or two interim targets (see Figure 13). Only 10% of the crude steel production from the top 60 producers in 2019 is covered by a single target: the largest 14 crude steel producers have more than one climate target. In sum, 46% of crude steel is covered by more than one climate target (see Figure 13). Among the top 60 crude steel producers, 2030 and 2050 are the most common target years. Many companies that have a net-zero emissions target, also have an emission reduction target as a first or second interim target for 2030.

Almost 500 Mt of the top 60 steelmakers' crude steel production is covered by net-zero emissions targets for 2050, of which just over 300 Mt is also covered by interim targets, mostly being emission reduction and intensity reduction targets, excluding Chinese SOEs. A few Chinese non-SOE steelmakers have a target to peak emissions before 2025, and often have intensity targets (see Box 5 for more details on Chinese SOEs).

Box 4

The role of Chinese state-owned enterprises.

Of the 60 top steelmakers studied in this report, 31 are headquartered in China, 18 out of these are state-owned enterprises (SOEs), where 16 are fully state owned, and 2 have more than 50% state ownership. Chinese SOEs are subject to China's national, regional and sectoral emission reduction targets, and therefore fall under China's national steel target of achieving net-zero emissions by 2060 and peaking emissions in 2030 (Lin, 2022).

Being responsible for 53% of global steel output (World Steel Association, 2022), efforts in decarbonising the Chinese steel sector will be imperative to reaching the 1.5°C temperature goal of the Paris Agreement. Due to the country's comparably large share of SOEs, its corporate climate action environment looks slightly different compared to most other parts of the world.

Chinese SOEs are responsible for 67% of steel production in 2020. Among the Chinese companies, only four (which are SOEs) have set GHG emission reduction targets. Three of the companies aim to reach climate or carbon neutrality by 2050 (ten years ahead of the national target), while one aims to reduce emissions by 30% by 2035 and to reach climate neutrality in an unspecified year as of yet. All aim to peak emissions by 2025 or earlier. All of those targets were announced after China declared to reach carbon neutrality by 2060 (Chen et al., 2021). And even though the governmental goal to peak CO_2 emissions from the steel sector to 2025 was moved five years forward in February 2022, SOEs existing early peaking targets remain in place (Tingyao Lin, 2022). Recent studies, however, show that peaking Chinese steel emissions before 2030 is not only needed to achieve the 1.5°C temperature target, but also feasible (Chen et al., 2021; Schäpe and Tsang, 2021; Nicholas and Basirat, 2022a).

By enjoying competitive advantage through governmental subsidies and local protectionism (Jingrong et al., 2020; Nilsson et al., 2021), SOEs are required to take lower financial risks with respect to investments in novel low-carbon technologies and are thus presented with the opportunity to take the lead in decarbonisation. What is more, because many Chinese SOEs are large relative to private companies, their engagement in R&D, piloting and demonstration could have a substantial influence on the global cost of near-zero emissions technologies and contribute to the generation of economies of scale. As an example, China's emerging green hydrogen sector – producing the cheapest electrolysers globally – is near exclusively lead by SOEs (FitchRatings, 2022). Similarly, SOEs could play an important role in the development of near-zero emissions steelmaking technologies.

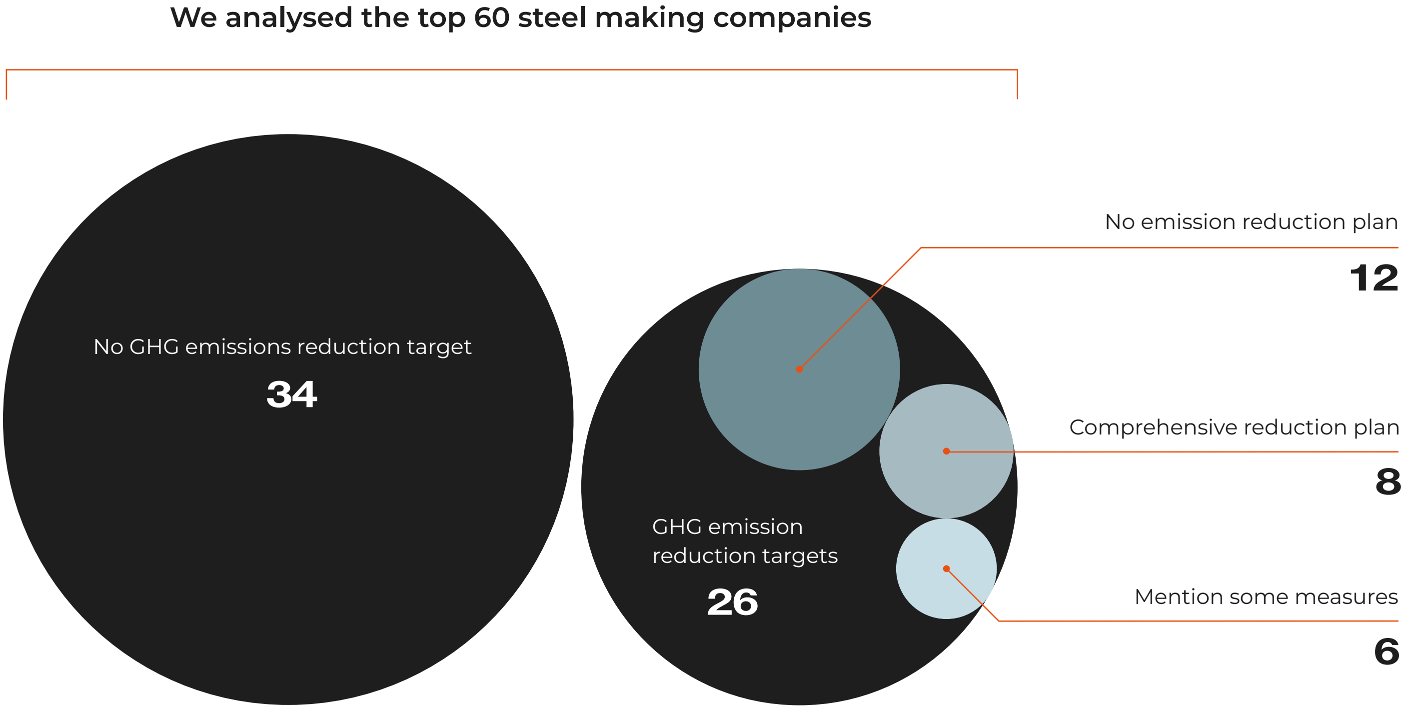
But so far, few Chinese SOEs have announced their own GHG emission reduction targets. Slow action among SOEs could also impede climate action in the private sector. Because Chinese SOEs enjoy a competitive advantage resulting from governmental support, early action from private steel companies could prove financially unfeasible unless backed by supporting climate policy.

4.3 Measures and technologies considered in emission reduction plans

In Section 2, we presented several options to reduce GHG emissions in the various steelmaking processes. As shown in Section 3.1, we found 26 steelmakers with one or more climate-related targets. Here, we present what emission reduction measures these 26 companies consider in their publicly available documentation to realise their climate-related targets (see Figure 14). In case a company considers more than one emission reduction measure, we show all measures in Figure 14. Hence, the number of emission reduction measures in Figure 14 exceeds the number of GHG emission reduction targets (26).

Figure 14

Emission reduction plans of top 60 global steelmakers by crude steel production in 2019.



Source: de Villafranca Casas et al. (2022)

Of the 26 steel producers, 12 do not provide an emission reduction plan; 6 mention some emission reduction measures and 8 steelmakers have a comprehensive, detailed emission reduction plan (Figure 14). These 8 companies present their mitigation measures in a coherent and comprehensive manner in the public domain. Of these, 3 are among the 10 largest steel crude steel producers. These companies provide, for example, a timeline, explain the targeted technologies and measures on a step-by-step basis, provide the corresponding emission reduction potential, and highlight any challenges toward implementation in publicly available information. None of these 8 companies are headquartered in China. For 6 companies, very little detail was given and for 12 we could not identify an emission reduction plan at all.

The vast majority of the 26 steelmakers do not explain how they will reduce emissions beyond short-term actions and limited mitigation measures (see Figure 15); they prioritise these short-term actions. From all the limited mitigation potential measures, 'higher share of renewable energy' in the production process is the most common followed by 'increased used of scrap steel in EAFs', 'increase use of BATs and energy efficiency', and use of hydrogen in BF-BOF. Although all these measures can reduce emissions in the short-term, it is crucial that companies invest in longer-term deep emission reduction measures, too (see Section 2.3). As explained in Section 3.2, these short-term improvements may even create a technology lock-in and could potentially create an investment barrier to the realisation of the steelmakers' long-term GHG emission reduction targets. It is unclear if these measures will be implemented in existing plants or are also included in plans of future plant developments. If companies mean the latter, then excluding deep mitigation potential measures from BF-BOF route would not only jeopardize achieving climate targets but would also risk stranded assets (see our first key priority area in Section 2.3.1).

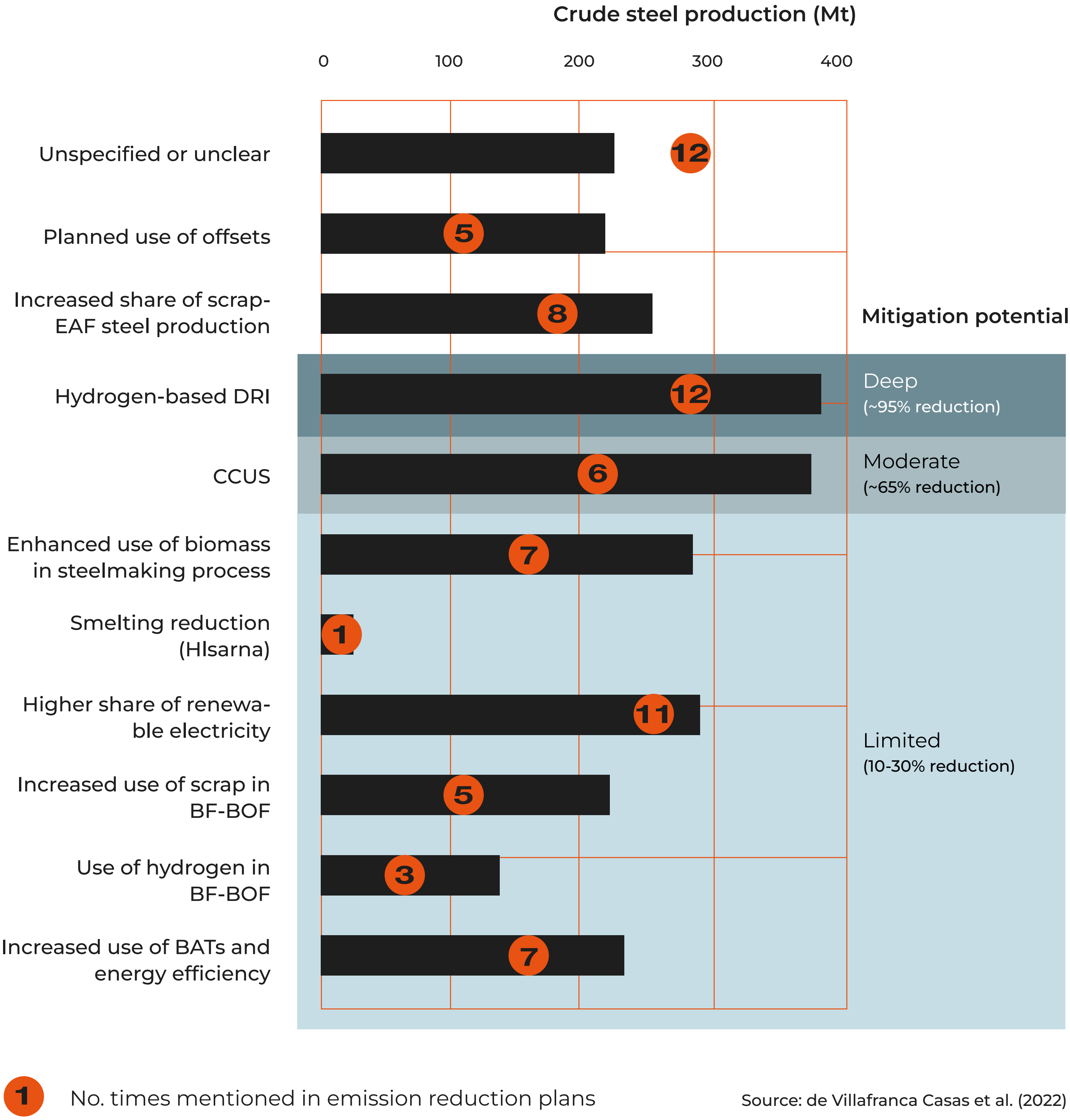
'CCU/S' and 'hydrogen-based DRI' are the two measures with moderate and deep emissions reduction potential being considered by companies in their emission reduction plans (see Figure 15). As presented in Section 2.3, these technologies will enable decarbonisation of primary steel making but are still at various levels of development. To be able to achieve decarbonisation, these reduction technologies need to be innovated and commercialised in the next years (see our second key supply-side priority area in Section 3.3). There are good examples underway of companies developing and implementing deep emissions reduction technologies to move away from traditional steel making (see Box 5).

Nine companies out of 26 with a GHG emissions reduction target intend to use CCU/S technologies to achieve their targets. We consider CCU/S a technology with moderate emissions reduction potential on its own, as leads to large residual emissions unless equipped with additional measures like energy efficiency (see Section 2.3.1). Given the vast existing capacity of BF-BOF, also within companies we analysed, we expected many companies to opt for CCU/S as an emissions reduction measure. However, we found only few companies currently considering it to achieve their GHG emission reduction targets. This could be due to the early developmental stage of these technologies or perhaps because they are currently only focusing on short-term, limited emission reduction measures.

Almost every company for which a public emission reduction plan was available considers more than one measure. For example, the company may consider increasing the use of renewable energy in the short-term and switch to hydrogen-based steelmaking in the long-term. Including more than one measure is a positive sign, especially for primary steel production. While we found that companies are mostly planning to use measures with limited emission reduction potential, we do not analyse specific cases

Figure 15

The emission reduction measures that are considered by the 26 companies with climate targets, showing the number of times measures were mentioned and the sum of crude steel production in 2019.



Source: de Villafranca Casas et al. (2022)

where a combination of measures are envisioned. As explained in Section 2.3 and Table 3, a combination of limited mitigation measures may lead to moderate to deep emissions reduction potential for primary steelmaking.

Fifteen of the 26 steelmakers with a GHG emission reduction target state that they want to pursue hydrogenbased steelmaking in DRI installations and/or use hydrogen in BF-BOF installations (Figure 14). The companies that stated that they want to use hydrogen-based DRI, were responsible for 20% of the global steel production in 2019, or a third of the top 60's crude steel production. Another 13% of the top 60's crude steel production is covered by companies who want to use hydrogen in their BF-BOF installations. While hydrogen can be used in both primary steelmaking routes, the impact on emissions reduction varies (see Section 2.3.). Hydrogen-based DRI steel production leads to deep emissions reduction potential of ~95% in comparison to traditional BF-BOF, whilst use of hydrogen in BF-BOF facilities leads to

Box 5

Case study: Replacement of traditional processes with green hydrogen-based steel.

HYBRIT, a project made possible through a private-public partnership with the Swedish Energy Agency, SSAB, LKAB and Vattenfall was initiated in 2016. The project aims at producing carbon-free steel and transition the whole value chain from mine to steel using fossil-free electricity and hydrogen (Hybrit, 2022). A pilot reduction plant was completed in 2020 while a demonstration plant including the production of green hydrogen and sponge iron by direct reduction is to be ready by 2026. The production sites have been strategically chosen based on, among other aspects, the access to renewable energy for green hydrogen production and electricity for the EAF.

The HYBRIT project provides a nice example in setting clear targets; not only do they include a clear overall emission reduction target, but also the definition of clear targets for various components of the project. Such components include, for instance, the development of an underground hydrogen storage facility (Hybrit, 2022). In the long-term, the objective is to have Sweden's three blast furnaces replaced by 2040 – five years ahead of the national carbon-neutrality target (Olsson, 2018)

Although the price of the steel is expected to be higher compared to steel produced from traditional processes based on 2018 electricity, coke and CO2 prices, the companies involved view the transition as a strategic decision considering the increasing political momentum around carbon pricing and emissions reduction in the heavy industry sector. The initiative is also already engaging with the downstream sector. By partnering with SSAB, Volvo is producing the world's first vehicle made with carbon-free steel, planning to initiate small-scale production of concept vehicles and machines in 2022, which will gradually be increased to large-scale production. Moreover, Volvo and SSAB will work together on research and development (SSAB, 2021) limited emissions reduction (of up to ~20% in comparison with BF-BOF. Although many companies also state they want to procure and/or generate more renewable energy, the majority of companies do not specify how they will ensure that the hydrogen production will be green and sustainable. In many cases, hydrogen supply is not considered or specified in the emission reduction plans, although it is a crucial element of a comprehensive green steel strategy.

Barely any steelmaker mentions the required transformation in the global steel sector; we found only a few signs of an integral transformation approach. Given the large number of BF-BOF steelmakers in our sample, large investments and substantial retrofits of the steel plants are required for decarbonisation (see Section 2.3.1). Some steelmakers highlight how challenging this will be for the company, but none acknowledge the challenge for the global steel sector. This may be concerning, as large challenges await the entire sector. An integral approach of sharing knowledge, resource division, and intelligent investments might be required. A few companies have signed up to international cooperative initiatives, that could help in generating the holistic transformation (see Section 5).

Five of the 26 companies, responsible for an estimated 370 $MtCO_2e$ of emissions in 2019 (scope 1 and 2) or 11% (~208 Mt) of global crude steel production, explicitly mention the use of offsetting, aiming to compensate for the residual emissions. The majority of companies do not mention residual emissions, nor how they would reach carbon or climate neutrality, or how they would achieve net-zero emissions. This may be considered a contentious strategy, since offsetting comes with various uncertainties regarding, for example permanence, additionality, and high environmental costs.

4.4 Quantification of potential GHG emissions reduction targets from steel companies

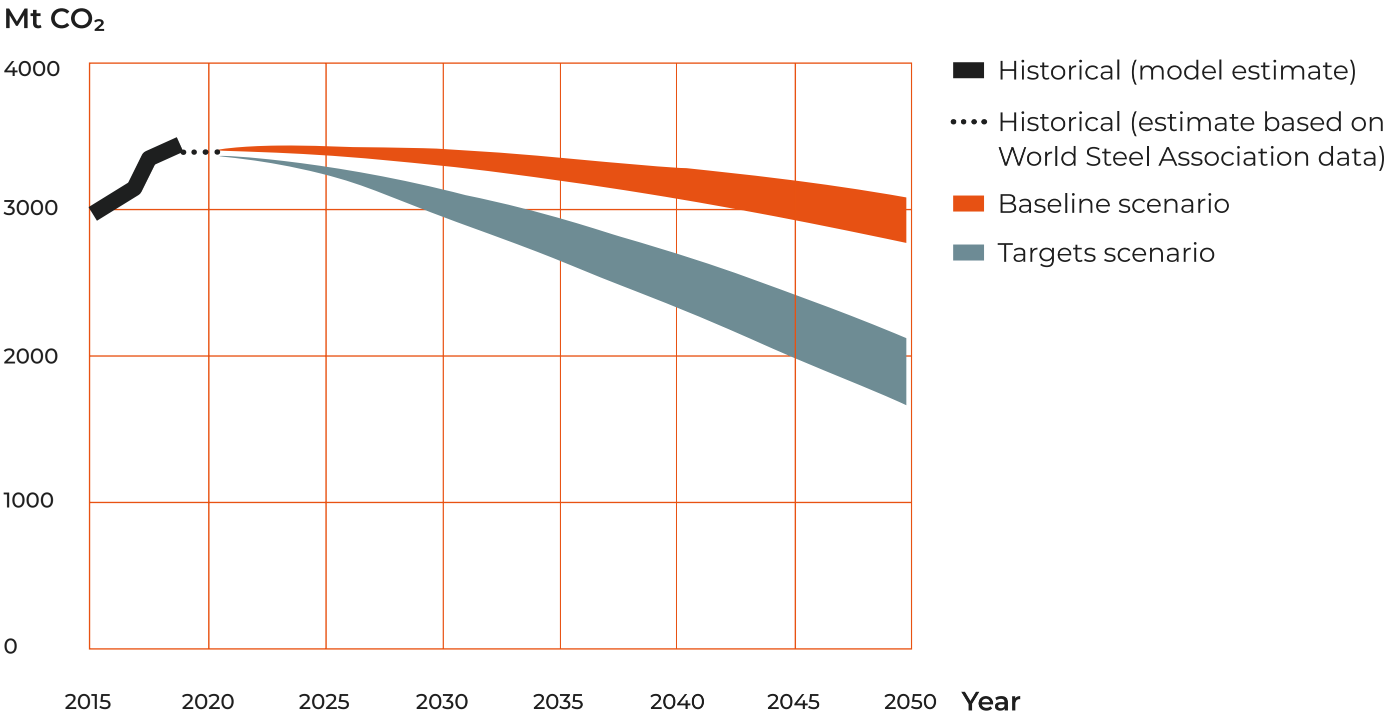
The global steel sector can significantly contribute to global decarbonisation. However, based on the assessment of existing GHG emission reduction targets, we find that the steel sector is far from being on track to achieve decarbonisation by 2050. If all GHG emission reduction targets from the steel sector are achieved, CO_2 emissions from steel production in 2030 will be around 8-11% lower than projected under the reference scenario and up to 31-41% lower in 2050 compared to the baseline scenario (Figure 16) (de Villafranca Casas et al., 2022). **This is equivalent to a reduction from 2019 levels between 7-13% in 2030 and 37-51% in 2050.** The “Targets scenario” include the targets from top 60 companies, an extrapolation of those to the rest of the world based on share, and the implied net zero targets for Chinese SOEs.

While it is encouraging to see that GHG emission targets from steel producers could drive the sector’s emissions down, it is questionable whether it will materialise. As our analysis of the companies’ emission reduction plans show, most companies do not have yet a comprehensive way to achieve their targets. And those that mention measures present mostly short-term actions with limited emissions reduction potential.

In terms of emissions intensity of steel production, we estimate that the global steel sector could potentially reduce between 18-23% in 2030 and between 54-63% in 2050 from 2019 levels if all GHG reduction targets are implemented. In contrast, 1.5°C compatible benchmarks from literature concur that the emissions intensity from steelmaking needs to gradually decline by more than 90% and up to 100% from 2019 levels by 2050.

Figure 16

CO_2 emissions reduction potential from GHG emission reduction targets worldwide (based on extrapolation from top 60 steel producing companies) compared to a baseline scenario.



Source: de Villafranca Casas et al. (2022)

5

International initiatives in the global steel sector

The climate-related targets and potential GHG emission reductions associated with those, as presented in Section 4.2, are not only driven by individual companies, but also by international cooperative initiatives (ICIs) or national-level initiatives. ICIs are multi-stakeholder arrangements, under which non-state and subnational actors collaborate internationally, often cooperating with national governments and other international organisations (Lui et al., 2020). ICIs are associated with various objectives and functions. ICIs can, for example, aim for knowledge sharing and technical implementation, develop sectoral standards or lobby and campaign for policy changes. Although ICIs may not always lead to direct emission reductions, they are highly relevant for sectoral transformations, mainly indirectly through the various functions and objectives (Chan et al., 2018; Hsu et al., 2020).

There is a range of ICIs operating in the global steel sector. Most prominently, the steel sector was one of the focus areas of the Glasgow Breakthroughs during COP26. This Breakthrough was formulated as “to make near-zero emission steel the preferred choice in global markets, with efficient use and near-zero emission steel production established and growing in every region by 2030” (Race to Zero, 2021). The Glasgow Breakthrough on steel brings together global governments to cooperatively accelerate innovation and create economies of scales (Race to Zero, 2021), therefore leaning towards a global climate club for steel decarbonisation (Hermwille et al., 2022). The Breakthrough is endorsed by 30 countries, including several steel-relevant geographies such as India, Japan, the European Union and the United States.

The Glasgow Breakthrough also recognises the importance of other, independent initiatives, that can contribute to the necessary transformation in the steel sector. These and others are presented in Table 5, providing an overview of the most relevant ICIs operating in the global steel sector. Among the most noteworthy and relevant initiatives is Responsible Steel. Eight of the 60 largest crude steel producers are member of this ICI, covering roughly 20% of the 2019 crude steel production of the top 60. Among various environmental and social responsibility topics, Responsible Steel members need to demonstrate that they are committed to the 1.5°C goal of the Paris Agreement.

Several of the ICIs presented in Table 5 focus on increasing the demand for low-carbon steel. Most notably SteelZero, under which organisations and companies publicly commit to only procure net-zero emissions steel by 2050. Although demand-side GHG emission reduction targets of the global steel sector have not been assessed under Section 4, these are highly relevant to further bring about the transformation in the sector. Steel-demanding companies, such as Volvo and A. P. Moller - Maersk, for example, have signed up for SteelZero. The United Nations Industrial Development Organisation's Industrial Deep Decarbonisation Initiatives has a similar approach, urging public and private organisations to set procurement targets for low-carbon industrial products. Such ICIs can ensure that the demand for low-carbon steel will be sufficient in the near- to long-term future and can generate extra incentives for steel producers to switch to low-carbon steelmaking.

The highlighted initiatives in this section, as well as other ICIs operating in the global steel sector, may generate more cohesion for a low-carbon transition. One of the main findings presented in Section 4.3 was a lack of cohesive climate action in the steel sector: companies often present a somewhat individualistic approach regarding their climate strategies. In addition, the companies often do not highlight their membership in public reporting. However, ICIs can play, and have already proven to play, a crucial role in knowledge sharing, campaigning, and agenda-setting. Moreover, they can act as a "bridge" between policymakers, private actors, financial institutions, and civil society, in order to bring about an effective transformation towards net-zero emissions in the global steel sector.

While this ICIs may help drive low-carbon steel demand and supply and facilitate knowledge transfer between various actors within the sector, there is a need for scrutiny. Most notably, for certification and labelling programs for 'green' steel that is produced in a carbon-intensive way. Not doing so risks compromising the sectors' decarbonisation efforts (Holzman, 2021).

Table 5

Non-exhaustive overview of international cooperative initiatives focused on the steel sector decarbonisation.

Processes under established international institutions (e.g. OECD, WTO, G7) and initiatives focussed on single countries are not included here.

→ Supply- side focused ! Demand- side focused

Initiative	Goal / aim as described by the initiatives themselves	Country
Responsible Steel → !	"Building a sustainable steel industry requires cooperation and mutual commitment from companies at all levels of the steel supply chain, representatives of civil society, and other stakeholders. ResponsibleSteel provides the forum for this multi-stakeholder approach. Committed to open dialogue and collaboration with stakeholders to ensure the shared mission is achieved." – Responsible Steel (2018)	Responsible Steel (Australia)
SteelZero !	"Organisations that join SteelZero make a public commitment to procure 100% net-zero steel by 2050. By harnessing their collective purchasing power and influence, sends a strong demand signal to shift global markets and policies towards responsible production and sourcing of steel." – The Climate Group (2022)	Climate Group (United Kingdom) and Responsible Steel (Australia)

Low-Carbon Metallurgical Innovation Alliance	Boost the global steel industry's low-carbon transformation. The alliance, initiated by China Baowu Steel Group, is comprised of 62 enterprises, colleges and universities and scientific research institutions from 15 countries. Backed by the collective research and development resources from global steel enterprises and research institutions, the alliance can carry out fundamental and forward-looking low-carbon metallurgical technology development, promote technological collaboration and exchanges and facilitate the low-carbon transformation of the steel industry." – Ying (2021)	China Baowu Steel Group (China)
Leadership Group for Industry Transition, LeadIT	"The Leadership Group for Industry Transition (LeadIT) is grounded in the conviction that partnership between the public and private sectors is key to achieving the industrial transition and reach net-zero carbon emissions by mid-century. LeadIT members subscribe to the notion that energy-intensive industry can and must progress on low-carbon pathways, aiming to achieve net-zero carbon emissions by 2050. LeadIT the organisation behind the Industry Transition Tracker, an online database that showcases publicly available industry transition roadmaps at national scale." – LeadIT (2022)	Representatives from the Government of Sweden, Government of India, and the World Economic Forum. Secretariat by Stockholm Environment Institute (Sweden)
Clean Energy Ministerial – Industrial Deep Decarbonisation	"The Clean Energy Ministerial Industrial Deep Decarbonisation Initiative (IDDI) is a global coalition of public and private organisations who are working to stimulate demand for low carbon industrial materials by: 1) Encouraging governments and the private sector to buy low carbon steel and cement, and 2) Sourcing and sharing data for common standards and targets. In collaboration with national governments, IDDI works to standardise carbon assessments, establish ambitious public and private sector procurement targets, incentivise investment into low-carbon product development and design industry guidelines." - Clean Energy Ministerial (2021)	United Nations Industrial Development Organisation; co-led by United Kingdom and India
Mission Possible – Net Zero Steel initiative	The Net-Zero Steel Initiative (NZSI) aims to put the global steel sector on a path to reach net-zero emissions by 2050 by: Partnering with an international group of steel industry leaders; Bringing zero-carbon primary steel production technologies to market by 2030; Accelerating the growth of scrap-based production; Focusing on supply dimensions; Demonstrating how steel can be a key part of a net-zero economy" – Mission Possible Partnership (2022).	Energy Transitions Commission (United Kingdom), We mean business coalition (Europe/United States of America), Rocky Mountains Institute (United Stated of America), World Economic Forum (Switzerland)
The Net-Zero Industries Mission	"The Mission will focus on unlocking emission reductions through demonstrations and cooperation across energy intensive and hard-to-abate industries such as steel, cement, chemical, etc. The Mission wants to catalyse the development and demonstration of cost competitive solutions for the efficient decarbonization of hard to abate energy intensive industries worldwide by 2030." – Mission Innovation (Mission Innovation, 2021)	Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (Austria) and Department of Climate Change, Energy, the Environment and Water (Australia)
Science Based Targets initiative (SBTi)	"The SBTi defines and promotes best practice in science-based target setting. Offering a range of target-setting resources and guidance, the SBTi independently assesses and approves companies' targets in line with its strict criteria." – SBTi (Science Based Targets, 2022)	CDP (United Kingdom), UN Global Compact, WRI (United States of America) and WWF (Switzerland)

6

Conclusions and way forward

This report proposed key indicators for assessing progress of the global steel sector, both on aggregate level and also on individual steel companies, toward long-term decarbonisation, and assessed those available in public databases. These proposed indicators are intended to supplement those that are already being assessed in the existing literature to enable comprehensive tracking of progress in the next years, which is a crucial period to materialise the sector transformation in consistency with the Paris Agreement's long-term temperature goal.

Our analysis based on available indicators has shown that the global iron and steel sector is overall in an early stage of its journey towards long-term decarbonisation. On the one hand, we see some encouraging signals such as an increasing number of low-carbon primary steelmaking project plans and company-level net-zero emission pledges. There have also been announcements recently from major steel companies that indicate their accelerated shift away from conventional primary steelmaking process. On the other hand, several sector-wide decarbonisation progress indicators we assessed still do not show substantive progress, and most large steel companies were found not to have a detailed strategy and roadmap yet to decarbonise their production. Even though the global discourse around decarbonisation of steel has advanced considerably in the past decade, our study supports the findings of other studies that the speed of action is not nearly fast enough to keep warming to 1.5°C at the end of the century.

Companies are considering a wide range of technological options with varying degree of emission reduction impact to achieve their climate-related targets. A main concern is on CCU/S, which was among those that are mentioned more frequently in companies' emission reduction plans. While it is evident that CCU/S will be needed to decarbonise the steel sector and achieve the 1.5°C goal of the Paris Agreement, it is important to acknowledge that the use of CCU/S in steel making will result in a range of residual CO_2 emissions depending on the production route. It will become increasingly important to continually monitor the type of technologies the companies would plan to introduce in the coming years.

A wide variety of measures with limited mitigation potential are mentioned in companies' emission reduction plans. Those are short-term measures, such as increased use of renewable energy, and increased use of BATs and energy efficiency. While these measures are crucial to lower emissions in the short-term, they are not enough to achieve decarbonisation in the long term.

Among the key indicators we identified, we found that some of the indicator data, e.g. sector-wide investment on low-carbon RD&D and steel scrap recycling rates, are not readily available. We anticipate that this data would become gradually available to enable comprehensive progress tracking in the next few years.

While this report focused on the supply-side measures in global steel sector, decarbonisation of steel cannot be achieved by the steel companies alone; as presented in Section 4 it requires fundamental transformation across all actors in our economy and society and close cooperation among them (Hermwille et al., 2022). Future progress tracking effort may investigate demand-side progress indicators as well as the progress of national governments (possibly in cooperation with the steel companies) and of international cooperative efforts across public and private actors.

In this report we have focused on scope 1 and 2 emissions from steel production as there is lack of data on scope 3 emissions. Tracking and reporting scope 3 emissions – those from the value chain of steel – could contribute to increase transparency to the sector and help identify areas of opportunity and/or further challenges to reduce emissions to zero.

References

Agora Industry, Wuppertal Institute and Lund University (2021) Global Steel at a Crossroads - Why the global steel sector needs to invets in climate-neutral technologies in the 2020s. Berlin, Germany: Agora Industry. Available at: https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021-06_IND_INT_GlobalSteel/A-EW_236_Global-Steel-at-a-Crossroads_WEB_V2.pdf.

Bashmakov, I.A., Nilsson, L.J., Acquaye, A., et al. (2022) 'Industry', in Climate Change 2022: Mitigation of Climate Change - Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change (IPCC). Available at: https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf.

Bataille, C., Åhman, M., Neuhoff, K., et al. (2018) 'A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement', Journal of Cleaner Production, 187, pp. 960–973. doi:10.1016/j.jclepro.2018.03.107.

Bataille, C., Stiebert, S. and Li, F.G.N. (2021) Global facility level net-zero steel pathways: technical report on the first scenarios of the Net-zero Steel Project. Paris, France: Institute for Sustainable and International Relations (IDDRI); Global Energy Monitor (GEM). Available at: http://netzerosteel.org/wp-content/uploads/pdf/net_zero_steel_report.pdf.

Baylin-Stern, A. and Berghout, N. (2021) Is carbon capture too expensive?, IEA. Available at: https://www.iea.org/commentaries/is-carbon-capture-too-expensive (Accessed: 10 November 2022).

Beswick, R.R., Oliveira, A.M. and Yan, Y. (2021) 'Does the Green Hydrogen Economy Have a Water Problem?', ACS Energy Letters, 6(9), pp. 3167–3169. doi:10.1021/acsenergylett.1c01375.

Biermann, M. (2022) Partial CO2 capture to facilitate cost-efficient deployment of carbon capture and storage in process industries. Chalmers University of Technology. Available at: https://research.chalmers.se/en/publication/531680.

Boehm, S., Lebling, K., Levin, L., et al. (2021) State of Climate Action 2021: Systems Transformations Required to Limit Global Warming to 1.5°C. Washington, DC: World Resources Institute. doi:10.46830/wrirpt.21.00048.

Boehm, S., Jeffery, L., Levin, K., et al. (2022) State of Climate Action 2022. Berlin, Germany and Washington, D.C.: Bezos Earth Fund, Climate Action Tracker, World Resources Institute. Available at: https://www.wri.org/research/state-climate-action-2022 (Accessed: 2 November 2022).

Budinis, S., Krevor, S., Dowell, N. Mac, et al. (2018) 'An assessment of CCS costs, barriers and potential', Energy Strategy Reviews, 22(May), pp. 61–81. doi:10.1016/j.esr.2018.08.003.

Bureau of International Recycling (2022) World Steel Recycling in Figures 2017 – 2021. Steel scrap - a raw material for green steelmaking. Brussels, Belgium: Bureau of International Recycling. Available at: https://www.bir.org/images/BIR-pdf/Ferrous_report_2017-2021_lr.pdf.

Burgess, J. (2021) Dutch CCS project scrapped after Tata Steel opts for hydrogen DRI production route, S&P Global Commodity Insights. Available at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/092121-dutch-ccs-project-scrapped-after-tata-steel-opts-for-hydrogen-dri-production-route (Accessed: 10 November 2022).

Calvin, K., Pereira, J.C. de O. de P., Oreane Edelenbosch Johannes Emmerling, S.F., et al. (2018) 'SPECIAL REPORT Global Warming of 1.5 oC Chapter2 Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', IPCC special report Global Warming of 1.5 oC, p. 82pp. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf.

Chan, S., Falkner, R., Goldberg, M. and van Asselt, H. (2018) 'Effective and geographically balanced? An output-based assessment of non-state climate actions', Climate Policy, 18(1), pp. 24–35. doi:10.1080/14693062.2016.1248343.

Chan, Y., Petithuguenin, L., Fleiter, T., et al. (2019) Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis. London and Karlsruhe, Uk and Germany: ICF Consulting Services Limited and Fraunhofer ISI. Available at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2021/industrial_innovation_part_1_en.pdf.

Chen, J., Li, S., Li, X. and Li, Y. (Agnes) (2021) Pursuing Zero-Carbon Steel in China: A Critical Pillar to Reach Carbon Neutrality. Beijing, China: RMI. Available at: https://rmi.org/insight/pursuing-zero-carbon-steel-in-china/.

Clean Energy Ministerial (2021) Industrial Deep Decarbonisation, Our solutions. Available at: https://www.cleanenergyministerial.org/initiatives-campaigns/industrial-deep-decarbonisation-initiative/ (Accessed: 15 November 2022).

Clercq, F. De, Doyle, A. and Voet, T. (2022) 'High coking coal prices provide glimpse into steelmaking's future', McKinsey & Company, January. Available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/high-coking-coal-prices-provide-glimpse-into-steelmakings-future (Accessed: 13 November 2022).

Climate Action Tracker (2020) Paris Agreement Compatible Sectoral Benchmarks: Elaborating the decarbonisation roadmap. Climate Action Tracker (Climate Analytics, NewClimate Institute). Available at: https://climateactiontracker.org/publications/paris-agreement-benchmarks/.

Davis, S.J., Lewis, N.S., Shaner, M., et al. (2018) 'Net-zero emissions energy systems', Science, 360(6396). doi:10.1126/science.aas9793.

Dawidowski, L.E., Kolmogortseva, O., Person Rocha e Pinho, I., et al. (2019) 'Chapter 4. Metal Industry Emissions', in 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, pp. 1–100. Available at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/3_Volume3/19R_V3_Ch04_Metal_Industry.pdf.

Delasalle, F., Speelman, E., Graham, A., et al. (2022) Making net-zero steel possible - An industry-backed, 1.5°C-aligned transition strategy. Mission Possible Partnership. Available at: https://missionpossiblepartnership.org/wp-content/uploads/2022/09/SteelTSExecutiveSummary.pdf (Accessed: 5 October 2022).

Denis-Ryan, A., Bataille, C. and Jotzo, F. (2016) 'Managing carbon-intensive materials in a decarbonizing world without a global price on carbon', Climate Policy, 16, pp. S110–S128. doi:10.1080/14693062.2016.1176008.

Draxler, M., Sormann, A., Kempken, T., et al. (2021) Technology Assessment and Roadmapping (Deliverable 1.2). Brussels, Belgium: Green Steel for Europe Consortium. Available at: https://www.estep.eu/assets/Uploads/D1.2-Technology-Assessment-and-Roadmapping.pdf.

Energy Transitions Commission (2019) Mission Possible - Sectoral focus: Steel. Energy Transitions Commision. Available at: https://www.energy-transitions.org/wp-content/uploads/2020/08/ETC-sectoral-focus-Steel_final.pdf (Accessed: 29 July 2022).

Fennell, P., Driver, J., Bataille, C. and Davis, S.J. (2022) 'Cement and steel - nine steps to net zero', Nature, 603(7902), pp. 574–577. doi:10.1038/d41586-022-00758-4.

Fischedick, M., Marzinkowski, J., Winzer, P. and Weigel, M. (2014) 'Techno-economic evaluation of innovative steel production technologies', Journal of Cleaner Production, 84(1 December 2014), pp. 563–580. doi:10.1016/j.jclepro.2014.05.063.

FitchRatings (2022) State Owned Enterprises and Climate Change. United States of America: FitchRatings. Available at: https://www.fitchratings.com/research/infrastructure-project-finance/state-owned-enterprises-climate-change-20-06-2022.

Garside, M. (2022) Iron ore mine production by country 2021, Statista. Available at: https://www.statista.com/statistics/267380/iron-ore-mine-production-by-country/ (Accessed: 10 November 2022).

Gielen, D., Saygin, D., Taibi, E. and Birat, J.P. (2020) 'Renewables-based decarbonization and relocation of iron and steel making: A case study', Journal of Industrial Ecology, 24(5), pp. 1113–1125. doi:10.1111/jiec.12997.

Global Energy Monitor (2022) 'Global Steel Plant Tracker'. San Francisco, CA: Global Energy Monitor. Available at: https://globalenergymonitor.org/projects/global-steel-plant-tracker/ (Accessed: 1 November 2022).

Grant, N., Hawkes, A., Mittal, S. and Gambhir, A. (2021) 'Confronting mitigation deterrence in low-carbon scenarios', Environmental Research Letters, 16(6), p. 064099. doi:10.1088/1748-9326/ac0749.

Hermwille, L., Lechtenböhmer, S., Åhman, M., et al. (2022) 'A climate club to decarbonize the global steel industry', Nature Climate Change, 12(6), pp. 494–496. doi:10.1038/s41558-022-01383-9.

Hindustan Times (2022) 'India to double steel production capacity in a decade's time: PM Modi', 28 October. Available at: https://www.hindustantimes.com/india-news/india-to-double-steel-production-capacity-in-a-decade-s-time-pm-modi-101666972547778.html.

Höhne, N., Roy, J., Gaffney, O., et al. (2021) A seismograph for measuring the transformation to net-zero greenhouse gas emissions. Available at: https://newclimate.org/2021/11/03/a-seismograph-for-measuring-the-transformation-to-net-zero-ghg-emissions-discussion-paper/.

Holzman, J. (2021) '"Green" steel label may end up on coal-made products, complicating climate goals', S&P Global Market Intelligence, August. Available at: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/green-steel-label-may-end-up-on-coal-made-products-complicating-climate-goals-66175358 (Accessed: 17 November 2022).

Hsu, A., Höhne, N., Kuramochi, T., et al. (2019) 'A research roadmap for quantifying non-state and subnational climate mitigation action', Nature Climate Change, 9, pp. 11–17. doi:10.1038/s41558-018-0338-z.

Hsu, A., Höhne, N., Kuramochi, T., et al. (2020) 'Beyond states: Harnessing sub-national actors for the deep decarbonisation of cities, regions, and businesses', Energy Research and Social Science, 70(May), p. 101738. doi:10.1016/j.erss.2020.101738.

Hybrit (2022) Fossil-free steel – a joint opportunity! Available at: https://www.hybritdevelopment.se/en/ (Accessed: 14 November 2022).

IEA (2020) Iron and Steel Technology Roadmap: Towards more sustainable steelmaking, Iron and Steel Technology Roadmap. Paris, France: IEA (International Energy Agengy). doi:10.1787/3dcc2a1b-en.

IEA (2021) Net Zero by 2050: A Roadmap for the Global Energy Sector. Paris, France: International Energy Agency. Available at: https://www.iea.org/reports/net-zero-by-2050 (Accessed: 10 August 2022).

IEA (2022) Achieving Net Zero Heavy Industry Sectors in G7 Members. Paris, France: International Energy Agency. Available at: https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members.

IEA, IRENA and UNCC HLC (2022) The Breakthrough Agenda Report. International Energy Agency, International Renewable Energy Agency, UN Climate Change High-Level Champions.

International Iron and Steel Institute (IISI) (2002) World Steel in Figures - 2002 Edition. Brussels, Belgium: World Steel Association. Available at: https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2002.pdf?x25904.

IPCC (2022) 'Summary for Policymakers', in Shukla, P.R. et al. (eds) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press. doi:10.1017/9781009157926.002.

IRENA (2020) Reaching zero with renewables: Eliminating CO2 emissions from industry and transport in line with the 1.50C climate goal. International Renewable Energy Agency.

Jingrong, K., Lu, X., Zhang, J. and Zheng, Y. (2020) 'State-owned enterprises in China : A review of 40 years of research and practice', China Journal of Accounting Research, 13(1), pp. 31–55. doi:10.1016/j.cjar.2019.12.001.

Johnson, O., Shawoo, Z., Talebian, S. and Sanchez, F. (2022) Industry Transition Tracker: Compare roadmaps. Stockholm Environment Institute (SEI). Available at: https://www.industrytransition.org/industry-transition-tracker/compare-roadmaps/ (Accessed: 5 October 2022).

Kolodziejczyk, B. (2022) Will a transition to a hydrogen economy affect water security?, World Economic Forum. Available at: https://www.weforum.org/agenda/2022/09/how-a-transition-to-a-hydrogen-economy-will-affect-water-security/ (Accessed: 11 November 2022).

Kuramochi, T., Ramírez, A., Faaij, A. and Turkenburg, W. (2012) 'Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes', Progress in Energy and Combustion Science, 38(1), pp. 87–112. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0360128511000293?via%3Dihub.

Kuramochi, T. (2016) 'Assessment of midterm CO2 emissions reduction potential in the iron and steel industry: a case of Japan', Journal of Cleaner Production, 132, pp. 81–97. doi:10.1016/j.jclepro.2015.02.055.

Leadership Group for Industry Transition (LeadIT) (2022) Transition - Net-zero carbon emission from industry by 2050. Available at: https://www.industrytransition.org/ (Accessed: 15 November 2022).

Lin, M.T. (2022) China suggests slower steel decarbonization, but retreat on national climate goals seen unlikely, S&P Global. Available at: https://cleanenergynews.ihsmarkit.com/research-analysis/china-suggests-slower-steel-decarbonization-but-retreat-on-nat.html (Accessed: 30 March 2022).

Löfgren, Å. and Rootzen, J. (2021) 'Brick by brick: Governing industry decarbonization in the face of uncertainty and risk', Environmental Innovation and Societal Transitions, 40(December 2020), pp. 189–202. doi:10.1016/j.eist.2021.07.002.

Lui, S., Kuramochi, T., Smit, S., et al. (2020) 'Correcting course: how international cooperative initiatives can build on national action to steer the climate back towards Paris temperature goals', Climate Policy [Preprint]. doi:10.1080/14693062.2020.1806021.

Material Economics (2019) Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry. Available at: https://materialeconomics.com/latest-updates/industrial-transformation-2050 [accessed on 13 July 2020].

Mission Innovation (2021) Net-zero Industries Mission, Missions. Available at: http://mission-innovation.net/missions/net-zero-industries-mission/ (Accessed: 14 November 2022).

Mission Possible Partnership (2022) Net-Zero Steel Initiative, Steel. Available at: https://missionpossiblepartnership.org/action-sectors/steel/ (Accessed: 14 November 2022).

Mission Possible Partnership and Net-zero Steel Initiative (2021) Net-Zero Steel Sector Transition Strategy. Mission Possible Partnership, Energy Transitions Commission, Rocky Mountain Institute. Available at: https://missionpossiblepartnership.org/wp-content/uploads/2021/10/MPP-Steel-Transition-Strategy-Oct-2021.pdf (Accessed: 4 August 2022).

NASA (2012) Technology Readiness Level (Last Updated: Apr 1, 2021). National Aeronautics and Space Administration. Available at: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level/ (Accessed: 10 October 2022).

Net Zero Tracker (2022) Net Zero Stocktake 2022. Cologne, Berlin, Oxford, London, North Carolina, Germany, UK, United States of America: NewClimate Institute, Oxford Net Zero, Energy & Climate Intelligence Unit; Data-Driven EnviroLab. Available at: https://ca1-nzt.edcdn.com/Net-Zero-Tracker/Net-Zero-Stocktake-Report-2022.pdf?v=1655074300 (Accessed: 14 July 2022).

Nicholas, S. and Basirat, S. (2022a) 'IEEFA: China's peak steel emissions shift unlikely to delay carbon reductions'. Institute for Energy Economics and Financial Analysis (IEEFA). Available at: https://ieefa.org/resources/ieefa-chinas-peak-steel-emissions-shift-unlikely-delay-carbon-reductions (Accessed: 12 July 2022).

Nicholas, S. and Basirat, S. (2022b) Iron Ore Quality a Potential Headwind to Green Steelmaking: Technology and Mining Options Are Available to Hit Net-Zero Steel Targets. Australia: Institute for Energy Economics and Financial Analysis (IEEFA). Available at: https://ieefa.org/resources/iron-ore-quality-potential-headwind-green-steelmaking-technology-and-mining-options-are.

Nicholas, S. and Basirat, S. (2022c) Solving Iron Ore Quality Issues for Low-Carbon Steel: Technology Solutions Are Under Development. Australia: Institute for Energy Economics and Financial Analysis (IEEFA). Available at: https://ieefa.org/resources/solving-iron-ore-quality-issues-low-carbon-steel.

Nilsson, A., Smit, S. and Kuramochi, T. (2021) Non-state and subnational climate action in China. Berlin an Cologne, Germany: NewClimate Institute. Available at: https://newclimate.org/wp-content/uploads/2021/12/NewClimate_ChinaNSA_Dec21.pdf.

Nwachukwu, C.M., Wang, C. and Wetterlund, E. (2021) 'Exploring the role of forest biomass in abating fossil CO2 emissions in the iron and steel industry – The case of Sweden', Applied Energy, 288(February), p. 116558. doi:10.1016/j.apenergy.2021.116558.

Oda, J. (2022) Estimated energy intensity in 2019: Iron and steel sector (BF-BOF route). Research Institute of Innovative Technology for the Earth (RITE). Available at: https://www.rite.or.jp/system/en/global-warming-ouyou/download-data/2019_BF-BOF_energy intensity by RITE.pdf (Accessed: 16 September 2022).

OECD (2018) Government Support for Primary and Secondary Metal Production. Paris, France: OECD; Resouce Efficiency & Circular Economy Project. Available at: https://www.bir.org/images/BIR-pdf/Policy-Highlights-Government-Support-for-Metal-Production.pdf.

Olsson, O. (2018) Low-emission steel production: decarbonizing heavy industry, Stockholm Environment Institute. Available at: https://www.sei.org/perspectives/low-emission-steel-production-hybrit/ (Accessed: 11 November 2022).

Por, Y.-L. (2020) Great Expectations - Asia , Australia and Europe Leading Emerging Green Hydrogen Economy, but Project Delays Likely. Lakewood, United States: Institute for Energy Economics & Financial Analysis. Available at: https://ieefa.org/resources/great-expectations-asia-australia-and-europe-leading-emerging-green-hydrogen-economy.

Race to Zero (2021) Steel - Glasgow Breakthrough. Available at: https://racetozero.unfccc.int/system/glasgow-breakthroughs/#:~:text=The Glasgow Breakthrough on Steel,a growing concern by 2030. (Accessed: 11 August 2022).

Responsible Steel (2018) Who we are. Available at: https://www.responsiblesteel.org/about/ (Accessed: 14 November 2022).

Rissman, J., Bataille, C., Masanet, E., et al. (2020) 'Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070', Applied Energy, 266(March), p. 114848. doi:10.1016/j.apenergy.2020.114848.

Rosa, L., Reimer, J.A., Went, M.S. and D'Odorico, P. (2020) 'Hydrological limits to carbon capture and storage', Nature Sustainability, 3(8), pp. 658–666. doi:10.1038/s41893-020-0532-7.

Rosa, L., Sanchez, D.L., Realmonte, G., et al. (2021) 'The water footprint of carbon capture and storage technologies', Renewable and Sustainable Energy Reviews, 138(April), p. 110511. doi:10.1016/j.rser.2020.110511.

Schäpe, B. and Tsang, B. (2021) 1+N: What's in China's upcoming climate plans?, E3G. Available at: https://www.e3g.org/news/1-n-china-upcoming-climate-plans-1n-xie-beijing-han/ (Accessed: 9 December 2021).

Science Based Targets (2022) Ambitious Corporate Climate Action. Available at: https://sciencebasedtargets.org/ (Accessed: 15 November 2022).

SSAB (2021) The future is here – the world's first vehicle made with fossil-free steel. Available at: https://www.ssab.com/en-gb/fossil-free-steel/the-future-is-here-the-worlds-first-vehicle-made-with-fossil-free-steel (Accessed: 11 November 2022).

Swalec, C. (2022) Pedal to the Metal 2022. It's not too late to abate emisssions from the global iron and steel sector. San Francisco, CA, United States of America: Global Energy Monitor. Available at: https://globalenergymonitor.org/wp-content/uploads/2022/06/GEM_SteelPlants2022.pdf.

Swalec, C. and Shearer, C. (2021) Pedal to the Metal 2021. No time to delay decarbonizing the global steel sector, Global Energy Monitor. San Francisco, CA, United States of America: Global Energy Monitor. doi:10.7551/mitpress/11314.003.0023.

Teske, S. (2022) 'Achieving the Paris Climate Agreement Goals. Part 2: Science-based Target Setting for the Finance industry — Net-Zero Sectoral 1.5˚C Pathways for Real Economy Sectors'. Springer. Available at: https://link.springer.com/content/pdf/10.1007/978-3-030-99177-7.pdf (Accessed: 24 August 2022).

The Climate Group (2022) About SteelZero, SteelZero. Available at: https://www.theclimategroup.org/steelzero (Accessed: 14 November 2022).

Tingyao Lin, M. (2022) China suggests slower steel decarbonization, but retreat on national climate goals seen unlikely | IHS Markit, IHS Markit. Available at: https://cleanenergynews.ihsmarkit.com/research-analysis/china-suggests-slower-steel-decarbonization-but-retreat-on-nat.html (Accessed: 28 August 2022).

Toktarova, A., Karlsson, I., Rootzén, J., et al. (2020) 'Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study', Energies, 13. doi:https://doi.org/10.3390/en13153840.

Toktarova, A. (2021) The low-carbon steel industry - Interactions between the hydrogen direct reduction of steel and the electricity system. Chalmers University of Technology. Available at: https://www.researchgate.net/publication/356980332_The_low-carbon_steel_industry_-Interactions_between_the_hydrogen_direct_reduction_of_steel_and_the_electricity_system.

UNFCCC (2021) Climate action pathway - Industry, Global Climate Action UNFCCC; Marrakech Partnership. UNFCCC. Available at: https://unfccc.int/sites/default/files/resource/Vision%26SummaryIndustry2.1.pdf.

de Villafranca Casas, M. J. et al. (2022) 'Climate action in major steel companies: a long way ahead towards zero emissions', [Preprint], Research Square. https://doi.org/10.21203/rs.3.rs-2322621/v1.

Visiongain (2022) Global Steel Market is projected to grow at a CAGR of 3.9% By 2031, Visiongain Ltd. Available at: https://www.globenewswire.com/en/news-release/2022/02/03/2378598/0/en/Global-Steel-Market-is-projected-to-grow-at-a-CAGR-of-3-9-By-2031-Visiongain-Research-Inc.html (Accessed: 11 November 2022).

Vogl, V., Sanchez, F., Gerres, T., et al. (2022) 'Green Steel Tracker'. Leadership Group for Industry Transition. Available at: https://www.industrytransition.org/green-steel-tracker/ (Accessed: 25 August 2022).

Vogl, V., Olsson, O. and Nykvist, B. (2021) 'Phasing out the blast furnace to meet global climate targets to meet global climate targets', Joule, 5(10), pp. 2646–2662. doi:10.1016/j.joule.2021.09.007.

Wang, P., Ryberg, M., Chen, W., et al. (2021) 'Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts', Nature Communications, pp. 1–11. doi:10.1038/

s41467-021-22245-6.

World Steel Association (2020a) Steel Statistical Yearbook 2020 concise version. Brussels, Belgium: World Steel Association. Available at: https://www.worldsteel.org/en/dam/jcr:5001dac8-0083-46f3-aadd-35aa357acbcc/Steel%2520Statistical%2520Yearbook%25202020%2520%2528concise%2520version%2529.pdf (Accessed: 8 June 2021).

World Steel Association (2020b) World Steel in Figures - 2020 Edition. Available at: https://worldsteel.org/wp-content/uploads/2020-World-Steel-in-Figures.pdf.

World Steel Association (2021) ‘Scrap use in the steel industry’. World Steel Association. Available at: https://worldsteel.org/wp-content/uploads/Fact-sheet-Scrap-use-in-the-steel-industry.pdf (Accessed: 16 November 2022).

World Steel Association (2022) 2022 World Steel in Figures. Brussels, Belgium: World Steel Association. Available at: https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2022-1.pdf.

Wu, M., Vora, M. and Chaudhary, I. (2022) Pedal to the metal: Iron and steel’s US$1.4 trillion shot at decarbonisation, Wood Mackenzie. Available at: https://www.woodmac.com/horizons/pedal-to-the-metal-iron-and-steels-one-point-four-trillion-usd-shot-at-decarbonisation/ (Accessed: 10 November 2022).

Xylia, M., Silveira, S., Duerinck, J. and Meinke-Hubeny, F. (2018) ‘Weighing regional scrap availability in global pathways for steel production processes’, Energy Efficiency, 11(5), pp. 1135–1159. doi:10.1007/s12053-017-9583-7.

Ying, W. (2021) ‘Metallurgical innovation alliance formed in Shanghai’, China Daily, 18 November, p. Industries. Available at: https://global.chinadaily.com.cn/a/202111/18/WS61965969a310cdd39bc76280.html.

Yu, S., Lehne, J., Blahut, N. and Charles, M. (2021) 1.5°C Steel: Decarbonizing the Steel Sector in Paris-Compatible Pathways. Alexandria, United States of America: Pacific Northwest National Laboratory, E3G. Available at: https://e3g.wpenginepowered.com/wp-content/uploads/1.5C-Steel-Report_E3G-PNNL-1.pdf.

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