15 Insights on the Global Steel Transformation

IMPULSE

Agora
Industry

Wuppertal
Institut

15 Insights on the Global Steel Transformation

PUBLICATION DETAILS

IMPULSE

15 Insights on the Global Steel Transformation

WRITTEN BY

Agora Industry
Anna-Louisa-Karsch-Straße 2 | 10178 Berlin
T +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-industry.org
info@agora-industrie.de

Wuppertal Institute for Climate,
Environment and Energy
Döppersberg 19 | 42103 Wuppertal
T +49 (0)202 2492-0
F +49 (0)202 2492-108
https://wupperinst.org/
info@wupperinst.org

PROJECT LEAD
Wido K. Witecka
wido.witecka@agora-energiewende.de

Ole Zelt
ole.zelt@wupperinst.org

AUTHORS
Wido K. Witecka (Agora Industry)
Oliver von Eitzen Toni (Agora Industry)
Julian Somers (Agora Industry)
Dr. Kathy Reimann (Agora Industry)
Ole Zelt (Wuppertal Institute)
Alexander Jülich (Wuppertal Institute)
Clemens Schneider (Wuppertal Institute)
Prof. Dr. Stefan Lechtenböhmer
(Wuppertal Institute)

Typesetting: grafikbuero.berlin
Proofreading: WordSolid
Title picture: Adobe Stock I yuliachupina

298/03-I-2023/EN
Version: 1.1, June 2023

ACKNOWLEDGEMENTS
We wish to thank the following colleagues for their contribution in various ways: Helen Burmeister, Dr. Oliver Sartor, Aylin Shawkat, Frank Peter (all Agora Industry), Dr. Jahel Mielke, Anja Werner, Alexandra Steinhardt, Kinita Shenoy (all Agora Energiewende), Saerok Jeong (NEXT group), Prof. Dr. Max Åhman (Lund University)

Please cite as:
Agora Industry and Wuppertal Institute (2023):
15 insights on the global steel transformation

www.agora-industry.org

Preface

Dear reader,

"We are walking when we should be sprinting." With these words the Intergovernmental Panel on Climate Change (IPCC) Chair Hoesung Lee summed up the latest IPCC Synthesis Report. This IPCC report estimates that with currently implemented policies, the world is projected to warm by 3.2°C by 2100. Much greater efforts are needed to drive down greenhouse gas emissions faster.

The steel sector can play a key role in this. Often labeled as a *hard-to-abate* sector, the steel sector has the potential to turn into a *fast-to-abate* sector: our study demonstrates that a net-zero iron and steel sector by the early 2040s is technically feasible. New key elements for an accelerated, lower-cost steel transformation include a swift roll-out of direct reduced iron technology, the creation of an international green iron trade, the phase-out of coal in steelmaking, and, above all, expanded international cooperation in tandem with targeted regulatory frameworks.

This study summarises the key findings of our work on the global steel sector. In future publications, we will provide more detailed analyses of low-carbon technologies, our 2050 decarbonisation pathways, the role of international green iron trade and the steel sector's potential to generate negative emissions.

We wish you a pleasant read!

Frank Peter
Director, Agora Industry

Prof. Dr. Manfred Fischedick
President, Wuppertal Institute

Key findings at a glance:

1	**A net-zero steel sector and a coal phase-out in steelmaking by the early 2040s are technically feasible. This can turn iron and steel from a *hard-to-abate* to a *fast-to-abate* sector and be a key element to increase global climate ambition.** The key strategies to achieve such an accelerated steel transformation are material efficiency, an increase of scrap- and hydrogen-based steelmaking plus bioenergy and carbon capture and storage (BECCS).
2	**Green iron trade can lower the costs of the global steel transformation and can be a win–win solution for green iron exporters and importers.** Transporting *embodied hydrogen (H_2)* as green iron will be significantly cheaper than transporting *H_2 and its derivatives* by ship. For countries with high renewable H_2 costs, green iron imports can increase the competitiveness of low-carbon steelmaking, thereby helping to safeguard local jobs in the steel industry. For green iron exporters, this can create new jobs and value added.
3	**Carbon capture and storage (CCS) on the coal-based blast furnace-basic oxygen furnace route (BF-BOF) will not play an important role in the global steel transformation.** CCS on the BF-BOF route is unlikely to reduce direct CO_2 emissions beyond 73% and cannot address upstream emissions (coal mine methane leakage). Compared to other key technologies, steelmakers' efforts to commercialise this technology are currently very low. If BF-BOF CCS does not materialise, new coal-based steel plants face a high carbon lock-in and stranded asset risk.
4	**To unlock the full acceleration potential of the steel transformation, national governments need to create an adequate regulatory framework and develop cross-country strategic partnerships.** International cooperation will be needed to address key bottlenecks (i.e. DRI plant engineering, suitable iron ore qualities, low-carbon H_2), minimise stranded assets and help to unlock green iron trade.

Content

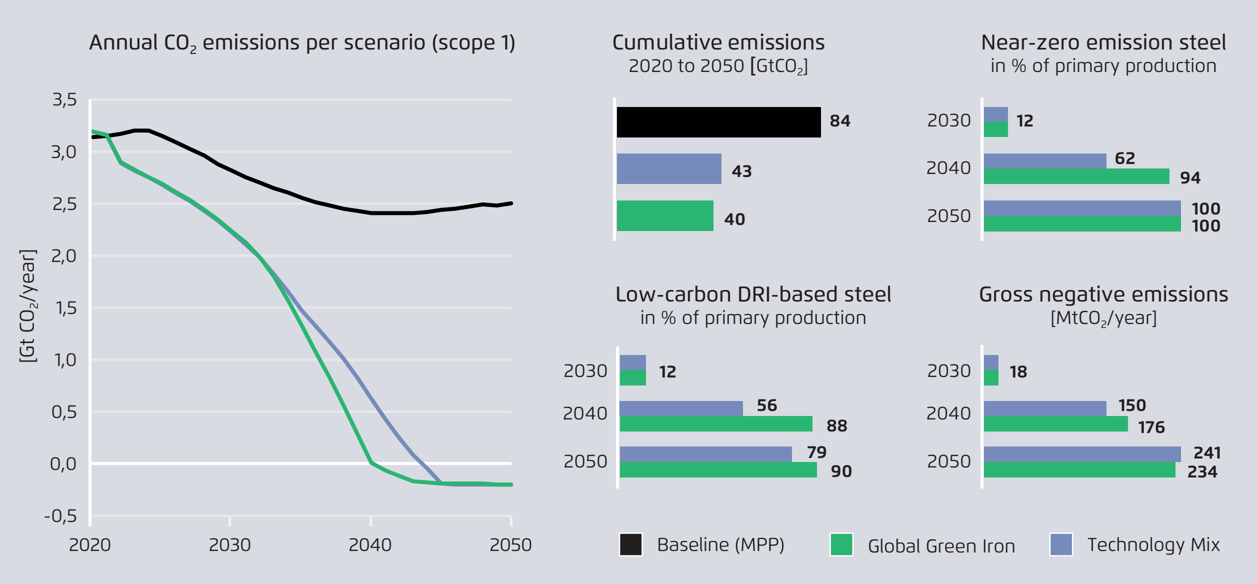
List of abbreviations

AEL	Alkaline iron electrolysis
ASEAN	Association of Southeast Asian Nations
BAU	Business as usual
BECCS	Bioenergy carbon capture and storage
BF-BOF	Blast furnace-basic oxygen furnace route
BF-BOF-CCS	Blast furnace–basic oxygen furnace with post-combustion carbon capture and storage
CAPEX	Capital expenditures
CBAM	Carbon border adjustment mechanism
CCfDs	Carbon contracts for difference
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CS	Crude steel
DACCS	Direct air carbon capture and storage
DR	Direct reduction
DRI	Direct reduced iron
DRI-EAF	Direct reduction and electric arc furnace
DRI-SMELT-BOF	Direct reduction, electric smelter and basic oxygen furnace
EAF	Electric arc furnace
EJ	Exajoule
EV	Electric vehicle
Fe content	Iron content
FIDs	Final investment decisions
GHG	Greenhouse gases
$GtCO_2$	Gigatonnes of carbon dioxide
H_2	Hydrogen
H_2-DRI	Hydrogen-based direct reduction
HBI	Hot briquetted iron
IEA APS	International Energy Agency Announced Pledges Scenario
IEA NZE	International Energy Agency Net Zero Emissions Scenario
IEA STEPS	International Energy Agency Stated Policies Scenario
$kgCO_{2e}$	Kilogram of carbon dioxide equivalent
kWh	Kilowatt-hour
LOHC	Liquid organic hydrogen carriers
MOE	Molten oxide electrolysis
Mt	Million tonnes
$MtCO_2$	Million tonnes of carbon dioxide
Mtpa	Million tonnes per annum
NDCs	Nationally Determined Contributions
NG	Natural gas

NG-DRI CCS	Natural gas-based direct reduction with carbon capture and storage
NZE-scrap EAF	Near-zero emissions scrap electric arc furnace
OECD	Organisation for Economic Cooperation and Development
OPEX	Operating expenditures
PCI	Pulverised coal injection
RES	Renewable energy sources
ROW	Rest of the world
SOGDC	Sabah Oil & Gas Development Corporation
TCO	Total cost of ownership
tCO_2	Kilotonnes of carbon dioxide
TRL	Technology readiness level
UN	United Nations
USD/kg H_2	US dollars per kilogram of hydrogen
WI	Wuppertal Institute
WV Stahl	German Steel Association

1 The iron and steel sector can turn from a *hard-to-abate* to a *fast-to-abate* sector. A net-zero iron and steel sector by the early 2040s is technically feasible

Pathways to net-zero: annual CO_2 emissions in the steel sector (left) and key metrics (right) Figure 1



Agora Industry and Wuppertal Institute (2023). Note: We did not model the Baseline scenario ourselves, but directly retrieved it from Mission Possible Partnership (MPP 2022). MPP's Baseline scenario covers scope 1 and scope 2 emissions. DRI = Direct reduced iron.

What if the global iron and steel sector could reach net-zero greenhouse gas (GHG) emissions in the early 2040s? Would you still call it a *hard-to-abate* sector?

Net-zero targets for steel have come a long way…

In October 2020, the IEA published its Iron and Steel Technology Roadmap, setting out a pathway for the steel sector to achieve a 90% GHG emissions reduction by 2070[1] (IEA 2020) in its main scenario (the Sustainable Development Scenario). This was followed in April 2021 by the IEA's Net Zero by 2050 report, which shows how the world can achieve net-zero CO_2 emissions across all sectors by 2050, thus limiting global warming to 1.5°C by 2100 (IEA 2021).

Since that time, steel companies accounting for more than 500 Mt of coal-based primary steel production have announced targets to reach carbon neutrality by 2050 or earlier. However, most carbon neutrality targets and steel decarbonisation scenarios still foresee residual emissions in the steel sector by 2050. For example, in the IEA Net Zero by 2050 report, the steel sector is one of the few sectors that still has residual emissions, with 200 $MtCO_2$ in 2050

---

[1] According to the IEA, the Sustainable Development Scenario is in line with **well below** 2°C global warming by 2100.

(IEA, 2021).[2] Today, the latest 1.5°C compatible steel decarbonisation pathways still show residual emissions of 300 $MtCO_2$ (MPP 2022) and 180 $MtCO_2$ (updated IEA NZE in IEA 2022a), respectively, in the steel sector by 2050, such that carbon dioxide removal (negative emissions) in other sectors is needed to reach net zero by 2050.

…but there is even more potential

Against this backdrop, is a net-zero date for the iron and steel industry well before 2050 possible? The short answer is: yes. Our two 1.5°C compatible pathways demonstrate that a net-zero steel sector by the early 2040s is technically feasible.

The core strategies for a fast transition include: the rapid deployment of key technologies (insight 3); an accelerated coal phase-out in the steel sector (insights 4, 9, 10, and 11); the development of green iron trade (insight 5) and bioenergy carbon capture and storage (BECCS) (insight 8); measures to address key bottlenecks (insights 7, 12, 13, and 14); the establishment of an adequate regulatory framework (insight 15); and, not least, strong international collaboration (insights 6, 11, and 15).

The *hard-to-abate* label for steel is no longer justified – the steel sector can be *fast-to-abate*

There are four key reasons why it is time to remove the *hard-to-abate* label from steel. First, a set of low-carbon technologies to start the transition are available now and we already know the key strategies and technologies that are required to reach net zero in

---

[2] In the IEA NZE 2021, the residual emissions of various sectors in 2050 are compensated by negative emissions through Direct Air Carbon Capture and Storage (DACCS) and Bioenergy Carbon Capture and Storage (BECCS).

From hard-to-abate to fast-to-abate: how the steel sector's role is changing

Figure 2

	The old narrative: Steel is hard-to-abate because…		The new narrative: Steel can be fast-to-abate because…
Technology	…the low-carbon technologies are not market-ready	→	…important key technologies to start the transition are available now and we know key strategies and further promising technologies to get to net zero.
Cost	…green steel is too expensive	→	…while green steel can cost up to 30–60% more than conventional steel, in most end products the cost increase is only 1–2%. Smart policies can address the issue of cost.
Zero-carbon electricity	…will require a lot of zero-carbon electricity	→	…the steel sector is one of the best use cases for zero-carbon electricity. Both the coal to electricity and the coal to renewable H_2 fuel switch will provide one of the largest CO_2 reduction levers per unit of zero-carbon electricity.
Speed	…will be one of the slowest sectors to decarbonise	→	…the steel sector can be one of the fastest sectors to reach net zero. If the full acceleration potential is realised a net-zero steel sector by the early 2040s is technically feasible.

Agora Industry and Wuppertal Institute (2023). Note: Green steel refers to near-zero emissions primary steel. The additional cost range for green steel given here is calculated based on Molten oxide electrolysis (MOE) and renewable H_2-based direct reduction (H_2-DRI-EAF) in the 2030s compared to a coal-based blast furnace – basic oxygen furnace route (BF-BOF) that is not subject to a CO_2 price. These global average costs will vary based on local cost parameters.

the steel sector – they need to be deployed quickly (insight 3). For example, direct reduced iron (DRI) technology is already commercially available and still leaves significant flexibility options for steelmakers, including variable feedstocks (natural gas, low-carbon H_2, biomass) and optional CCS.

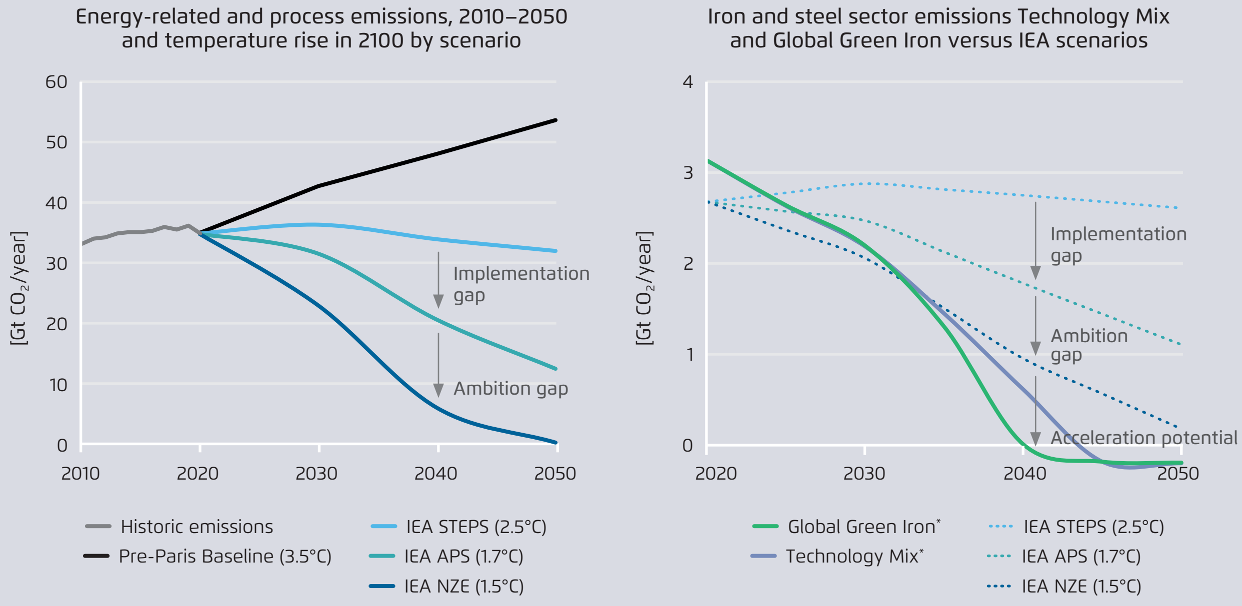
Second, while the costs for near-zero emission steelmaking are projected to be between 30 to 60% higher than conventional coal-based steelmaking without CO_2 costs, near-zero emission steel would add only 1 to 2% to the final cost of end products (such as cars, buildings, or household appliances) (IEA 2023; MPP 2022). Moreover, smart policy instruments and an adequate regulatory framework can address the issue of higher costs (insight 15).

Third, the steel sector is one of the best use cases for zero-carbon electricity. The fuel switch from coal to electricity or coal to renewable H_2 (see insight 12) presents one of the largest CO_2 reduction levers per unit of zero-carbon electricity.

Fourth and finally, our scenarios demonstrate that it is technically feasible for the steel sector to reach net-zero GHG emissions by the early 2040s. This would place the steel sector among the ranks of the first sectors to decarbonise globally. In other words, steel can become a *fast-to-abate* sector.

2 The accelerated transformation of the global steel industry can be a key element to increase global climate ambition

Scenario comparison: Global CO_2 emissions (left) and iron and steel sector emissions (right) Figure 3



Energy-related and process emissions, 2010–2050 and temperature rise in 2100 by scenario

Iron and steel sector emissions Technology Mix and Global Green Iron versus IEA scenarios

Agora Industry and Wuppertal Institute (2023) based on IEA (2022a). Note: STEPS = Stated Policies; APS = Announced Pledges; NZE = Net-Zero Emissions. *CO_2 emissions from industrial power plants on integrated steel sites accounted for in steel CO_2 emissions instead of power sector.

The world is not on track to limit global warming to well below 2°C

Despite significant progress since the Paris Agreement in 2015, the world is currently not on track to limit global warming to well below 2°C (IPCC 2023; IEA 2022a). According to the International Energy Agency (IEA), currently stated policies (STEPS) put the world on track for 2.5°C warming by 2100.[3] In the announced pledges scenario (APS), which includes net-zero commitments by governments and companies that have yet to be implemented, the projected global temperature increase reaches 1.7°C by 2100 (IEA 2022a). Between STEPS and APS there is still a large implementation gap; and between APS and a 1.5°C compatible net-zero emission (NZE) pathway there is still an ambition gap (see figure 3).

---

[3] The latest IPCC Synthesis Report found that implemented policies result in projected emissions that lead to warming of 3.2°C by 2100, with a range of 2.2°C to 3.5°C (medium confidence) (IPCC 2023).

The steel sector can help to increase global climate ambition

The iron and steel sector is currently responsible for 7 to 8% of GHG emissions – depending on the accounting methodology.[4] Given that steel demand is expected to increase further to accommodate the needs of developing and emerging economies, without adequate measures steel sector emissions will continue to rise up to 2030 (see IEA STEPS for steel). A key question for global climate ambition is how fast the steel sector can bend its CO_2 emissions curve by producing a growing share of near-zero emissions steel.

Our modelled pathways for the iron and steel sector show the potential to contribute significantly to closing both the implementation and ambition gaps (see figure 3). In the best case, they even offer further acceleration potential beyond the latest 1.5°C compatible NZE pathway for the iron and steel industry by the IEA (IEA 2022a). However, achieving this potential will only be possible through international cooperation and if governments and industry act swiftly to address important bottlenecks.

1.5°C compatible steel decarbonisation pathways are possible

The magnitude of global warming we experience will depend on the world's cumulative GHG emissions. Therefore, cumulative GHG emissions of each sector along with carbon budgets – although subject to constant change – are an important metric for measuring progress and assessing the climate commitments of companies. For example, many steel companies work together with the Science-Based Targets Initiative to certify that their climate targets are 1.5°C compatible (SBTi 2022). In a first cross-sectoral attempt, MPP 2022 derived a 1.5°C compatible cumulative budget for the steel industry of 56 $GtCO_2$ from 2020 to 2050. Our two 1.5°C compatible scenarios (40 and 43 $GtCO_2$, respectively) demonstrate that the steel industry could stay significantly below the threshold of 56 $GtCO_2$ for a 1.5°C compatible carbon budget if the full acceleration potential of the global steel transformation were to be unlocked (figure 4).

Translating the steel sector's acceleration potential into more ambitious climate action will be key – updated targets are a first step

Today, companies that produce primary steel that have net-zero targets before 2050 cover only 5% of global primary steel production. Another 23% are subject to a net-zero target by 2050, but more than 70% of primary steel production is not yet subject to 2050 carbon neutrality commitments by companies. Translating the global steel sector's acceleration potential into more ambitious climate targets and action will be key.

Steelmakers in industrialised countries therefore need to start moving net-zero targets to well before 2050. Given that a net-zero steel sector in the early 2040s is technically feasible and considering as well the burden of historical emissions, a 2050 net-zero target for steel companies in industrialised countries is hardly 1.5°C compatible.

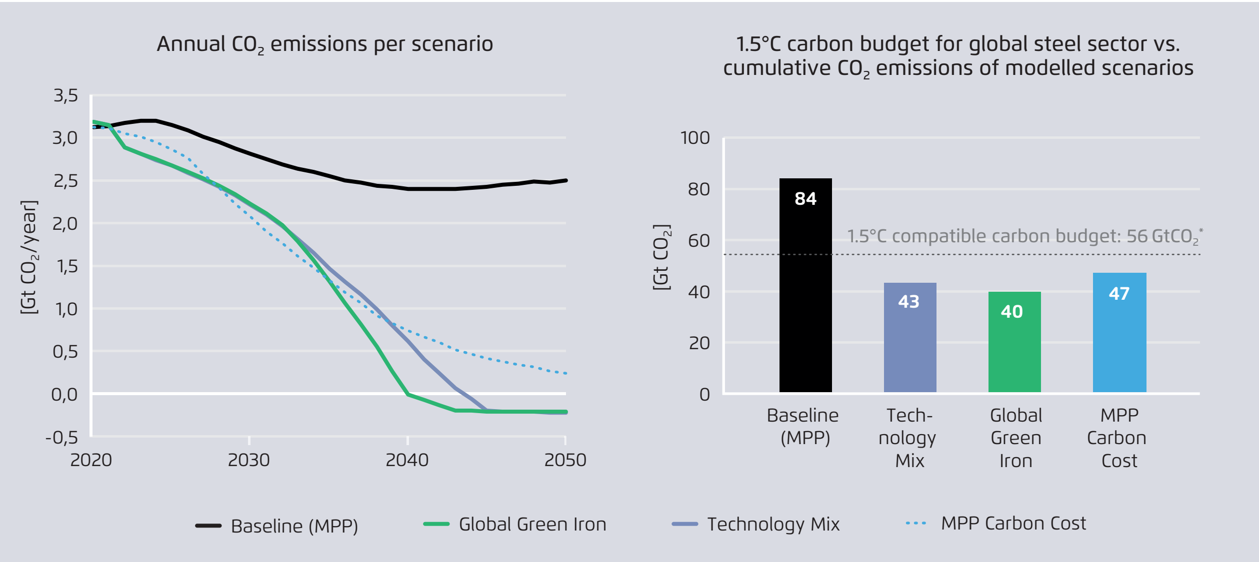
For steelmakers in emerging market economies, net-zero targets need to be moved to 2050 or earlier, if 1.5°C compatibility is the objective. These ambitious targets and accompanying implementation

---

[4] According to the IEA World Energy Outlook 2022, in 2021 the steel sector emitted 2.76 $GtCO_{2e}$, which accounts for 7% of the 40.8 $GtCO_{2e}$ that were emitted in 2021 (IEA 2022a). However, in the IEA's accounting methodology CO_2 emissions from industrial power plants at integrated steel sites are accounted for in the CO_2 emissions of the power and heat sector. In our methodology for the scenarios in this study, in which these CO_2 emissions are accounted for in the steel sector, the steel sector emitted 3.15 $GtCO_2$ in 2021 and thus 8% of global GHG emissions.

Scenario comparison: Iron and steel sector CO_2 emissions per year (left) and cumulative iron and steel sector CO_2 emissions (right)

Figure 4



Annual CO_2 emissions per scenario

1.5°C carbon budget for global steel sector vs. cumulative CO_2 emissions of modelled scenarios

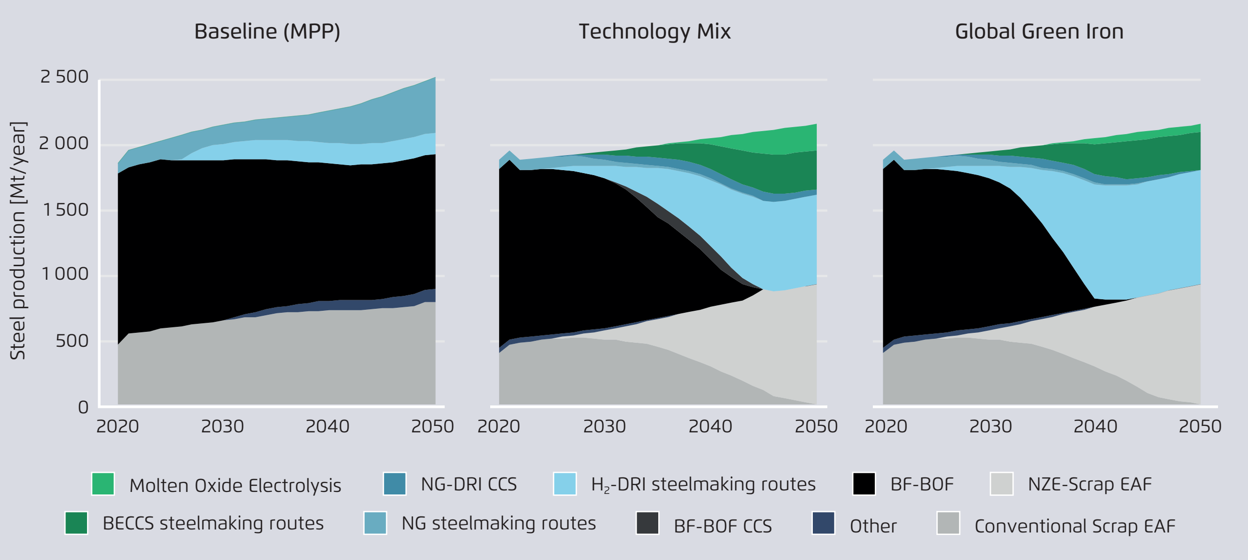
Agora Industry and Wuppertal Institute (2023). *The 1.5°C compatible carbon budget from the steel sector is derived from MPP (2022). Note: The IEA NZE scenario was not included in the carbon budget comparison because it uses a different CO_2 accounting method, in which CO_2 emissions from industrial power plants in integrated steel mills are accounted for under the CO_2 emissions of the power sector.

strategies need to be set now in order to avoid stranded assets in the future (see insight 11).

In light of the fact that the steel sector can turn from a *hard-to-abate* to a *fast-to-abate* sector, governments need to adopt concrete enabling policies, including measures to deliver sufficient clean energy and address the social and regional consequences of phasing out fossil-based assets. In addition, governments must update their Nationally Determined Contributions (NDCs) to reflect this increased ambition.

3 The key levers for enabling 1.5°C compatible steel decarbonisation pathways are material efficiency, an increase in scrap-based steelmaking, hydrogen-based steelmaking, and bioenergy carbon capture and storage (BECCS)

Scenario comparison: steel production per route (2020–2050) Figure 5



Agora Industry and Wuppertal Institute (2023), MPP (2022). NZE-scrap EAF stands for near-zero emissions scrap electric arc furnace which is defined as a scrap-EAF route with lower emissions than 0.01 tCO_2 per t of crude steel. NG = natural gas; BECCS = Bioenergy and carbon capture and storage.

There are enough decarbonisation levers to rapidly accelerate the reduction of fossil fuels in the steel industry. They need to be implemented fast.

Pathways for 1.5°C compatible steel decarbonisation

In this study, we modelled two 1.5°C compatible steel decarbonisation scenarios. We contrast them with the MPP 2022 Baseline scenario, which serves as a point of reference (MPP 2022). Our 1.5°C scenarios are technically feasible if major bottlenecks are addressed rapidly, key technologies and infrastructure are ramped up quickly, and key policies as well as an appropriate regulatory framework are put in place on time. Our scenarios are not a forecast, but rather demonstrate what could be possible under ideal conditions from a technical point of view. They are intended to specifically direct attention to the technical bottlenecks (insights 7, 12, 13, and 14) and potential technology trends (insights 4, 5, 7, 8, 9) with regards to the global steel transformation.

However, our chosen approach has also limitations: for example, it is not based on a regional breakdown of steel production. Furthermore, it assumes that a regulatory framework for near-zero emissions steelmaking will be in place in several world regions to enable the construction of the maximum amount of near-zero emission capacity that is technically feasible. Today, such a framework is not yet in place. However, all of the major building blocks for such a regulatory framework are already known (see insight 15) and international cooperation (see insight 6) could strongly incentivise investments in near-zero emission steelmaking plants in additional world regions.

Our scenarios are based on the following key assumptions:

- → **Baseline (MPP, 2022)**: In the baseline scenario no material efficiency is assumed. Steel assets switch to the technology with the lowest total cost of ownership (TCO) at each major reinvestment decision, without a net-zero constraint.
- → **Technology Mix**: A moderate improvement in material efficiency is presumed, which mitigates global steel demand growth. Low-carbon key technologies are deployed once they become commercially available. Their adoption is driven by ambitious deployment rates – technology cost plays an important role for deployment, but is not the only determining factor.
- → **Global Green Iron**: This scenario contains the same assumptions as that of the Technology Mix scenario, with the exception that DRI deployment rates are doubled after 2030 to illustrate a potentially disruptive scenario, if international green iron trade takes off internationally.

The key levers for our two 1.5°C compatible scenarios are as follows:

Material efficiency: Compared to the Baseline scenario that assumes sustained growth to around 2 550 Mt steel production by 2050, steel production in our two modelled scenarios reaches 2 150 Mt by 2050. Thanks to measures such as improving manufacturing yields, near-net-shape casting, improved building design and construction practices, extending the lifetimes of buildings, and lightweighting in vehicles, steel demand in 2050 can be up to 20% lower while providing the same services (Agora Industry, 2022; IEA 2020a). Our material efficiency assumption (-16% vs. Baseline in 2050) provides a middle-of-the-road approach compared to other 1.5°C compatible scenarios (see figure 6). Policies such as updated building codes that avoid the over-specification of structural steel or incentives for a modal shift in transport are examples that could incentivise higher material efficiency (IEA, 2020a).

Increase in scrap-based steelmaking: Given that secondary steelmaking requires five to seven times less energy than primary steelmaking, an increase in scrap-based steelmaking is another key strategy. However, this is limited by the availability of scrap. In our scenarios, scrap availability increases from 710 Mt in 2020 to 880 Mt in 2030 and to 1 240 Mt in 2050. This allows an increase in the global share of secondary steel production from 21% in 2020 to 43% in 2050. Apart from its availability, the quality of the scrap will be a key factor. Policies to keep scrap flows clean will be needed to ensure that secondary steel can be used in most applications rather than being downcycled and confined to few market segments (see insight 15).

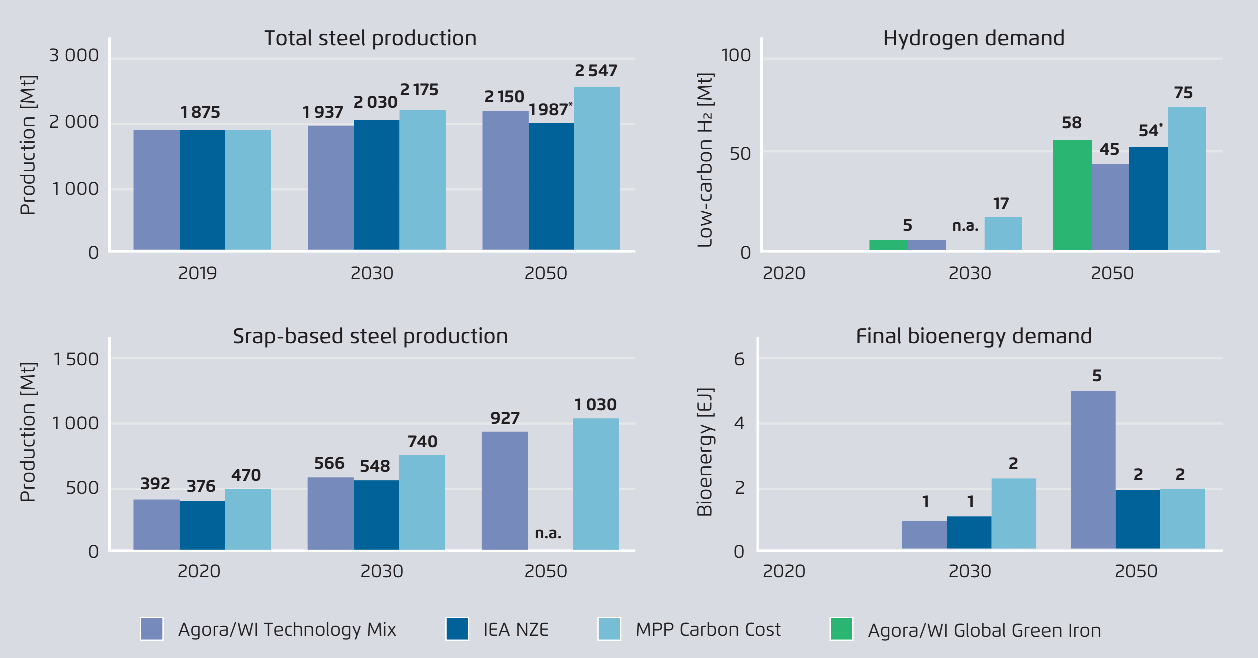
H_2-based steelmaking: H_2-based steelmaking in the direct reduction route is the main strategy to decarbonise primary steelmaking in our scenarios. By 2030, 96 Mt of steel are produced via H_2-based DRI plants that run on either 100% low-carbon H_2[5] or a mix of low-carbon H_2 and natural gas. By 2050, 683 Mt and 873 Mt of crude steel are supplied by H_2-based DRI routes in the Technology Mix and the Global Green Iron scenario, accounting for 56% and 72% of primary steelmaking, respectively. Compared to the MPP Carbon Cost scenario, the low-carbon H_2 demand of

---

[5] In this study, low-carbon H_2 is defined as either renewable or fossil fuel-based H_2 with CCUS.

Scenario comparison of 1.5°C compatible steel decarbonisation scenarios

Figure 6



Agora Industry and Wuppertal Institute (2023) based on MPP (2022) and IEA (2021), IEA (2022a), IEA (2022b), IEA (2023). *Numbers are retrieved from IEA NZE 2021. Note: If not indicated differently, the Agora/WI Global Green Iron scenario numbers are identical to the Agora/WI Technology Mix scenario numbers.

our scenarios is significantly lower, which can be mainly attributed to a lower overall steel production volume due to material efficiency measures.

BECCS-based steelmaking: In our scenarios bioenergy in combination with carbon capture and storage (BECCS) plays a key role in the steel industry to generate negative emissions (see insight 8). DRI routes or smelting reduction routes such as HIsarna could be operated with sustainable biomass and equipped with CCS.[6] Given that sustainable biomass supply will be very limited due to land-use competition (i.e. from afforestation and food production), BECCS-based steelmaking is limited and the efficient allocation of biomass from a systems perspective will remain subject to future debates (see insight 8). In our Technology Mix scenario, by 2050 BECCS-based routes account for 25% of primary steelmaking (300 Mt).

Direct electrification-based technologies could be a game changer – once they become available

Direct electrification-based technologies such as molten oxide electrolysis (MOE) or alkaline iron electrolysis (AEL) exhibit the lowest CO_2 abatement costs among the near-zero emissions steelmaking technologies (see insight 15).[7] But due to their

---

[6] Although BECCS on the BF-BOF route is also conceivable in principle, due to the significantly lower efficiency when generating negative emissions per unit of biomass in this process compared to DRI-based routes and HIsarna BECCS, within the steel sector, biomass should not be allocated for use in the BF-BOF route (see insight 8).

[7] One major difference between these two technologies is that MOE requires temperatures above 1500°C whereas alkaline electrolysis can work at temperatures around 110°C (Agora/WI/Lund, forthcoming).

comparatively low technology readiness level, these are still subject to high uncertainties (Agora/WI/Lund forthcoming). Expecting availability of full-scale plants only between 2030 and 2035 (MOE) and 2040 (AEL), we used a very conservative deployment of MOE to reach 200 Mt steel production by 2050 in the Technology Mix scenario, since we did not want to rely too much on technologies that are still far away from commercial readiness from today's point of view. From a pure cost perspective, they could become more economical than H_2-based DRI routes, but given the large uncertainties concerning if and when they will become commercially available, this should not delay the deployment of H_2-based routes today.[8]

Coal-based technologies in combination with CCS have a marginal role in our scenarios

Contrary to many other scenarios, BF-BOF CCS plays only a marginal role in our Technology Mix scenario and is not deployed at all in our Global Green Iron scenario. This is the case for a number of reasons: CCS on the BF-BOF route will likely leave considerable direct residual emissions, cannot address the upstream methane emission that are linked to the mining of metallurgical coal, and is prone to disruptive cost reduction developments in other technologies – for example, if direct electrification technologies such as MOE become commercially available (see insights 4 and 9).

DRI-based routes offer steelmakers significant flexibility

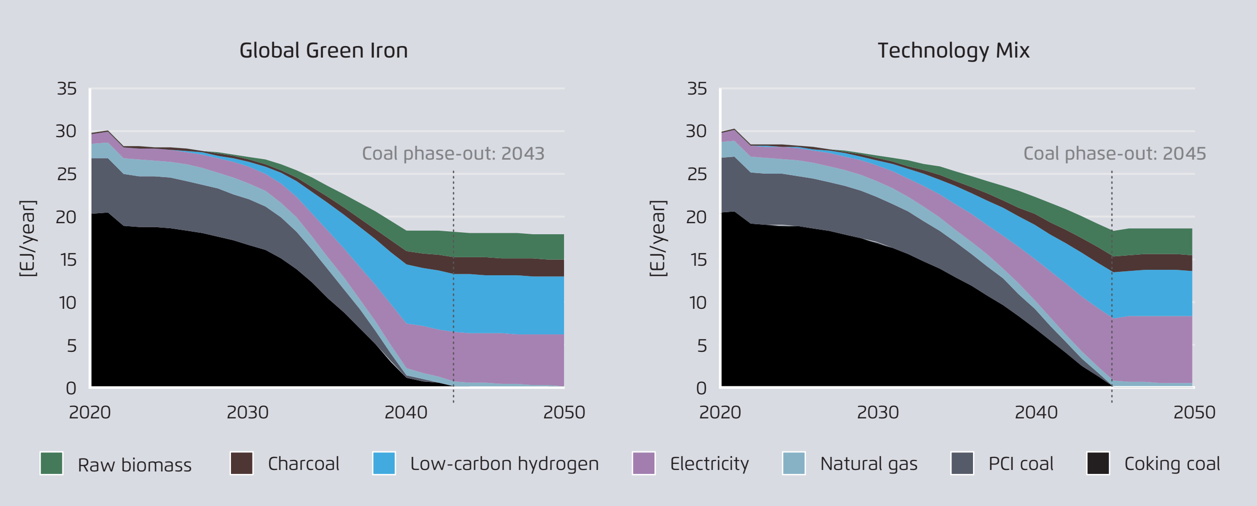
Offering steelmakers great flexibility is one of the advantages of DRI plants: new state-of-the-art DRI plants could be operated with any mix of natural gas and H_2 before transitioning to 100% H_2, natural gas with CCS, and even bioenergy in combination with CCS to generate negative emissions. In our scenarios, we focus mainly on H_2-based DRI routes and BECCS in DRI-based routes and deploy only a moderate share of natural gas-based routes with CCS. With regards to H_2-based DRI routes, the rationale is to minimise direct residual emissions and upstream methane emissions from natural gas. In the case of BECCS, the rationale is to generate some technical negative emissions (for more details, see insight 8). However, these developments are not set in stone. If there is less sustainable biomass available, more DRI routes could be using low-carbon H_2. Similarly, if low-carbon H_2 remains in short supply, more DRI routes could use natural gas with CCS. In all cases, deploying new DRI capacity will be key (see insight 7).

---

[8] Given the low technology readiness level (TRL 4) of MOE, cost assessments for a commercial-scale plant are subject to high uncertainty. According to our technology assessment, the MOE route will require around 14.8 GJ of electricity per t of crude steel. This would result in a slightly higher energy demand than the renewable H2-based DRI-EAF route, which will require 14.3 GJ per t of crude steel under the assumption of an electrolyser efficiency of 70% (Agora Industry/WI/Lund forthcoming). However, given that the MOE route will use electricity directly without additional process steps to produce renewable H_2, overall, this could still be cheaper than renewable H_2-based steel production routes (see figure 30).

4 A phase-out of coal in the steel sector by the early 2040s is technically feasible

Scenario comparison: Final energy demand **Figure 7**



Agora Industry and Wuppertal Institute (2023). Note: Our modelling scope was limited to ironmaking and steelmaking. The energy demand from steel finishing is not included. PCI = pulverised coal injection.

The continued use of fossil fuels in steelmaking up until 2050 will cause avoidable residual emissions

In most other 1.5°C compatible steel decarbonisation scenarios neither coal nor natural gas are fully phased out by 2050 (see i.e. IEA NZE in IEA 2022a and Carbon Cost in MPP 2022). Even though both aforementioned scenarios assume the use of CCS in combination with fossil fuels, due to imperfect CO_2 capture rates, the continued use of fossil fuels up to 2050 results in residual emissions of 180 $MtCO_2$ and 300 $MtCO_2$ per year, respectively. Most of these emissions could be avoided.

A phase-out of coal in the steel industry is possible

Our scenarios demonstrate for the first time that the phase-out of coal in the steel industry well before 2050 is technically feasible.[9] In the Global Green Iron and Technology Mix scenarios, coal is phased out by 2043 and 2045, respectively.

---

[9] Our modelling scope includes ironmaking and steelmaking, but not steel finishing. Our aggregated final energy demand is based on a bottom-up approach of the final energy consumption of various steelmaking technologies. They will be detailed in a forthcoming technology analysis. Due to our modelling scope and bottom-up approach our numbers may deviate from other sources.

CCS technologies with fossil fuels leave residual direct emissions and potential upstream emissions

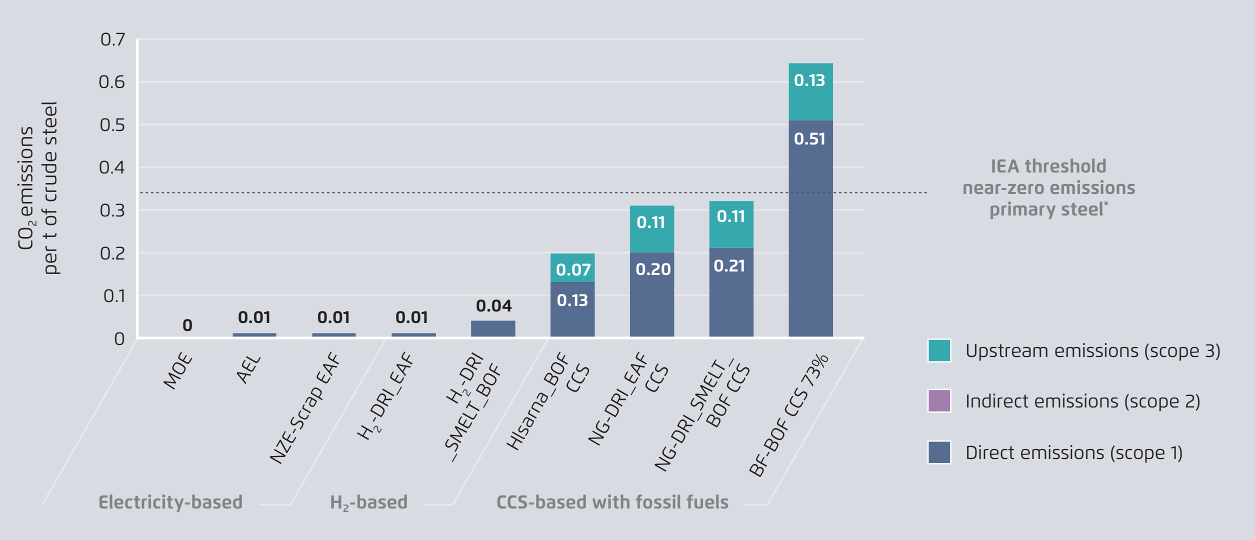
Out of a variety of low-carbon technologies that we assessed, all CCS-based technologies exhibit significantly higher residual emissions than H_2-based or direct electrification technologies such as molten oxide electrolysis (MOE; see figure 8). Moreover, both coal and natural gas are currently linked with considerable upstream emissions from methane leakage that cannot be addressed by CCS technologies. For example, in 2021 the coal mine methane leakage for coal used in the steel industry amounted to 384 $MtCO_{2e}$ per year, which would increase the CO_2 emissions from the steel industry by ~12%.[10] While measures exist to reduce methane leakage, it is uncertain how and at what scale they could be implemented. Substituting coal in the steelmaking process is a way to eliminate these emissions altogether.

Offsetting avoidable residual emissions with negative emissions comes at an opportunity cost

The most important reason to reduce residual emissions to the strict minimum is that offsetting residual emissions with negative emissions always comes at an opportunity cost. This is because instead of counterbalancing avoidable residual emissions, the negative emissions could be used to actually reduce the CO_2 concentration in the atmosphere. In a world that will scramble to achieve the much-needed carbon dioxide removal to avert the worst impacts of climate change (see insight 8), it is hard to imagine that high avoidable residual emissions from the use of

Residual CO_2 emissions (scope 1 and 3) of breakthrough technologies and proposed IEA near-zero emission threshold for primary steel

Figure 8



Agora Industry and Wuppertal Institute (2023), based on authors' analysis and IEA (2022g). Note: All primary steel production technologies in this figure have been calculated with a share of 16.5% scrap. *Due to scrap share adjustment the IEA threshold for near-zero emissions primary steel is around $0.34tCO_2/t$ of crude steel. Upstream emissions for CCS technologies are retrieved from IEA (2022) based on 2050 values for "indirect emissions of fossil fuels". They assume already large cuts of methane emissions relative to today. Indirect emissions (scope 2) are assumed to be zero if only zero-carbon electricity is used. MOE = molten oxide electrolysis; AEL = alkaline iron electrolysis; NZE-scrap EAF = near-zero emission scrap electric arc furnace; DRI-EAF = direct reduction and electric arc furnace; DRI-SMELT-BOF= direct reduction, electric smelter and basic oxygen furnace; BF-BOF CCS = blast furnace-basic oxygen furnace with post-combustion CCS.

---

[10] This calculation is based on the global warming potential over 100 years of methane emissions (GWP100).

coal and other fossil fuels will still be acceptable – particularly as economically viable alternatives exist.

Minimising stranded assets will require a set of measures

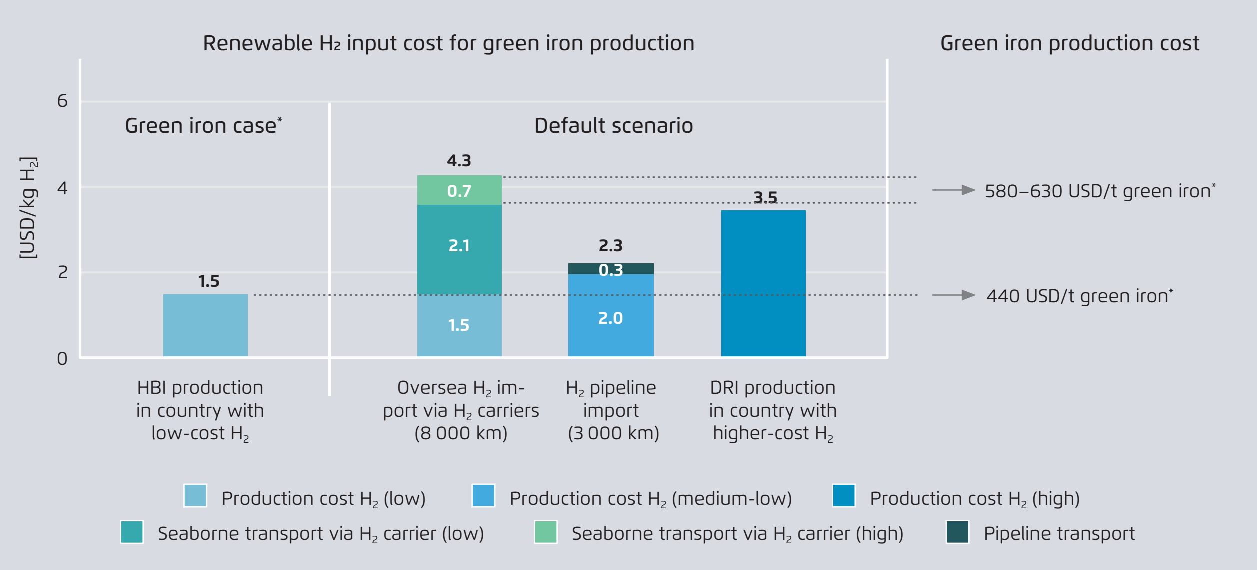
In our scenarios stranded assets are reduced to an absolute minimum. While the stranded asset risk for existing coal-based blast furnaces is limited (see insight 10), for the large 2030 pipeline of potential new coal-based BF-BOF plants in emerging economies the carbon lock-in and stranded asset risk in the 2040s is very high (see insight 11). While many steel decarbonisation scenarios deploy BF-BOF CCS to avoid stranded assets, it is likely that the opposite could be true: retroactive CCS on the BF-BOF route cannot protect such plants from becoming stranded assets (see insight 9). For steel companies and national governments, coal phase-out targets along with alternative strategies[11] and a regulatory framework to build up near-zero emission compatible capacities (see insight 15) could make existing net-zero claims more credible, ensuring that avoidable residual emissions from coal-based steel production routes will be eliminated. This would minimise the carbon lock-in and stranded asset risk and help, among other enabling factors (see insight 11) to provide reliable conditions for net-zero compatible investments.

---

[11] Defining these alternative strategies goes beyond the scope of this study, but could be the subject of future research and discussion.

5 International green iron trade can lower the cost of the global steel transformation

Impact of renewable H_2 input cost on green iron production cost 2030 under various scenarios Figure 9



Agora Industry and Wuppertal Institute (2023), authors' analysis based on IEA (2022c). Note: Renewable H_2 production costs are derived from BNEF (2022a) and IEA ETP (2023) but are for illustration only. Actual assumptions in our modeling can deviate (see upcoming publication on key technologies for a net-zero steel industry). *According to IRENA (2022a), shipping costs of green iron could range from 15 to 50 USD/t. According to McKinsey (2022), shipping costs for green iron in the form of hot briquetted iron (HBI) are similar to those of iron ore pellets; reheating the HBI for use in steelmaking would require 100 to 150 kWh.

What if the world were to ship *embodied* H_2 in the form of green iron instead of H_2 *and its derivatives*[12] for overseas transport? A cheaper global steel transformation is possible.

Renewable and low-carbon H_2 costs vary by country and region

Based on the expected cost of renewable electricity generation and availability of cheap natural gas, the cost of renewable or fossil-based H_2 with CCS vary greatly by country and region. In the case of renewable H_2, between the lowest-cost (around 1.50 USD/kg H_2) and highest-cost countries (3.50 to 4 USD/kg H_2), various studies see a production cost gap of up to 1.50 to 2.50 USD/kg of renewable H_2 (i.e. BNEF 2022a; IEA 2023). Many projected high-cost countries are therefore actively striving towards importing large amounts of renewable or low-carbon H_2.

Transporting H_2 *and its derivatives* by ship is costly

How H_2 will be imported will have a major impact on the delivered cost of H_2. While imports per repurposed gas pipeline over 3 000 km would add roughly 0.30 USD/kg H_2 for transport, all major H_2 import options via ship such as ammonia, liquid organic

---

[12] In this study, H_2 *and its derivatives* refers to liquid H_2, liquid organic hydrogen carriers and ammonia that enable the transport of H_2 by ship.

hydrogen carriers (LOHC), and liquid H_2 would add between 2.10 to 2.80 USD/kg H_2 just for transport alone by 2030 (IEA 2022c). Today, in most steel-producing countries that aim to switch from the coal-based BF-BOF route to H_2-based steelmaking, the public discussion is revolving around producing renewable H_2 domestically or importing H_2 by pipeline or ship (see default scenario, figure 9).

Transporting embodied H_2 is much cheaper for overseas transport…

A frequently overlooked option is to transport H_2 as *embodied* H_2 in the form of green iron, for example as hot briquetted iron (HBI). Since this is a bulk material, this does not lead to any energy losses during transport, in contrast to transporting H_2 *and its derivatives* by ship. By way of comparison, due to energy and conversion losses for H_2 *and its derivatives* in shipping, only 76% (liquid H_2), 64% (ammonia), and 58% (LOHC) of the initial amount of H_2 before transport is available after transport (IEA 2022c). Transporting HBI will therefore be much cheaper.

…and this cost advantage is structural

What is noteworthy is that the cost advantage is structural. In other words, it does not matter by how much the cost of transporting H_2 *and its derivatives* by ship can be reduced in the future, as these costs do simply not occur in the process chain of green iron transport, since H_2 does not need to be transported separately (see figure 10). Moreover, transport costs for HBI are roughly the same as for transporting the iron ore pellets that would be required in the H_2-based DRI-EAF route (McKinsey 2022). Transportation costs for HBI would thus only be additional in a case in which the steelmaking country does not import iron ore but produces it domestically.

For the global steel transformation this has two far-reaching implications:

→ Importing H_2 *and its derivatives* by ship will likely never be a competitive option for H_2-based steelmaking
→ The world's cheapest renewable H_2 costs can be directly transferred to all steelmaking countries of the world, if HBI is transported by ship and if a liquid world market with competition between green iron producers exists

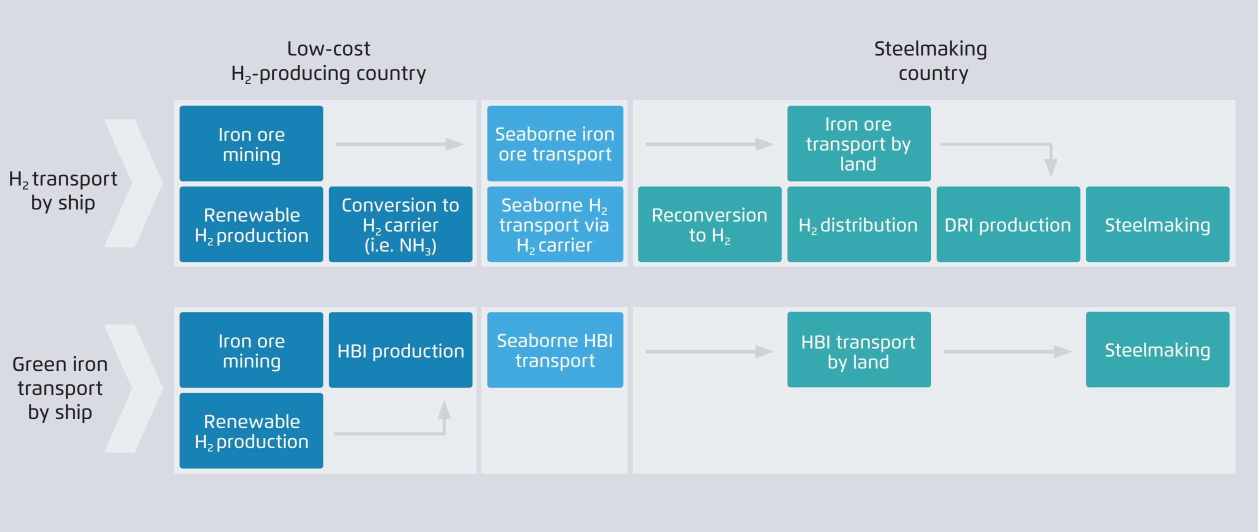
Green iron trade can reduce the need for H_2-related infrastructure

Moreover, shipping green iron instead of H_2 *and its derivatives* will require significantly fewer process steps and less additional H_2-related infrastructure. For example, compared to H_2 transport by ship via ammonia which would require an ammonia plant in the exporting country, an ammonia cracking plant to reconvert to H_2 in the importing country, as well as a H_2 distribution pipeline to transport the H_2 to the steel site, green iron transport will only require the construction of one HBI plant in the exporting country (see figure 10). Other than that, HBI can basically use the same existing infrastructure as iron ore and can be transported by ship, inland vessel, and train. This is already happening today. In 2021, 8 Mt of HBI produced by natural gas-based HBI plants were shipped overseas and 15 Mt of HBI were transported by land via trains or inland vessels (Midrex, 2022a).

While the case for green iron transport compared to overseas H_2 transport by ship is strong from a purely economic point of view, there are further factors such as strategic autonomy, technology innovation, market power, and the benefits of hot charging the DRI in integrated steel plants that need to be accounted for when comparing green iron imports to integrated DRI production in steel plants. Another key question is how green iron trade could affect jobs in green iron importing countries. This is discussed under insight 6.

Comparison of two cross-country low-carbon steelmaking process chains

Figure 10

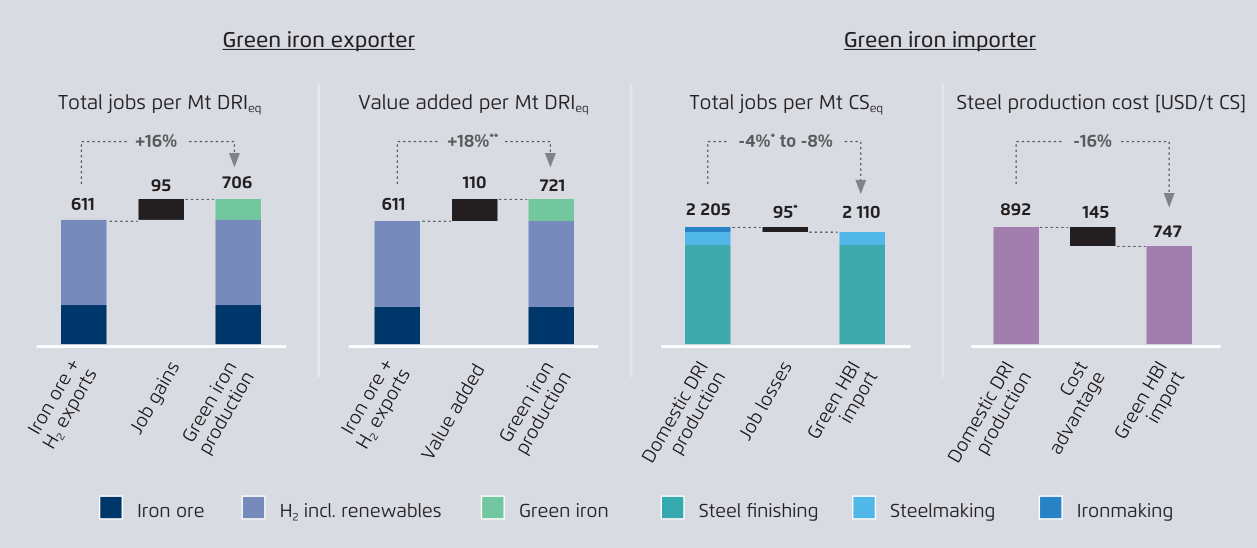


Agora Industry and Wuppertal Institute (2023). HBI = hot briquetted iron, DRI = direct reduced iron.

6 International green iron trade can be a win–win for importers and exporters. Unlocking the full speed and scale of the green steel transformation requires an international level playing field and strategic partnerships

Green iron trade can be a win-win for importers and exporters

Figure 11



Agora Industry and Wuppertal Institute (2023). Note: The job intensity of steelmaking varies significantly across different countries. For our calculations we used a weighted average for iron ore mining jobs in the largest five iron ore exporting countries and assumed a job intensity of 8 full time equivalents for the production of 1000 t renewable H_2 per year and 53 kg H_2/per t of DRI. The numbers for green iron importers are derived from employment numbers in steelmaking from Germany. *The 4% share includes direct jobs in DRI ironmaking but does not include potentially associated jobs in administration and logistics. **Wages of jobs per Mt DRI_{eq} used as proxy + 2% depreciation rate of CAPEX. DRI = direct reduced iron; CS = crude steel

For future H_2-exporting countries, green iron trade will offer new business opportunities and jobs

Green iron exports will provide new opportunities to countries that plan to export renewable or low-carbon H_2, by creating additional jobs domestically and allowing countries to capture an additional value-added part of the steelmaking value chain. Many of today's major iron ore-exporting countries are projected to have comparatively low production costs for renewable H_2 (see figure 12). Compared to a scenario in which those countries were to export iron ore and *H_2 and its derivatives* by ship, exporting green iron could allow for around 16% gain in local jobs and 18% increase in value added (see figure 11). Even for low-cost H_2-exporting countries without domestic iron ore resources, importing iron ore and exporting green iron could likely become a viable business case. While the opportunity for green iron exporting countries is apparent, how would green iron trade affect importers? Wouldn't it lead to significant job losses?

For future green iron importers, the rise of green iron trade can increase the competitiveness of their steel industry in green lead markets – thereby safeguarding over 90% of jobs

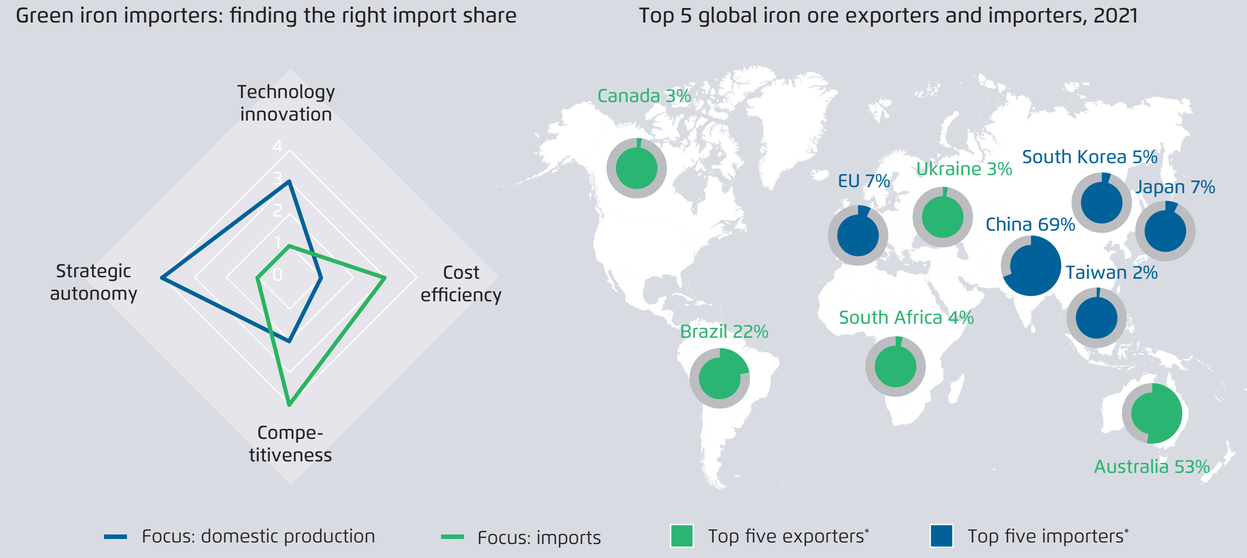
A somewhat surprising finding is that green iron imports would only have marginal negative impacts on employment in importing countries. This is because employment across the steelmaking value chain is unequally distributed. Based on German employment data, we found that ironmaking accounts for around 4%, steelmaking for 11%, and steel finishing for 85% of direct employment in the steel sector (WV Stahl, 2021). For countries with structurally higher renewable H_2 costs, this has important implications for the transformation strategy to H_2-based steelmaking. Simply building H_2-based DRI plants and running them on comparatively higher renewable H_2 costs than other countries will pose a risk to competitiveness. In the worst case, this will not only affect direct employment in ironmaking but endanger jobs along the entire steelmaking value chain. As one pillar of a diversified set of strategies, green iron imports can represent an important means of increasing the competitiveness of the steelmaking value chain by lowering the cost of near-zero emission steelmaking, thereby safeguarding over 90% of jobs (see figure 11).

Green iron importers: finding the right level of autonomy in the value chain

In other words, for countries with comparatively higher low-carbon H_2 costs, green iron imports could be an important hedging strategy against both high costs and potential shortages in the supply of low-carbon hydrogen. Against this backdrop, it will be important for potential green iron importing

Green iron importers and exporters: due to potential market power risks diversified strategies will be key

Figure 12



Green iron importers: finding the right import share

Top 5 global iron ore exporters and importers, 2021

Agora Industry and Wuppertal Institute (2023) illustration (left) and Australian government Resources and Energy Quarterly, 2022 (right). The examples in the spiderweb diagram are for illustration only. They assume that the production cost of green iron in countries with cheap and abundant renewables and the purchasing cost for green iron importers does not deviate too much, so that the cost advantage is to some extent passed on to allow for greater cost efficiency. This does not always have to be the case in reality. * % of world imports/exports in 2021 world trade data countries to pursue a diversified approach that balances different factors. Key arguments in favour of domestic green iron production are that it would contribute to strategic autonomy and the technological innovation of the H_2-based processes that will enable the global steel transformation. By contrast, key arguments in favour of green iron import are that it could contribute to higher cost efficiencies and thereby to overall competitiveness (see figure 12). However, beyond these high-level arguments there are further considerations: the green iron market may be small initially and subject to high market power, so purchasing costs for importers may be significantly higher than the production cost for green iron in low-cost H_2 countries. Domestic DRI can be charged hot whereas imported green iron would require additional energy for hot briquetting in the exporting country and would have to be reheated,[13] leading to an energy penalty. Accordingly, each country and each company will have to weigh these and potentially other factors to find the best way forward.

Unlocking the potential of green iron trade will require international collaboration and strategic partnerships

Despite favourable economics, a liquid world market for green iron will not establish itself on its own but will require international collaboration and a global level playing field. For green iron exporters some key aspects may include: access to climate finance; access to green lead markets in industrialised countries; de-risking instruments to lower the cost of capital for the build-out of renewables, electrolysers, H_2-related infrastructure, and HBI plants; and the buy-in and participation of local communities. For green iron importers key aspects may include reliable long-term off-take agreements and fair import prices.

It is unlikely that the private sector alone can address this diverse and complex set of requirements. Unlocking the potential of international green iron trade in an equitable and sustainable manner will require the involvement of governments and the establishment of strategic partnerships on an equal footing.[14]

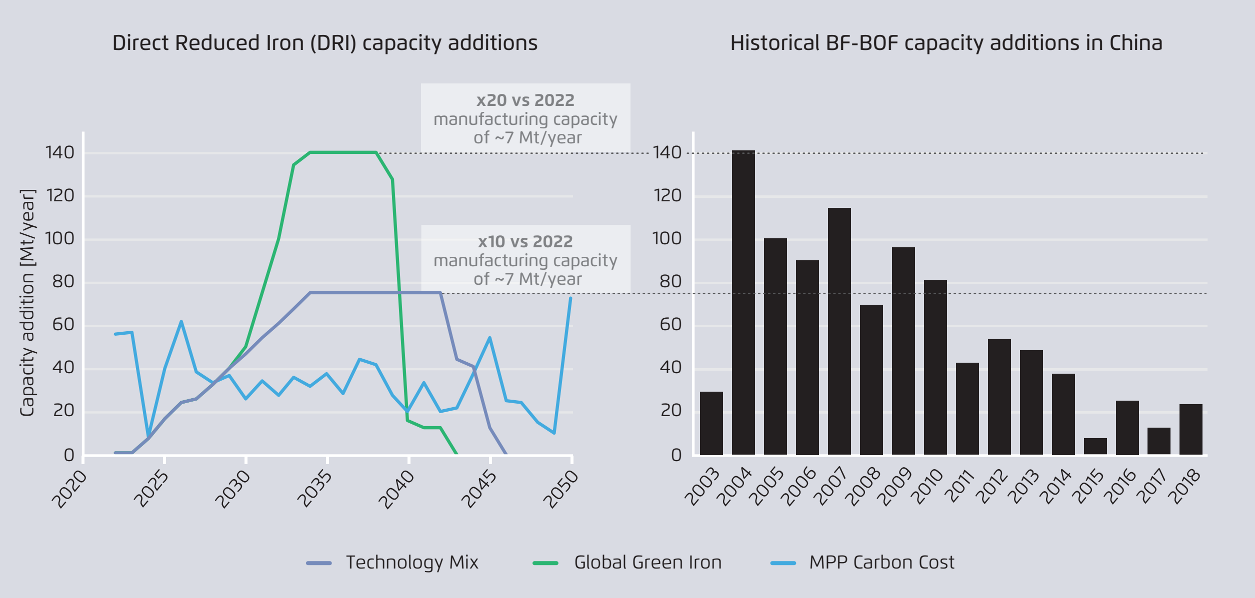
---

[13] According to McKinsey (2022), reheating the HBI for use in steelmaking requires between 100 to 150 kWh compared to integrated DRI production that can be charged hot.

[14] One existing example of a strategic partnership between two industrialised countries is the *Low and Zero Emissions Technology Partnership* between the Republic of South Korea and Australia (Australian government, 2021). The two countries have agreed to cooperate across existing and emerging low and zero emission technologies in the areas of hydrogen supply, low emissions steel and iron ore, as well as carbon capture, use, and storage.

7 Direct reduced iron (DRI) plant engineering and construction capacities are currently a major bottleneck and need to be massively scaled up as they will set the pace of the global steel transformation

A massive scale-up of DRI is necessary to accelerate the global steel transformation Figure 13



Agora Industry and Wuppertal Institute (2023) left; Vogl et al (2021) right. Note: MPP = Mission Possible Partnership's 1.5°C compatible Carbon Cost Scenario from September 2022; Technology Mix and Global Green Iron Scenario by Agora Industry and Wuppertal Institute (2023).

DRI deployment will set the pace of the global steel transformation

The deployment speed of DRI plants will be a key enabler of a significantly accelerated global steel transformation. One point of distinction that separates our scenarios from other 1.5°C compatible scenarios is that significantly more DRI capacity is deployed after an ambitious market ramp-up (see figure 13). Given the benefits of green iron trade, from an economic point of view this makes sense. But is it also feasible?

Today's market for DRI technology is small and highly concentrated

Currently, there are only two technology providers that account for 97% of the market for gas-based DRI plants: Midrex (80%) and Tenova HYL (17%) (Midrex 2022a). With regard to the engineering companies that build DRI plants, Tenova HYL also designs and constructs DRI plants while Midrex uses a licensing model with SMS group and Primetals. So today there are only three main established technology suppliers that build gas-based DRI plants. From 2011 to 2020, 50 Mt of gas-based DRI capacity were built, which represents an average annual construction capacity of 5 Mt (Midrex 2022a).

DRI engineering and construction capacity is the biggest bottleneck for an accelerated transformation

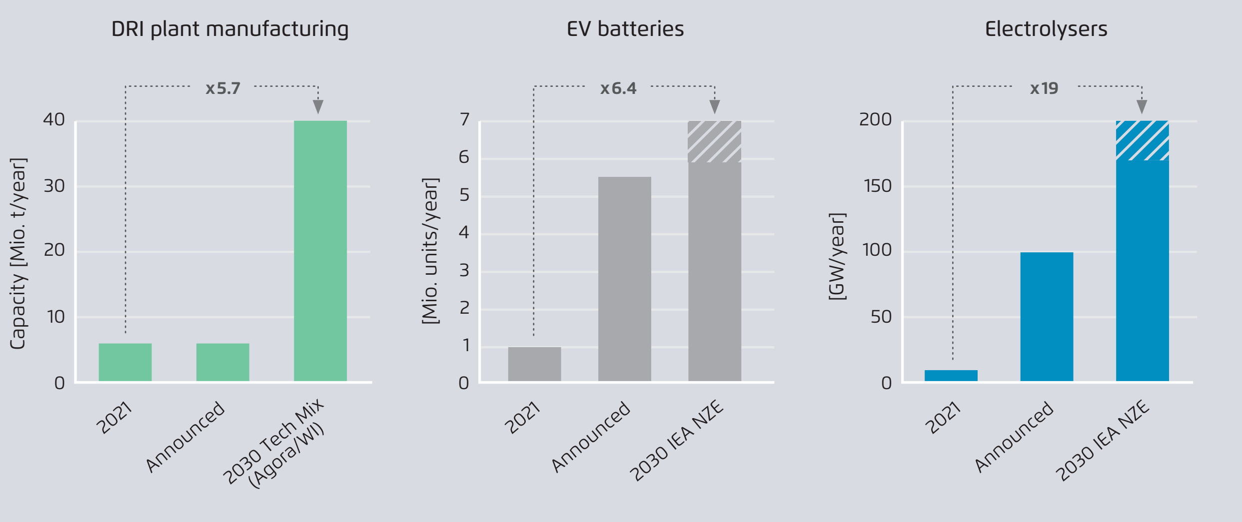
Based on expert interviews, we estimate today's DRI engineering and construction capacity to be between 6 and 8 Mt per year. In an ambitious base case, we estimate that around 70 Mt of additional H_2-ready DRI capacity could be built by 2030. The current 2030 project pipeline of H2-ready DRI plants stands at 84 Mt and thus already exceeds this 70 Mt figure, putting into question whether this current project pipeline can be realised without further measures (Agora Industry, Global Steel Transformation Tracker). Furthermore, this only amounts to roughly half of the 120 to 150 Mt of additional DRI capacity required by 2030 for a 1.5°C compatible pathway (see insight 14). In this way, although we estimate that capacity expansions by existing players could allow up to 100 Mt of additional DRI capacity to be built by 2030, in order to match the trend of rapidly rising demand for DRI plants, it is likely that additional solutions will be required.

Solutions to ramp up DRI deployment are available

One key solution to address this capacity bottleneck would be to retrain engineers and construction workers to build DRI plants. Overall, the global steel industry does not lack specialised engineering and construction capacity. Moreover, DRI plants are not necessarily more complex in design and construction than BF-BOF plants, but retraining would be required to make some engineering and construction capacity that is currently dedicated to BF-BOF build-out and relinings available for the design and construction of DRI plants. For example, in 2004 China alone built 140 Mt of BF-BOF capacity, which is equivalent to

Direct reduced iron deployment in our scenarios compared to deployment of selected clean energy technologies in the IEA NZE Scenario

Figure 14



Agora Industry (2023) based on own analysis and IEA (2023). Note: For this comparison, clean technologies were selected that are at the beginning of a potential S-technology adoption curve. 2030 Tech Mix = Technology Mix scenario for the steel sector. IEA NZE = IEA Net Zero Emissions scenario based on IEA (2023). The range for the 2030 IEA NZE targets indicates some residual capacity to accomodate for potential demand fluctuations.

the global annual DRI deployment capacity in our Global Green Iron scenario in the mid-2030s (see figure 13). Another key solution will be new market entrants in the field of H_2-based DRI technology.[15]

The DRI deployment speed for 1.5°C compatible scenarios is similar to other key technologies

As for any technology that stands at the beginning of a technology adoption curve, the long-term deployment speed of DRI is hard to predict. However, in comparison to the IEA Net Zero Emissions by 2050 (IEA NZE) scenario, the deployment speed in our scenarios is similar to that of other clean energy technologies such as EV batteries and slower than that of electrolysers (IEA 2023, see figure 14). While these technologies may not be perfectly comparable, the examples of EV batteries and electrolysers illustrate what is possible when industry and governments work together on the deployment of key technologies.

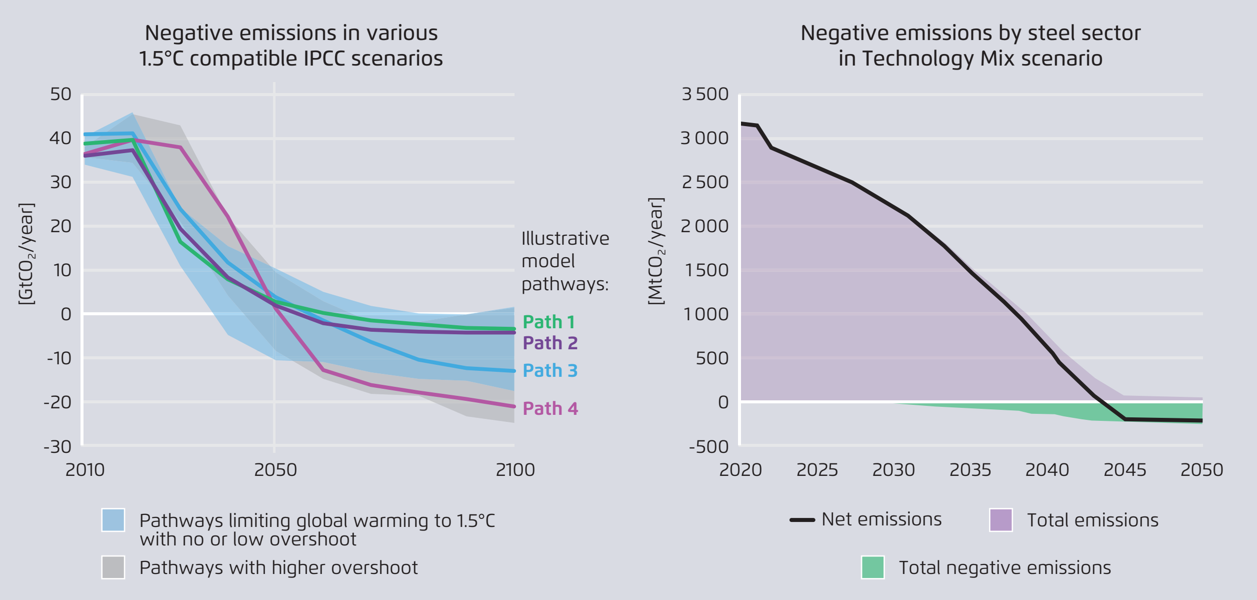
The combination of international green iron trade and an accelerated DRI deployment has major disruptive potential. In our Technology Mix scenario, in which annual DRI deployment between now and 2035 is increased tenfold, the global steel sector reaches net zero by 2044. In our Global Green Iron scenario, in which annual DRI deployment by 2035 is increased twentyfold, net zero is reached by 2040. Even though the actual deployment speed is hard to predict today, what is clear already is that any deployment rate that comes close to this will pose an enormous risk of stranded assets to fossil legacy technologies (see insights 4, 9, and 11).

---

[15] For example, Circored, POSCO, and Primetals are working on the commercialisation of a novel innovative H_2-based DRI plants that use fluidised bed reactors. The commercialisation of the technology is expected by 2030.

8 The steel sector can contribute to negative emissions via bioenergy carbon capture and storage (BECCS)

Negative emissions in different IPCC scenarios (left) and in our Technology Mix scenario (right) Figure 15



Based on IPCC 2018 (left) and Agora Industry and Wuppertal Institute (2023) (right)

Negative emissions will be needed to limit global warming

Limiting global warming to levels compatible with the Paris Agreement will first and foremost require the rapid mitigation of GHG emissions. But it will also require negative emissions through carbon dioxide removals from the atmosphere. This is the case for two main reasons: (1) to offset the last residual emissions that cannot be abated otherwise to reach net-zero GHG emissions (i.e. livestock farming, cement and lime production)[16] and (2) to correct for an overshoot of atmospheric CO_2 emissions, as foreseen by virtually all 1.5°C compatible scenarios (see IPCC 2018).[17]

A broad portfolio of carbon dioxide removal methods will be required

The magnitude of carbon dioxide removal (CDR) in major 1.5°C compatible scenarios varies considerably, ranging from 1.9 $GtCO_2$ (IEA 2021) and 4.5 $GtCO_2$ (IRENA 2022b) to between 3.5 and 16.5 $GtCO_2$ per year by 2050 (IPCC 2018).[18] Nature-

---

[16] These unavoidable residual emissions include i.e. methane emissions from livestock farming and residual process-related emissions in cement and lime that cannot be fully abated through CCS due to imperfect capture rates.

[17] Well below 2°C pathways will also require carbon dioxide removals for the reasons mentioned above.

[18] Scenarios with the lowest amount of CDR such as the IEA NZE 2021 assume the steepest emission cuts until 2050.

based CDR solutions such as afforestation are limited due to the increasing scarcity of land and the adverse effects of global warming on ecosystems that have a significant carbon storage and sequestration function. Therefore, technical CDR solutions such as DACCS and BECCS are required to complement natural sinks. The steel sector could contribute to generate negative emissions via BECCS (see figure 15).

Beyond net zero – the steel sector can contribute to negative emissions via BECCS

The basic function of BECCS is simple: biomass absorbs CO_2 from the atmosphere in its growth phase. If the steel industry uses biogenic carbon as a reducing agent or to generate heat and subsequently stores the generated CO_2, it could provide negative emissions, effectively ensuring permanent removal of CO_2 from the atmosphere and the carbon cycle. However, the potential for BECCS to generate negative emissions – regardless of the sector in question – will be limited by two main factors: the limited global supply of biomass and how it will be allocated most efficiently to various end uses.

Sustainably available biomass is limited due to competing land use options...

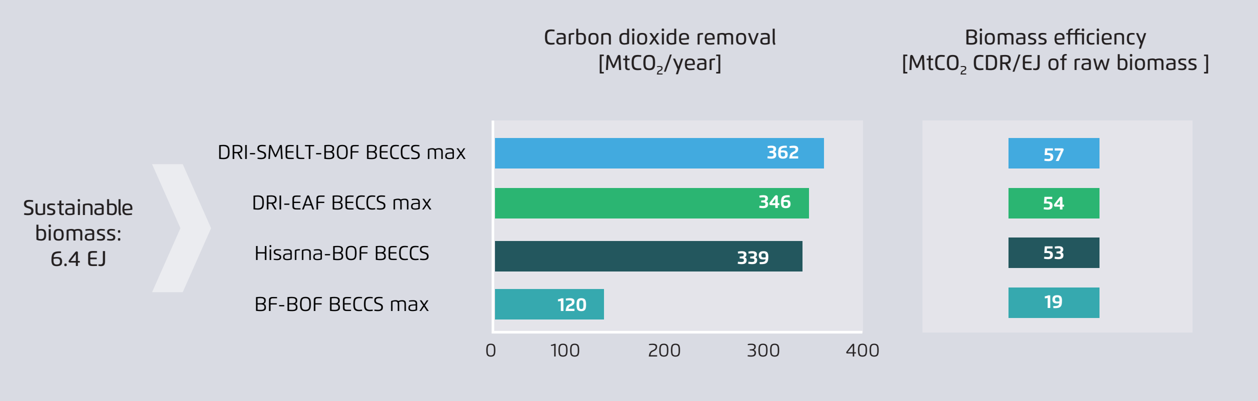
Land is a scarce resource and land-use competition is expected to increase in the future due to a growing world population, continued consumption of animal proteins, urbanisation, adverse impacts of climate change on productivity, as well as the need to reverse the trend of biodiversity loss (Agora/WI, forthcoming). Presuming that the extraction of biomass, regardless of what it is used for, should not imply detrimental effects on ecosystems and carbon cycles, biomass availability for BECCS will remain limited. Examples of estimates of biomass supply for material and energetic use by 2050, which apply strict sustainability criteria, range between 44 and 64 EJ[19] (ETC 2021) to over 102 EJ (IEA 2021) or even as high as 153 EJ

---

[19] This is based on the prudent case of ETC 2021 (30 to 50 EJ) but includes 10 EJ of woody biomass from forestry used as materials as well as 4 EJ from recycled materials.

Carbon dioxide removal potential of various BECCS technologies in the steel sector for 6.4 EJ of sustainable primary biomass use

Figure 16



Agora Industry and Wuppertal Institute (2023). The potentials of this figure are theoretical max. potentials that may be difficult to be fully achieved in reality. They assume that the biomass has zero lifecycle emissions. A biomass to biochar conversion efficiency of 60% was assumed for the Hisarna and BF-BOF BECCS routes. The potentials are non-cumulative as they illustrate the BECCS potential, if all biomass was used in one route. Based on a literature review including ETC 2021, IEA 2021 and IRENA 2022b, we assume that 64 EJ of sustainable raw biomass may be available by 2050 and that the steel sector uses up to 10% of this biomass.

(IRENA 2022b).[20] We chose a conservative middle-of-the road approach and assume that 64 EJ of sustainable biomass may be available by 2050.

…and should be allocated for the most efficient use cases

Given the limited supply of biomass to meet the demand for material and energy uses, allocation to the most efficient use cases is essential. To this end, three core principles should be: prioritising material use over energetic use; a cascading use of biomass whenever possible; and use cases that allow for negative emissions over GHG-neutral operations for which viable decarbonisation alternatives exist. While certain direct material uses (like wood products, pulp and paper, and bio-based plastics in a closed carbon cycle) should be prioritised over BECCS use cases, some of today's biomass use in sectors such as building heat and road transport where direct electrification is possible could be freed up and may become available for BECCS applications to generate negative emissions.

If the steel industry were to use 6.4 EJ of sustainable primary biomass by 2050 (10% of the overall supply of biomass for energetic and material use) it could generate up to 360 Mt of negative emissions per year (figure 16). Yet, in reality, it will be hard to achieve this full potential.[21] In our Technology Mix scenario we assume the use of 6.2 EJ of primary biomass, corresponding to 5 EJ of final bioenergy consumption for BECCS-based steel production routes, which allows for yearly negative emissions of ~240 $MtCO_2$ by 2050. Due to the significantly lower efficiency to generate negative emissions per unit of biomass compared to DRI-based BECCS routes or HIsarna-BOF BECCS, our scenarios do not deploy any BECCS on the BF-BOF route.

---

[20] For further information, please see the report Bioresources within a Net-Zero Emissions Economy (ETC, 2021).

[21] This would require that biomass has zero lifecycle emissions, which is unlikely to be the case in reality.

9 CCS on the BF-BOF (blast furnace–basic oxygen furnace) route will not play an important role in the global steel transformation

Where the global steel industry is heading: 2030 pipeline of low-carbon steelmaking announcements

Figure 17

Agora Industry, Global Steel Transformation Tracker (2023). Note: The 2030 project pipeline of DRI plants includes H_2-ready DRI plants that may operate with natural gas initially. To date, the 3D project in Dunkirk is the only demonstration-scale CCS project on the BF-BOF route announced and aims to capture 1 $MtCO_2$ per year.

Will CCS on the BF-BOF route only be a pipedream?

In 2020, the IEA Iron and Steel Technology Roadmap assigned the same Technology Readiness Level (TRL 5) to 100% renewable H_2-based direct reduction and BF-BOF CCS. The commercial readiness of both technologies was anticipated by 2030 (IEA 2020a). However, since 2020, commercial-scale project announcements for both technologies have developed remarkably differently: to date, virtually all steel companies that plan to build low-carbon steelmaking capacity have opted for H_2-based or H_2-ready DRI plants. While the 2030 project pipeline of H_2-ready DRI plants has grown to 84 Mt, the pipeline for commercial-scale CCS on the BF-BOF route amounts to just 1 Mt (see figure 17).

Post-Combustion CCS on the BF-BOF route will leave high residual direct emissions

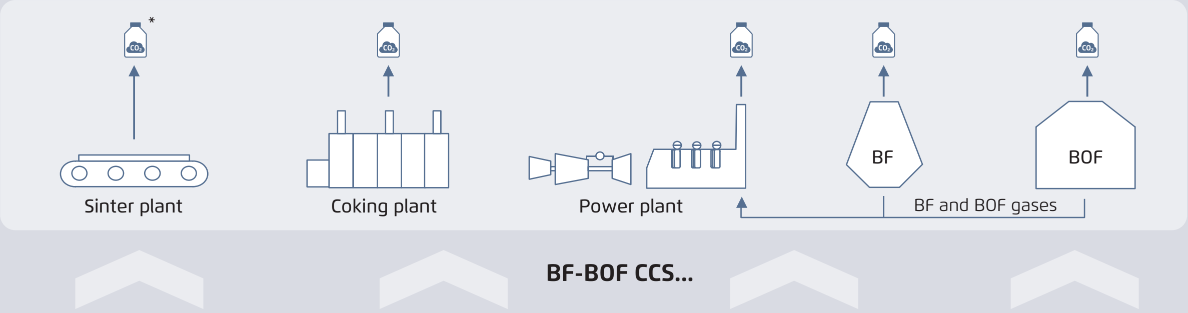
Many steel decarbonisation scenarios assume that BF-BOF CCS can reduce CO_2 emissions by 90% relative to the conventional BF-BOF route (Bataille et al, 2021; MPP 2022, IEA 2022a). Based on a detailed in-depth technology assessment (forth-coming), although technically feasible in theory, we find this assumption to be unrealistically optimistic.[22] First, connecting the many CO_2 point sources in the BF-BOF route to CCS will likely never be economically viable. Second, the CO_2 concentration in the waste gas stream of a sintering plant is only 4 to 5% and thus very low. Because of these two reasons, in our technology assessment (forthcoming) we conclude that BF-BOF CCS will likely only achieve a 73% emission reduction (default case) relative to the unabated BF-BOF route. This would represent an optimum in which the large CO_2 point sources (coke oven underfiring, hot stoves, and power plant) with relatively high CO_2 concentrations are connected to carbon capture, but not the sintering plant and small CO_2 point sources, for which CO_2 capture is technically feasible, but would increase the capturing costs exponentially.

BF-BOF CCS plants will be prone to disruptive cost reduction in other technologies

The costs of BF-BOF CCS will vary based on a wide range of factors, including electricity prices and a connection to onshore or offshore CO_2 storage. However, in the future, BF-BOF CCS could be outcompeted by other emerging technologies. For example, according to our calculations, once MOE is available at commercial scale, with delivered electricity prices of 60 USD/MWh it would outcompete even

Several risk factors make CCS in combination with the BF-BOF route unattractive

Figure 18



BF-BOF CCS...

... leaves high residual emissions

- BF-BOF CCS will likely only reduce direct CO_2 emissions by 73% compared to the BF-BOF route
- While higher emission reductions are technically possible, it is questionable whether they are economically viable

... will be prone to disruptive technology cost developments

- Direct electrification technologies such as molten oxide electrolysis would likely be cheaper once they become commercially available in the 2030s
- There is a risk that the combination of cost factors (CO_2 transport, storage and residual emissions compensation) will make BF-BOF CCS uncompetitive

... cannot address upstream emissions

- Upstream emissions from coal mine methane leakage currently add ~12% in addition to the current direct CO_2 emissions of the steel industry**
- BF-BOF CCS cannot address upstream emissions directly and if they are included in the future regulation of the steel industry, they may worsen the business case for BF-BOF CCS

... faces an offtake risk in green lead markets

- Progressive companies that strive to decarbonise their supply chains (i.e. automotive, household appliances) and want to advertise this fact to their customers may not want to be associated with coal-based technologies

Agora Industry and Wuppertal Institute (2023). BF-BOF CCS costs vary significantly depending on which CO_2 point sources are included in capture and whether the CO_2 is stored onshore or offshore. Offshore CO_2 storage tends to be more expensive than onshore CO_2 storage. *The figure illustrates the capture of CO_2 from the sintering plant which is technically feasible, but may not be economically viable. **Upstream methane emissions from coking coal are currently estimated to be 384 $MtCO_{2e}$ based on a GWP 100 measurement (authors' calculations, IEA Methane Tracker, 2022).

---

[22] MPP 2022 presents a case in which only 50% capture rate for CCS on the BF-BOF route is realised, which indicates doubts as to whether 90% capture rates are realistic. Yet, in their scenario modeling, they assume a 90% CO_2 reduction.

the best BF-BOF CCS locations (Agora/WI/Lund, forthcoming). If international green iron trade gains traction, comparatively cheaper H_2 input costs in countries with abundant renewables could start to challenge BF-BOF CCS production in cost.

BF-BOF CCS cannot address upstream emissions from coal mine methane leakage

Another risk is that BF-BOF CCS cannot address the emissions that are associated with methane leakage in coal mines. Accounting for coal mine methane emissions linked to coking coal, which totalled 12 Mt of methane emissions in 2021, would increase the GHG emissions of the steel sector by 384 $MtCO_{2e}$ and thus by around 12% (Ember 2023, IEA 2020b and 2022d).[23] While some methane emissions could be reduced, they cannot be fully abated (IEA 2023). Once upstream emissions are taken into account by regulations and included in a green steel definition, this will present a major risk for steelmakers that bet on retroactive CCS and will likely worsen the economics of BF-BOF CCS.

Steel from the BF-BOF CCS route faces an offtake risk in green lead markets

Besides, there is a risk that steel-consuming companies that aim to decarbonise their supply chain do not want to be associated with coal-based technologies at all. Companies that wish to market green products at a higher price to end consumers (e.g. automobiles or household appliances) may fear the reputational damage of being associated with coal-based projects, which they may view as incompatible with their brand identities and decarbonisation strategies.

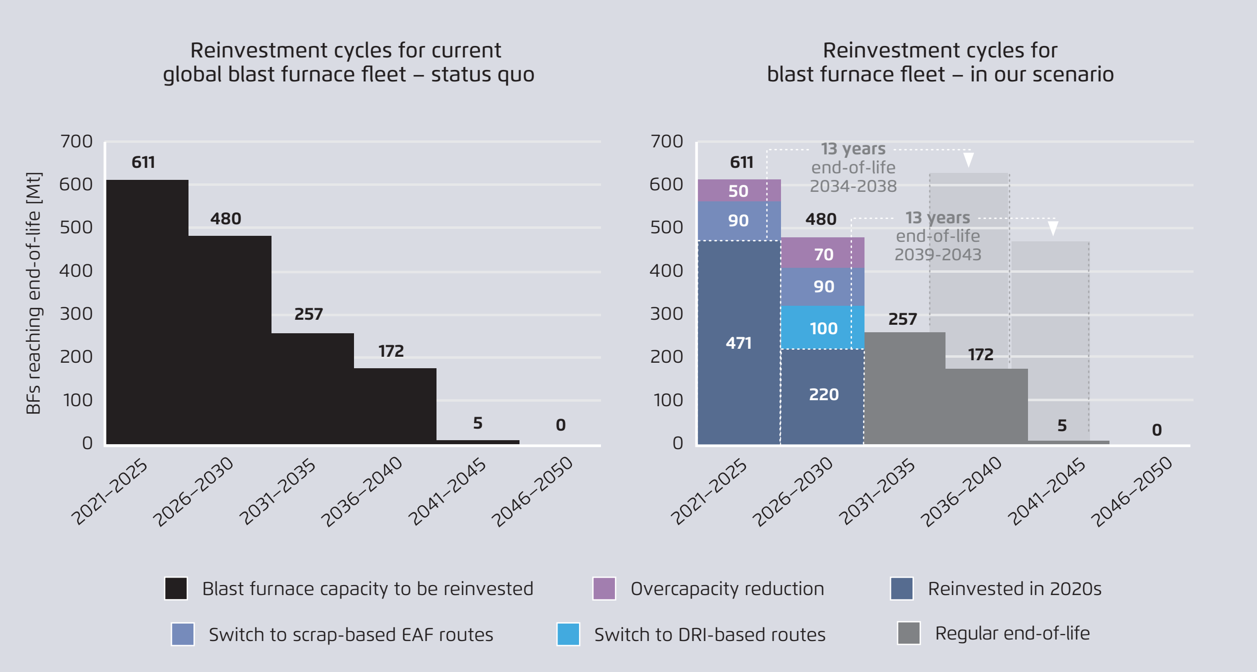
In conclusion, it's the combination of various risk factors that need to be analysed for a detailed assessment of the future potential of BF-BOF CCS. If BF-BOF CCS does not materialise in the future, this has important implications for the risk of blast furnaces becoming stranded assets (see insights 10 and 11).

---

[23] This calculation is based on an average Global Warming Potential of methane over 100 years of 32 tons of CO_2 per ton of methane (see IEA 2020b).

10 By 2040, over 90% of existing blast furnaces can be phased-out without a premature shutdown

By 2040, over 90% of existing blast furnaces can be phased out without a premature shutdown Figure 19



Agora Industry (2023), authors' calculations based on Global Steel Transformation Tracker (2023). Note: We assume that out of 150 Mt additional DRI capacity that could be built by 2030, 100 Mt are used to replace existing capacity. Overcapacity reduction assumptions are based on company announcements and an estimation of the capacity swap mechanism in China.

By 2030 more than 70% of existing blast furnaces require reinvestment

The 2020s are a crossroads for much of the existing blast furnace fleet. More than 70% (1 090 Mt capacity) will reach the end of their campaign life and require reinvestment. These blast furnace operators will face a choice: relining their blast furnaces and locking in high emissions for more than a decade or substituting blast furnaces that have reached the end of their campaign life with low-carbon technologies. Ideally, all blast furnace operators should choose the latter option. But is that possible?

The scale-up of low-carbon technologies cannot substitute all blast furnaces that reach the end of their campaign life by 2030

There are two main options to replace blast furnaces at the end of their campaign life before 2030: A switch to DRI technologies, or scrap-based steelmaking in electric arc furnaces.[24] Yet even if these

---

[24] Based on a detailed technology assessment (forthcoming analysis), we do not expect other low-carbon steelmaking technologies to reach commercial readiness and to scale up significantly before 2030.

technologies scale up fast, they will realistically not be able to replace 1 090 Mt of blast furnace capacity by 2030 (see figure 19).

In a best-case scenario, we estimate that out of a maximum of 150 Mt of DRI capacity that could be built by 2030 (see insight 14), 100 Mt of DRI will be used to substitute existing blast furnaces and that increased scrap supply would allow for an increase of scrap-based steelmaking of around 180 Mt by 2030 relative to 2020.[25] Moreover, in some world regions blast furnace capacity may be shut down without replacement due to overcapacity issues. We estimate this capacity shutdown at 120 Mt by 2030. Overall, this would still leave around 690 Mt blast furnace capacity that would have to be relined in the 2020s. Is this a major problem that would lock in emissions for another 20 to 25 years or create stranded assets? The short answer is no. This is because real-world data shows that blast furnaces have a much shorter campaign life after relinings (around 13 years on average) than is widely assumed.

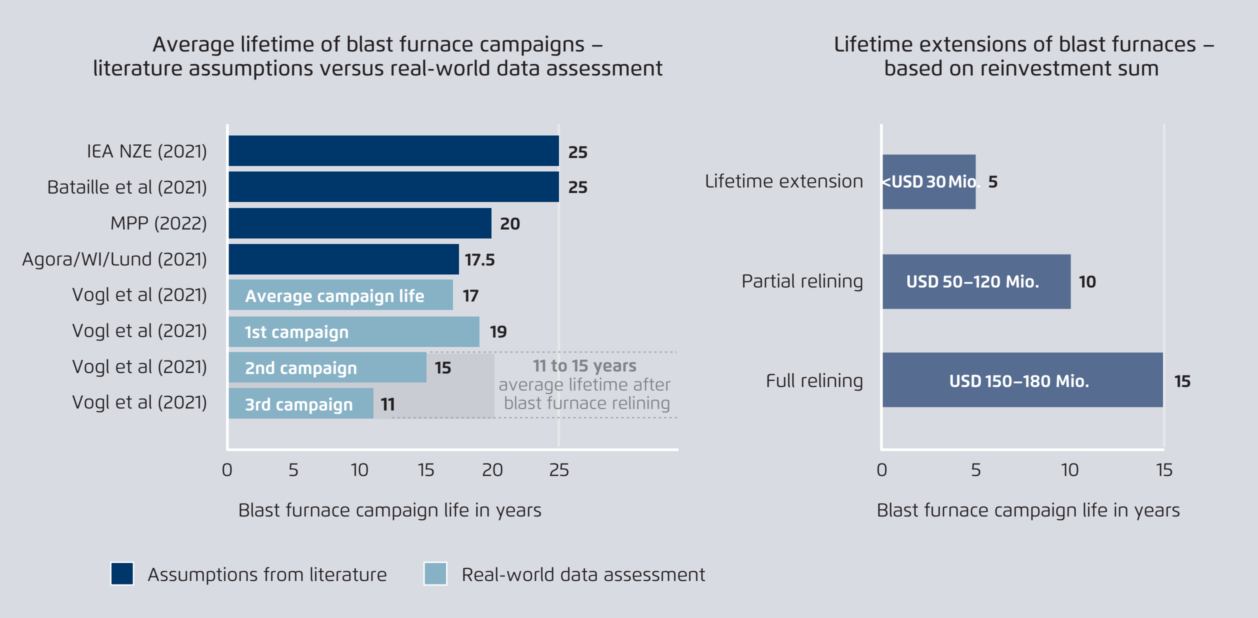
Blast furnace relinings have shorter lifetimes than previously assumed…

In most existing steel decarbonisation scenarios the assumptions for an average blast furnace campaign life range from 20 (MPP 2022) to 25 years (IEA 2021 and Bataille et al 2021). However, to our knowledge all these assumptions regarding the campaign life of blast furnaces are based on literature values.

The only study that assessed a real-world dataset of blast furnace campaigns concluded that the average campaign life of blast furnaces is 17 years (Vogl et al 2021). Moreover, the second (15 years) and the third blast furnace campaign (11 years) tend to be significantly shorter than the 20 to 25 years that are

Lifetime of blast furnace campaigns and various blast furnace retrofit measures

Figure 20



Agora Industry (2023) based on Vogl et al (2021) and own analysis (right). Note: The numbers on the right-hand side are based on our analysis of retrofit measures by various European steelmakers.

---

[25] The other 50 Mt additional DRI capacity are assumed to be built in emerging economies instead of new BF-BOF plants (see insight 11).

uniformly assumed for all blast furnace campaigns in most steel decarbonisation studies.

…and blast furnace operators can choose different retrofit measures with varying lifetimes…

Besides, there are various blast furnace retrofit measures, including minor lifetime extensions measures (up to 5 years), partial relinings (8 to 12 years), and full relinings (15 years). The investment sum of the retrofit measure directly correlates with the lifetime extension (see figure 20).

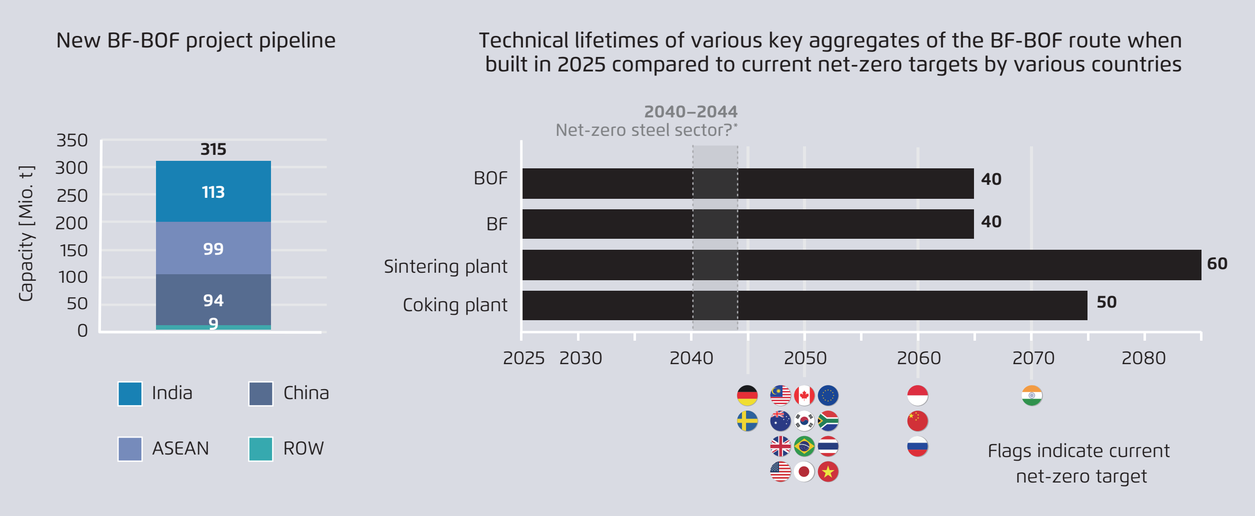
…therefore by 2040 more than 90% of blast furnaces can be phased out without a premature shutdown

So even if a sizeable chunk of blast furnace capacity would have to be relined in the 2020s because low-carbon technologies cannot scale up quickly enough to replace all of them, due to the shorter lifetimes and the option of different retrofit measures, by 2040 more than 90% of all existing blast furnaces could be phased out without a premature shutdown. By 2043, all existing blast furnaces could be phased out without a premature shutdown. Overall, from a global perspective the stranded asset risk for existing blast furnaces is low.

11 The current 2030 pipeline of unabated coal-based blast furnaces in emerging economies is facing a large carbon lock-in and stranded asset risk

The current project pipeline for new coal-based BF-BOF plants is facing a large carbon lock-in and stranded asset risk

Figure 21


New BF-BOF project pipeline

Technical lifetimes of various key aggregates of the BF-BOF route when built in 2025 compared to current net-zero targets by various countries

Agora Industry (2023) assessment and IEA (2020a), Paul Wurth (2022). Note: The current blast furnace – basic oxygen furnace (BF-BOF) pipeline is based on an analysis of announcements in India (IBEF 2022, GEM 2022 and various press releases); for Southeast Asia we used data from OECD (2022) based on data from the Southeast Asian Iron and Steel Institute; for China we analysed public quarterly local government statistics; data for rest of the world is derived from GEM (2022). *2040 and 2044 are the net-zero dates in our Global Green Iron and Technology Mix scenarios.

Today's investments into new coal-based steel plants will likely be tomorrow's stranded assets

The 2020s will likely determine the amount of stranded assets that the global steel transformation to net-zero GHG emission produces. This is because key aggregates of the coal-based BF-BOF route have technical lifetimes ranging from 40 (BF and BOF) to 50 (coking plant) or 60 years (sinter plant). If BF-BOF CCS does not materialise in the future, which appears likely from a present-day perspective (see insight 9), these core aggregates of the BF-BOF route face an enormous risk of premature shutdown before the end of their technical lifetimes. Apart from country-specific net-zero targets, the question will also be how fast the steel sector as a whole will decarbonise. If the emergence of disruptive developments such as international green iron trade (insight 5) or MOE deployment plays out, new coal-based BF-BOF plants from the 2020s will be exposed to high public pressure and a carbon lock-in and stranded asset risk in the 2040s.

The 2030 project pipeline of new BF-BOF plants in emerging economies is large

Steel demand in key emerging economies is still projected to grow to satisfy the infrastructure and development needs of a growing population (IEA 2022a; MPP 2022). We estimate the current project pipeline of new coal-based BF-BOF plants in emerging economies to be around 315 Mt. To date, India (113 Mt), ASEAN[26] countries (99 Mt), and China (94 Mt) account for 97% of the project pipeline (see figure 21).[27]

The 2020s are a crossroads for the global steel sector

The 2020s are a crossroads for investment into new steel plants. They present a choice between a pathway that will lock-in high CO_2 emissions for decades and incur a high risk of carbon lock-in and stranded assets, or alternatively, a pathway of net-zero compatible investment that provides future-proof jobs. However, due in no small part to overly optimistic assumptions regarding the role of retroactive CCS on the BF-BOF route, this is not yet conventional wisdom in all 1.5°C compatible steel decarbonisation scenarios. For countries or steel companies that have net-zero targets by 2050, there is a major carbon lock-in and stranded asset risk, if CCS on the BF-BOF pipeline does not materialise. And for steel companies in countries with net-zero targets later than 2050, there is a major carbon lock-in and stranded asset risk if net-zero government targets were to be pushed forward over the next years or if the steel transformation were to accelerate significantly in the rest of the world.

Apart from long-term risks, there are also short-term risks related to global overcapacity of steel production assets. For example, according to the Southeast Asian Iron and Steel Institute (SEAISI), capacity utilization rates in the ASEAN-6 countries are already comparatively low – in particular for long steel producers (OECD, 2022). Against this backdrop, building new coal-based steel plants may also face risks regarding short and medium-term profitability, unless overcapacity issues are addressed (OECD, 2022).

Solutions to start shifting investments from coal to clean before 2030 will be required

Starting to shift the project pipeline of new steel plants in emerging economies from coal to clean will be an enormous challenge, but there is a lot to gain. A wide set of enabling factors needs to be put in place, including massive investment into renewables, low-carbon H_2, and related infrastructure.

Another key issue will be cost. In terms of investment, capital expenditures (CAPEX) that are earmarked for new BF-BOF plants in India, Southeast Asia, and China could be used for DRI plants. The outlays would be similar and thus would not represent additional costs. The real challenge will be to address the additional operational expenditures (OPEX) for H_2-based DRI plants. They range from 30 to 62%, depending to a large extent on the future cost of low-carbon H_2 (see figure 22). Without adequate solutions to address the OPEX cost gap, costs will continue to remain the key issue.

International cooperation will be key

In order to shift a growing share of investment to net-zero compatible investments, international

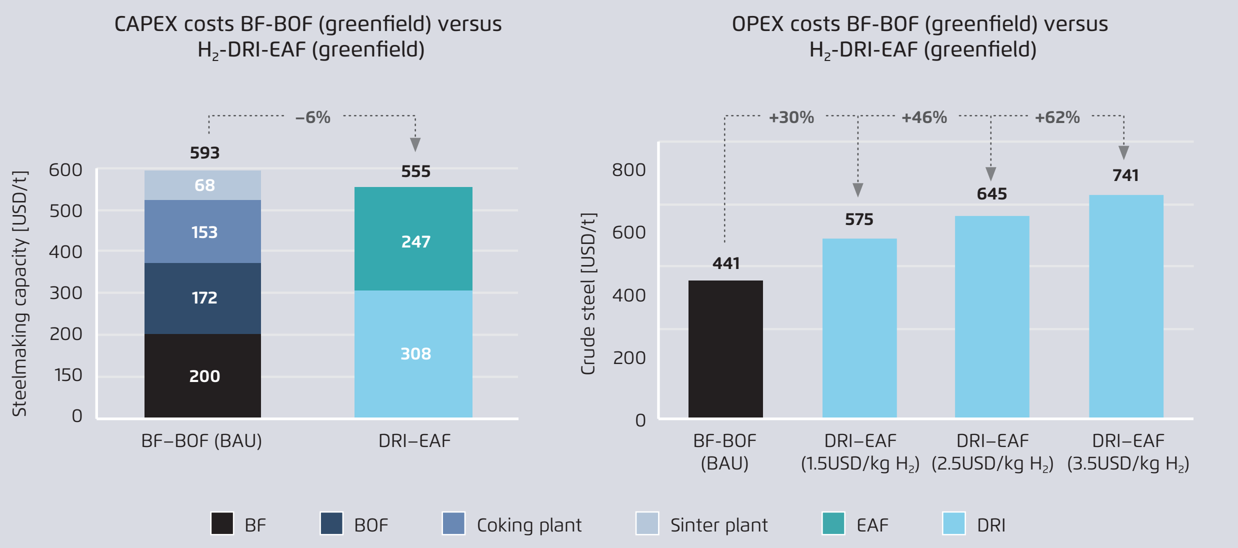
---

[26] ASEAN stands for Association of Southeast Asian Nations.

[27] While new BF-BOF plants in India and Southeast Asia represent additional net steelmaking capacity, as a result of the so-called *capacity swap mechanism*, China has been retiring more blast furnace capacity in recent years than it has added (authors' analysis based on publicly available Chinese local government data).

Shifting investments in emerging economies from coal to clean will require a solution for the higher OPEX costs

Figure 22



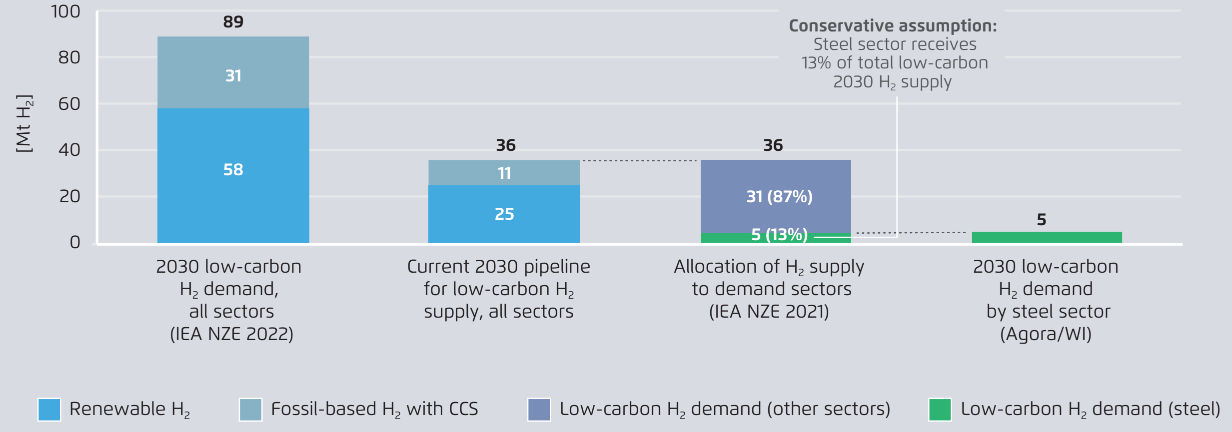
Wörtler et al., 2013 (left) and Agora Industry and Wuppertal Institute, 2023 (right). Note: Numbers on the left were originally given in euros for the year 2010. We adjusted the numbers from euros to US dollar based on the conversion rate from 1 to 1.34 for the relevant year (2010). Right: authors' calculations. CAPEX = capital expenditure; OPEX = operational expenditure.

cooperation will be required. Important fields of cooperation include, by way of example, significantly increased climate finance for emerging economies, de-risking policies to lower the cost of capital, non-distortive trade agreements, and joint technology development. And while the challenges are enormous, the first ambitious actors have demonstrated that net-zero compatible investments in emerging economies before 2030 are possible. For example, in 2022, SOGDC announced that it will build a new H_2-ready integrated DRI-based steelwork in Malaysia by 2025 that will be initially operated with natural gas and use low-carbon H_2 as it becomes available (Borneo Post 2022). To be sure, shifting a growing share of new steel plant investment from coal to clean is possible through international cooperation.

12 If the limited supply of low-carbon H_2 is channelled into no-regret applications, low-carbon H_2 supply will likely not be a major bottleneck for the global steel transformation

2030 low-carbon H_2 supply pipeline versus low-carbon H_2 demand from steel sector by 2030 in our scenarios

Figure 23



Agora Industry (2023) based on IEA (2021), IEA (2022a), IEA (2023) and BNEF (2022b). Note: H_2 allocation to steel compared to other sectors based on IEA NZE (2021). 2030 low-carbon H_2 demand from steel sector based on Technology Mix scenario.

Will low-carbon H_2 supply be a major bottleneck of the steel transformation?

H_2-based steelmaking in DRI routes requires low-carbon H_2. To date, low-carbon H_2 production is less than 1 Mt (IEA 2022e). This begs the question as to whether a shortage of low-carbon H_2 supply is likely to delay or slow the global steel transformation. The short answer is no, not necessarily.

The 2030 low-carbon H_2 project pipeline is growing rapidly, but final investment decisions are still rare

2030 demand for low-emission H_2 is projected to be large, but the project pipeline is growing quickly. In its latest update of their IEA NZE, the IEA projects that 89 Mt of low-carbon H_2 supply by 2030 will be needed across all sectors for a 1.5°C compatible pathway. Out of this amount, the IEA projects that roughly two thirds will be supplied by renewable H_2 and one third by fossil fuel-derived H_2 with CCS (IEA 2022a).

The current 2030 project pipeline of low-carbon H_2 projects amounts to 36 Mt. Currently announced renewable H_2 accounts for 25 Mt by 2030 (BNEF 2022b) and fossil fuel-derived H_2 with CCS accounts for 11 Mt (IEA 2023). While this only covers 40% of the 89 Mt required, the low-emission H_2 project pipeline is growing rapidly. For example, the 36 Mt pipeline figure corresponds to a 50% increase since September 2022, when the low-emission H_2 pipeline stood at 24 Mt – which in turn already marked a 40% increase compared to the previous year (IEA 2022e). However, based on IEA's Hydrogen Project Database up to October 2022, only H_2 projects totalling 4 Mt have reached the stage of final investment decision (IEA 2022f).

On a global level, low-carbon H_2 supply may not be a bottleneck for the global steel transformation

A somewhat surprising finding is that the supply of low-carbon H_2 up to 2030 may not be a bottleneck for the global steel transformation. In our two steel decarbonisation scenarios, the low-carbon H_2 demand of the steel sector amounts to 5 Mt by 2030. This corresponds to 13% of the current low-carbon H_2 project pipeline, if all projects are fully realised. Coincidentally, 13% is exactly the share of low-carbon H_2 that the IEA NZE 2021 allocated to the steel sector in 2030, which represents a very conservative assumption, as will be described below.

The coal to H_2 switch in the steel sector offers one of the comparatively highest CO_2 reduction levers

There is a growing scientific consensus that low-carbon H_2 should not be used in sectors in which direct electrification alternatives are possible and already available today (i.e. Liebreich, 2022; Agora Energiewende, 2022). However, efficiency considerations should not stop there. Indeed, this is also relevant for the question how to allocate low-carbon H_2 amongst certain no-regret applications. Whenever a coal to H_2 fuel switch is possible (like in steel), this will have a far bigger CO_2 reduction impact compared to a natural gas to H_2 switch (fertiliser) or an oil to H_2 derivative switch (ammonia or methanol in maritime shipping) (figure 24).

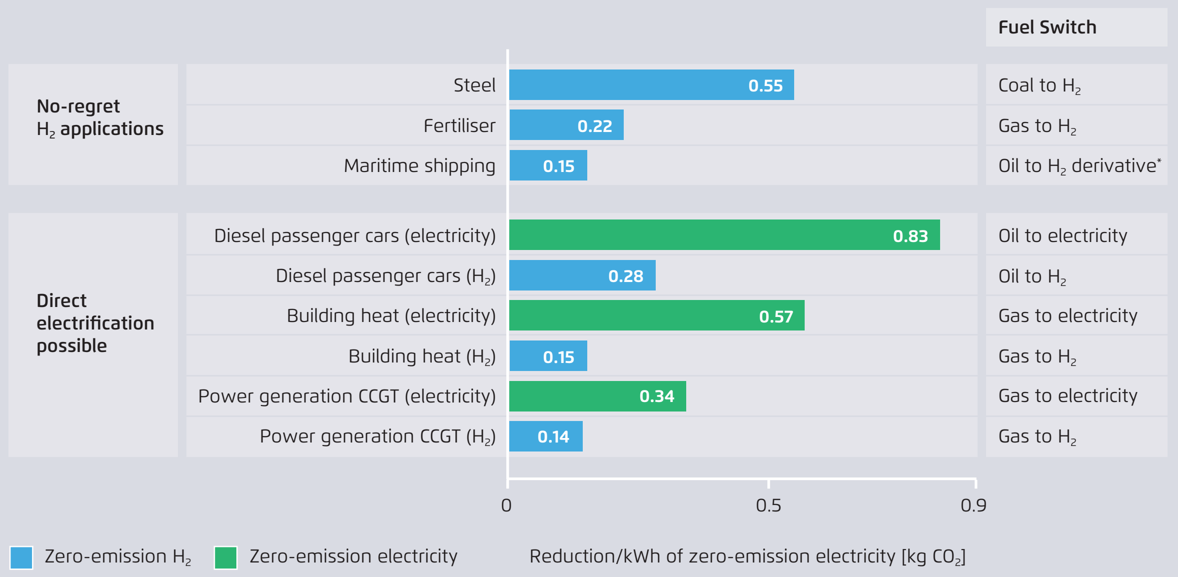
To be sure, the climate mitigation impact is not the only relevant criterion for H_2 allocation. Technological innovation to produce synthetic fuels for maritime shipping, aviation, and chemicals to enable climate neutrality in these sectors is also important. Yet the steel industry has a very strong case for using more than just 13% of the available low-carbon H_2 supply. For the steel industry, the major bottleneck will likely not be H_2 supply, but rather the fast deployment of DRI plants that can use it (see insights 7 and 14).

Steelmakers have a wide range of options to start the transition before 2030

Although on a global level low-carbon H_2 supply will likely not be a major bottleneck for the steel industry, this can and will often be different in specific regional contexts – especially in the short-term. Apart from H_2 supply, the connection of an iron and steel manufacturing site to H_2 infrastructure will be crucially important. But even when such connection is difficult, there are several options for starting the steel transformation now. A first option that does not require any H_2 is to substitute blast furnaces with electric arc furnaces. If steelmakers produce high-quality secondary steel that can substitute primary steel in certain use cases, this can incentivise better practices for scrap recycling to ensure clean scrap flows, thus improving circularity while unlocking new market segments for secondary steel. Several steelmakers such as Algoma Steel, voestalpine, and Liberty Steel are already implementing this option at various sites. A second option is to build H_2-ready DRI plants and operate them with natural gas initially

No-regret H_2 use: steel has the highest CO_2 mitigation potential compared to various other H_2 applications

Figure 24



Agora Industry and Wuppertal Institute (2023) based on concept developed by RMI (2022) and authors' calculations in Agora Energiewende (2023). Note: We assume 2.1 t CO_2/t of crude steel for a world average conventional BF-BOF plant and an electricity requirement of 3.84 MWh/t of crude steel for the DRI-EAF route that runs on 100% renewable H_2. *For maritime shipping based on RMI 2022, we assumed that ammonia replaces heavy fuel oil in a 39% efficient internal combustion engine. All other assumptions are retrieved from Agora Energiewende (2023).

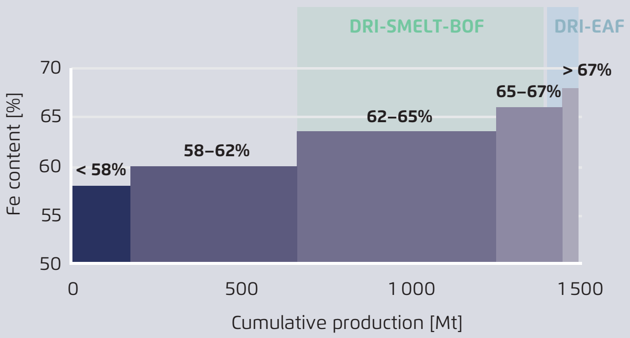
until the DRI plant can be connected to H_2 infrastructure. Examples of steelmakers that pursue this option include thyssenkrupp and ArcelorMittal Dofasco. And finally, steelmakers could choose to import green iron from abroad, which would circumvent the problem of long lead times for the build-up of H_2 infrastructure and high overseas H_2 transport costs, but still allow the production of near-zero emission steel before 2030. POSCO and Nippon Steel have announced plans that pursue this strategy.

13 The availability of DR-grade pellets is a major potential bottleneck for the global steel transformation. Solutions exist, but they need to be actively pursued

How the bottleneck of DR-grade pellets can be addressed

Figure 25

Status quo of seaborne iron ore freight by grade



- Develop new iron ore mining projects with > 66% iron content
- Build more DRI-SMELT-BOF plants
- Beneficiate more iron ore with lower iron content to supply DR-grade level

Agora Industry and Wuppertal Institute (2023), based on MPP (2021). Note: DRI-SMELT-BOF = direct reduced iron – electric smelter – basic oxygen furnace; DRI-EAF = direct reduced iron – electric arc furnace. DR-grade pellets refers to direct reduction grade pellets, which are required for the DRI-EAF route, but not the DRI-SMELT-BOF route.

DR-grade pellet supply could be a major bottleneck for the global steel transformation

DR-grade pellet supply is often mentioned as a major bottleneck for the switch to H_2-based steelmaking (McKinsey 2021; Midrex 2022b; IEEFA 2022a). What is the current state of play and are there solutions for addressing this issue?

The switch to the H_2-based DRI-EAF route requires so-called DR-grade pellets…

In the short term, the H_2-based DRI-EAF route will be the most promising option to significantly reduce the CO_2 emissions of primary steelmaking. The DRI-EAF route requires the use of so-called DR-grade pellets. The requirements for DR-grade pellets of low impurities (gangue) and high iron (>66%) content mean that only high-quality iron ore is suitable unless lower-grade iron ore is beneficiated (Midrex 2022a; IEEFA 2022a).

…but today only 3 to 4% of iron ore shipments are DR-grade pellet quality

Today only 3 to 4% of seaborne iron ore shipments are DR-grade pellet quality that would be suitable for the DRI-EAF route (MPP 2021, Vale in IEEFA 2022a). Unless this problem is addressed, this risks being a major bottleneck for the deployment and operation of DRI-EAF plants (see also insight 14).

Can DR-grade quality iron ore supply match DR-grade pellet demand?

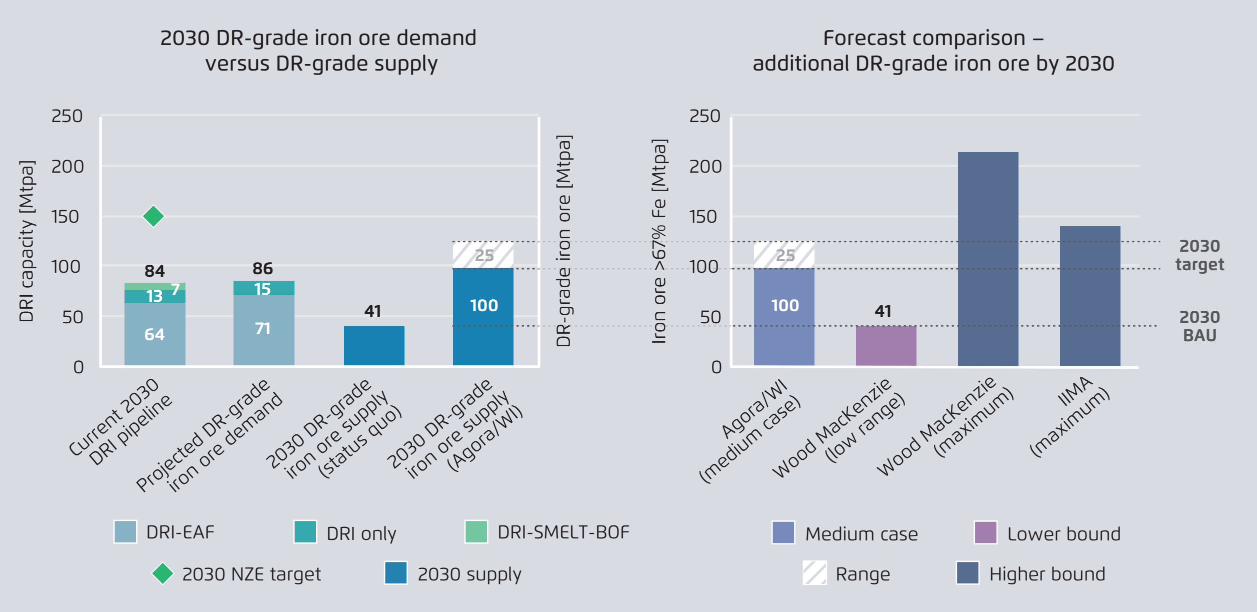
One key question is how much additional DR-grade iron ore can be made available by 2030 to supply a rapidly growing demand for DR-grade pellets. The currently announced 2030 DRI-EAF project pipeline of 64 to 77 Mt of additional DRI-EAF capacity[28] will require between 71 and 86 Mt of DR-grade pellets from suitable iron ore per year. This would already more than exceed the current 2030 pipeline of new iron ore mining projects that could supply DR-grade quality iron ore – making this a major bottleneck (see figure 26). Solutions to address this bottleneck exist, but they need to be pursued.

More iron ore mining projects that can supply DR-grade iron ore quality need to be developed

Based on Wood MacKenzie's 2021 iron ore project review, IEEFA concluded that the current project pipeline of iron ore mining projects that could supply DR-grade quality stands at 41 to 213 Mt per year by 2030 (IEEFA 2022a). The lower range of 41 Mt is based on projects for which realisation by 2030 is highly probable or probable, whereas the higher bound estimate includes projects that are possible. Other projections see the maximum supply at 140 Mt by 2030 (IIMA 2021). Given the long lead times for new iron ore mining projects, it is unlikely that all

Unless urgent action is taken 2030 DR-grade iron ore demand will significantly outstrip DR-grade iron ore supply

Figure 26



Agora Industry and Wuppertal Institute (2023), authors' analysis based on IEEFA (2022a). Note: We assume that DRI capacity will have a utilisation rate of 80% and that the DRI-EAF route will require 1.4 t DR-grade pellets and 0.2 t of scrap per t of crude steel, whereas the DRI-SMELT-BOF route does not require DR-grade pellets. "DRI only" plants were considered as DRI-EAF. We further assume that all existing DR-grade pellet supply is used by existing DRI plants.

---

[28] These numbers are only referring to DRI-EAF and DRI only capacity and do exclude DRI-SMELT-BOF capacity, because the latter does not require DR-grade pellets.

possible projects can be realised by 2030. We therefore estimate that 100 to 125 Mt per year of additional DR-grade quality iron supply by 2030 is an ambitious target but achievable if actively pursued.

Innovative H_2-based steelmaking routes can alleviate pressure from the DR-grade pellet bottleneck

The DRI-EAF route is not the only option for H_2-based steelmaking. There are innovative H_2-based DRI routes that do not require DR-grade pellets. For example, the DRI-SMELT-BOF route can use conventional BF-grade pellets that only require iron ore with 62 to 65% iron content. A contract for the first commercial-scale DRI-SMELT-BOF plant has been awarded (Thyssenkrupp, 2023). The current 2030 pipeline stands at 7 Mt per year. Apart from steelmakers, iron ore mining companies such as BHP and Fortescue in partnership with Primetals are also currently developing and testing electric smelter solutions to make a wider range of ore qualities available for DRI-based steelmaking routes (BHP, 2023; Primetals 2022). Shifting some announced DRI-EAF investments to DRI-SMELT-BOF investments would help to alleviate pressure on the DR-grade pellet bottleneck.

Moreover, innovative H_2-based DRI routes based on fluidised bed reactors are being developed that could use an even wider range of iron ores (Metso Outotec 2021; POSCO 2022; Primetals 2022). The commercial availability of this technology route is currently anticipated around 2030.

Iron ore benefication is another key option to increase DR-grade pellet supply

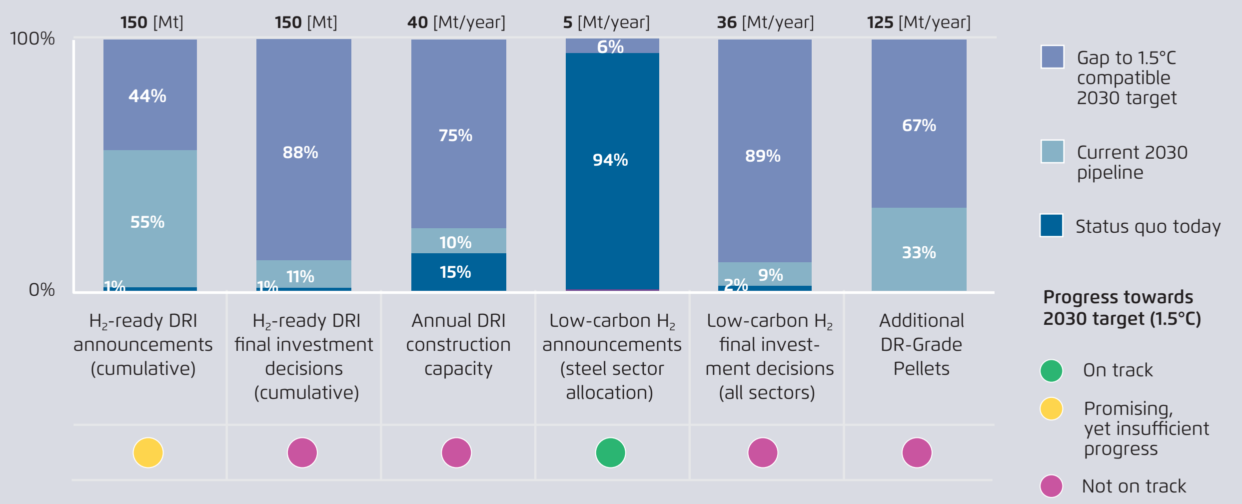
Another major solution to increase the supply of iron ore that is suitable for DR-grade quality is iron ore beneficiation (IEEFA 2022b). Iron ore mining companies could build up iron ore beneficiation facilities, in which lower-grade iron ore can be upgraded to DR-grade quality.

From a present-day perspective, it is likely that all three solutions will be required to address this bottleneck.

14 The bottlenecks for a 1.5°C compatible steel transformation pathway are manageable, but joint action from governments and industry is needed to address them

Key bottlenecks up to 2030: The state of play

Figure 27



Agora Industry (2023), based on Agora Industry Global Steel Transformation Tracker (2023), IEA (2022a), IEA (2023), BNEF (2022b); IEEFA (2022a). Note: The target of 120 to 150 Mt H_2-ready DRI capacity is based on our modelling and the latest Breakthrough Agenda Report 2022 which called for "more than 100 Mt of near-zero emissions primary steel by 2030". The figure displays the upper range of the 2030 target numbers for H_2-ready DRI announcements (120 to 150 Mt) and additional DR-grade pellets (100 to 125 Mt). With regards to final investment decisions, status quo today refers to plants that have begun operations since 2021 and current 2030 pipeline refers to final investment decisions. Based on BNEF 2022b and IEA ETP 2023, we estimate the current low-carbon H_2 project pipeline to be 36 Mt by 2030. In our modelling scenarios the steel sector requires around 5 Mt low-carbon H_2 by 2030, which constitutes 13% of total low-carbon H_2 supply, if the entire current low-carbon H_2 project pipeline is realised.

A 1.5°C compatible steel decarbonisation pathway is possible but will require concerted action from governments and industry to address key bottlenecks. Specifically, both solutions to technical challenges (i.e. DRI deployment, low-carbon H_2 supply, and DR-grade pellets) and an appropriate regulatory framework that is conducive to low-carbon steelmaking must be developed in parallel if the global steel industry is to enter on a 1.5°C compatible steel decarbonisation pathway. By 2030, we estimate that between 120 and 150 Mt of additional DRI capacity will be needed to produce "more than 100 Mt of near-zero emissions primary steel", which is indicated as a potential 1.5°C compatible target for 2030 in the recent Breakthrough Agenda report (IEA/IRENA/UN High Level Champions 2022).[29] Figure 27 undertakes a first attempt to measure progress toward this goal.

---

[29] The 2022 Breakthrough Agenda report does not indicate which technologies will contribute towards that goal. Based on our technology analysis (forthcoming), we think that DRI plants will likely be the only key technology available to decarbonise primary steelmaking that can scale up significantly before 2030.

Several bottlenecks require urgent action to meet 1.5°C compatible 2030 targets

H_2-ready DRI announcements: To date, steel companies have announced the development of 84 Mt of H_2-ready DRI capacity by 2030, which corresponds to a 56% fulfilment of the upper range of the 2030 target. If DRI project announcements continue to develop as in previous years (average of 33 Mt/year for 2021 and 2022), reaching the 2030 target in this category could be already achieved by the mid-2020s. **Current status**: Promising, yet insufficient progress.

H_2-ready DRI – final investment decisions (FIDs): FIDs for low-carbon steel technologies are one of the most important key indicators for tracking the real-world progress of the steel transformation. They require sufficient confidence by the steel company and investors that the enabling conditions for the operation of a low-emission steel plant are in place. Such enabling conditions will depend in no small part on the establishment of a regulatory framework that addresses the higher cost of low-carbon steelmaking (see insight 15) and the other aforementioned bottlenecks. To date, one commercial-scale H_2-ready DRI plant has already been constructed in China, and the announcement of several FIDs for H_2-ready DRI plants is expected in 2023. If these FIDs are counted, 12% of the 2030 target would be fulfilled (figure 27 and 28). Accordingly, urgent action is needed to provide an adequate regulatory framework and the necessary infrastructure to enable further FIDs. **Current status**: Not on track.

Annual DRI construction capacity: DRI engineering and construction capacity is a key enabler of the steel transformation – yet also a major bottleneck. The current 2030 DRI project pipeline (84 Mt by 2030) already significantly exceeds our estimate of the plant development potential that is possible with existing engineering and construction capacities (70 Mt by 2030). This is currently a major, if not the biggest, bottleneck. Unless urgent action is taken to address this problem, this will jeopardise attainment of the 2030 targets (see insight 7). **Current status**: Not on track.

Low-carbon H_2 announcements: The supply of low-carbon H_2 is a key enabler for near-zero emission steelmaking in H_2-based DRI plants. Today, the 2030 project pipeline for renewable H_2 is estimated to be 36 Mt, thus covering 40% of the 89 Mt of 2030 H_2 demand in IEA NZE (IEA, 2022a). In our scenarios the steel industry's low-carbon H_2 demand by 2030 is around 5 Mt, accounting for 13% of the 36 Mt. Even if only the current 2030 project pipeline is realised, this will not be a major bottleneck for the steel transformation globally, so long as H_2 is prioritised for no-regret applications (see insight 12). However, in addition to government policies to incentivise the channelling of H_2 into no-regret applications – for example, by encouraging an ambitious ramp-up of H_2 use in H_2-ready DRI plants – steel companies should also state much clearer targets on how much low-carbon H_2 they plan to use by when.[30] Otherwise, sufficient global low-carbon H_2 supply may not translate into meeting the 2030 low-carbon H_2 demand of the steel industry. **Current status**: On track.

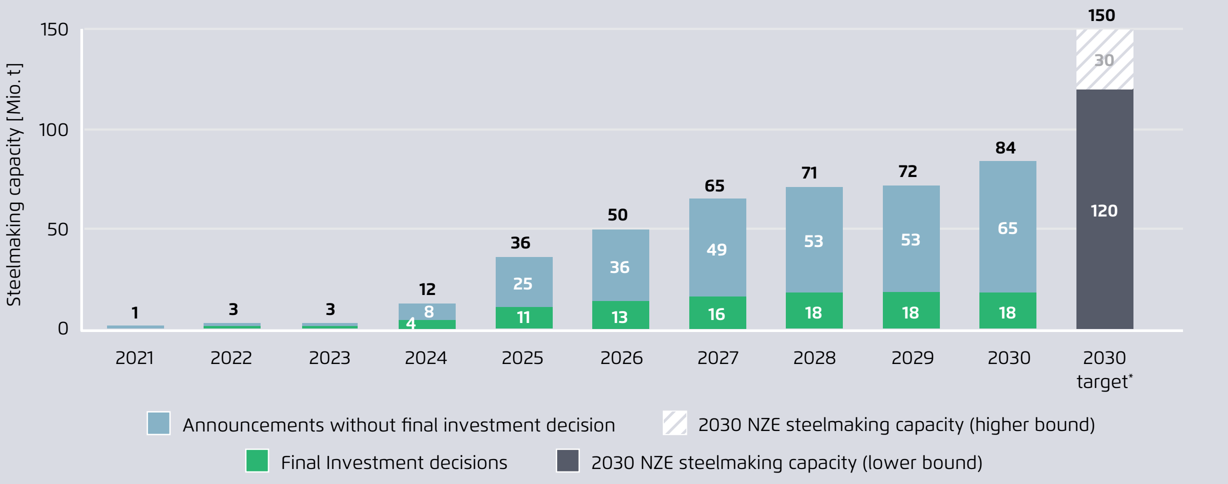
Low-carbon H_2 final investment decisions: Currently, 0.6 Mt of low-carbon H_2 are being produced (IEA, 2022e). According to the IEA Hydrogen Project Database, by October 2022 around 4 Mt had reached final investment decision or under construction status. Accelerating the introduction of a strong regulatory framework for low-carbon H_2 will be important for increasing the number of final investments decisions. **Current status**: Not on track.

---

[30] Many steelmakers have announced their intentions to build H_2-ready DRI plants, and have stated they could be converted to low-carbon H_2 use in the future, but without specifying concretely when this would take place. Specific objectives for low-carbon H_2 use could help to coordinate the ramp-up of H_2 and related infrastructure, to track progress towards net-zero goals, and to connect producers of near-zero emission steel with potential buyers (IEA, 2023).

2030 pipeline: near-zero emissions primary steelmaking capacity announcements and final investment decisions

Figure 28

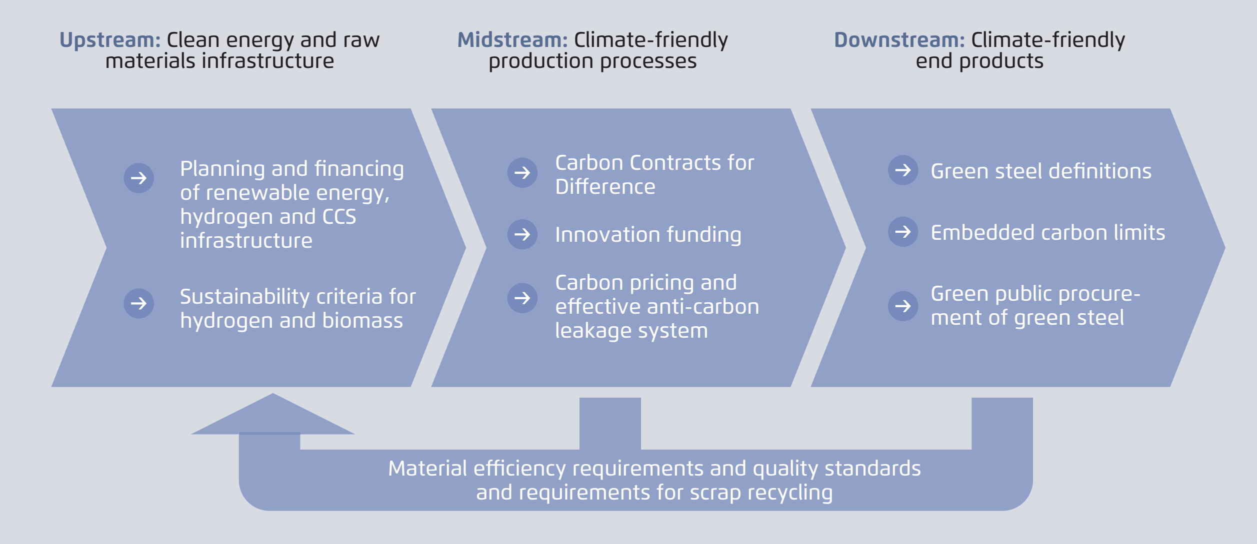


Agora Industry (2023), Global Steel Transformation Tracker (2023). Note: All announced projects can be H_2-ready DRI plants, in principle. However, to date only around 25% of the project pipeline is designed at outset to accommodate switch to renewable H_2. All other DRI plants will run on natural gas or a mix of natural gas and H_2 with the stated intention of most companies to switch to 100% low-carbon H_2 eventually, once it becomes available (see Agora Industry, Global Steel Transformation Tracker). *The 2030 targets refer to the near-zero emissions primary steelmaking capacity that would be needed to be on a 1.5°C compatible pathway based on IEA, IRENA, UN 2022 and authors' scenarios.

DR-grade pellet supply: The supply of DR-grade pellets is often cited as a key requirement for the switch to H_2-based DRI plants (McKinsey 2021; Midrex 2022b; IEEFA 2022a). However, this is only true for the DRI-EAF route, but not for the so-called DRI-SMELT-BOF route. While options exist to address this bottleneck, the current plans for DR-grade pellet supply cover only 33% of our estimated 2030 demand and thus fall significantly short of what is needed by 2030 (see insight 13). **Current status**: Not on track.

15 Achieving a net-zero steel sector will require governments to adopt a comprehensive policy framework that addresses the entire value chain. International coordination and cooperation will be key in this regard

A net-zero steel sector requires a comprehensive policy framework across the entire value chain Figure 29



Agora Industry (2023)

The steel transformation will not happen on its own – a comprehensive policy framework is needed

Kickstarting the steel transformation will require specific conditions to be put in place quickly. These conditions can be enabled through a comprehensive policy framework that encompasses the entire steelmaking value chain (see figure 29). Upstream, this will require the build-out of clean energy and raw materials infrastructure. Midstream, policy instruments are needed to enable a business case for near-zero emission steelmaking. And downstream, market-pull policy instruments are needed to unlock the potential of green lead markets.

Upstream: Clean energy and raw materials infrastructure

- → **Planning and financing of renewable energy and hydrogen and CCS infrastructure**: The steel transformation will require large amounts of clean energy and the necessary grid and transport infrastructure for power, H_2, and CO_2 .
- → **Sustainability criteria for H_2 and biomass**: Strict and commonly agreed sustainability rules for renewable and low-carbon H_2 and truly sustainable biomass will be required to create an international level playing field.

Midstream: Climate-friendly production processes

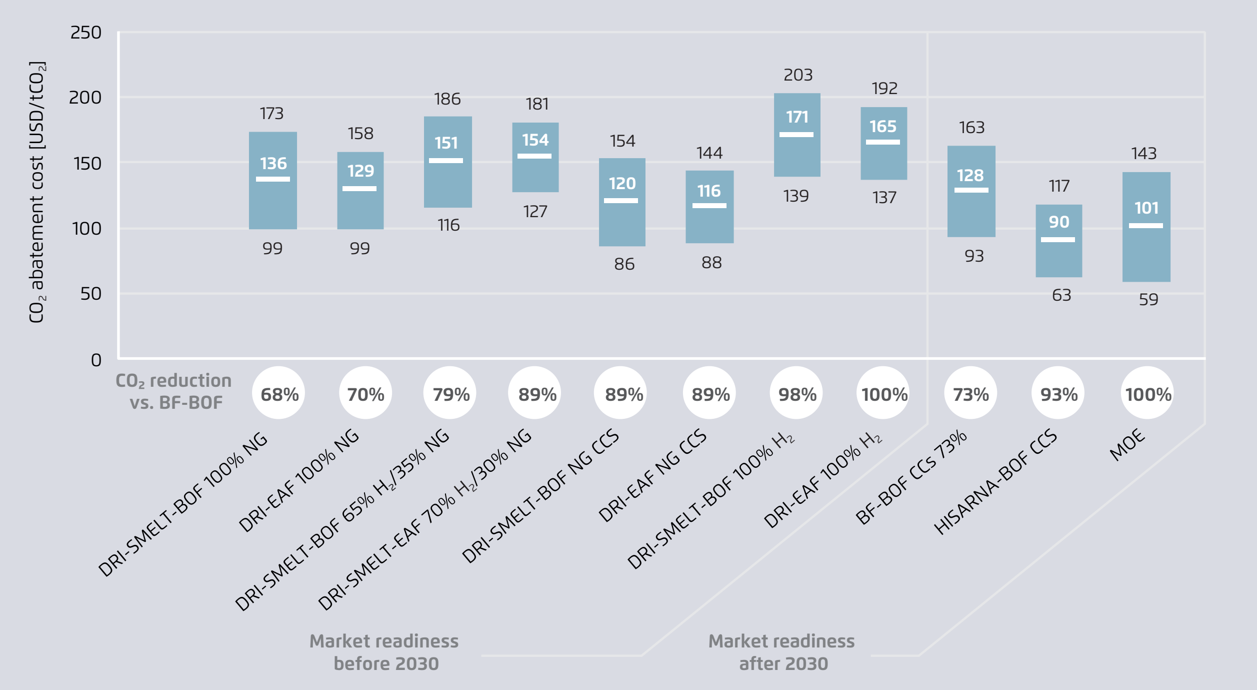
- **Carbon contracts for difference (CCfDs)**: CCfDs can address the additional costs (especially OPEX) of near-zero emission steelmaking technologies relative to CO_2 -intensive production methods. Their design can be adjusted to complement carbon pricing or a carbon border adjustment mechanism (CBAM), but could also work alone (Agora/WI/Futurecamp, 2022).
- **Innovation funding**: Additional funds to support net-zero compatible investments can help to support the commercialisation and ramp-up of near-zero emission steelmaking technologies.
- **Carbon pricing and effective anti-carbon leakage system**: CO_2 pricing is a key element of the policy mix, as it helps to internalise the costs of CO_2 -intensive production methods. This can help to close the cost gap between near-zero emissions steel production and CO_2 -intensive methods. To avoid the exposure of steel companies to carbon leakage vis-à-vis other countries with lower or no carbon pricing, anti-carbon leakage systems like a CBAM or equivalent measures are required.

Downstream: Climate-friendly end products

- **Green steel definitions**: A commonly agreed definition of what constitutes green steel is key to unlock the potential of green lead markets (i.e. see IEA 2022g). Based on clearly defined rules, private companies and governments could procure green and/or low-emission steel for a higher premium, creating a business case for green steel that does not rely on continued subsidies.

2030 CO_2 abatement cost of key technologies versus the unabated blast furnace – basic oxygen furnace route

Figure 30



Agora Industry and Wuppertal Institute (2023). Note: Our cost assumptions are based on a literature review and a "middle-of-the-road" approach, in which the lowest and the highest costs are excluded from our cost range. Input assumptions for 2030 are: 50 to 80 USD/MWh for delivered zero-carbon electricity; 2 to 3 USD/kg for delivered low-carbon H_2; 13 to 31 USD/MWh for natural gas; 30 to 60 USD/t of CO_2 for CO_2 transport and storage excluding CO_2 capture.

- **Embedded carbon limits**: Embedded carbon limits on final products such as near-zero emission material mandates provide another important policy option to create a market for near-zero emission products and could help to gradually phase-out CO_2 -intensive final products that are above certain thresholds.
- **Green public procurement of green steel**: Government and other public agencies procure large amounts of steel, e.g. for public infrastructure projects or public transport. Governments could use their procurement power to buy an increasing share of green steel.
- **Material efficiency requirements and quality standards for scrap recycling**: Material efficiency potentials extend over the entire value chain. Policy instruments that can help to enhance material efficiency include, for example, updated building codes that reduce the overspecification of structural steel, incentives that allow for an extension of the lifetime of buildings, as well as policies that incentivise a modal shift in the transport sector.

  With regard to scrap recycling, steel scrap is often contaminated with tramp elements like copper. This leads to lower-quality scrap-based steel that is limited to a few applications (downcycling). Clear requirements for scrap sorting and shredding at the end-of-life of steel-containing products during recycling can avoid this (Agora Industry, 2022).

International coordination and cooperation will be key

The average CO_2 abatement cost of various low-emission steelmaking technologies by 2030 is expected to range from 110 to 160 USD/tCO_2 (Agora/WI/Lund, forthcoming). Few countries are expected to have such a CO_2 price level by 2030. Without a comprehensive policy framework, final investment decisions for near-zero emission steel plants before 2030 are unlikely. International coordination and cooperation will be crucially important. Such coordination and cooperation can help to create an international level playing field; lower the costs of the global steel transformation (insight 5); create win–win opportunities (insight 6); help to jointly remove key bottlenecks (insight 14); minimise stranded assets (insight 11); and ensure a just transition. As Fatih Birol, the head of the IEA, put it, when the IEA Energy Technology Perspectives Report was launched in January 2023: “By working together, countries can be greater than the sum of their parts.”

References

Agora Energiewende (2022). *12 Insights on Hydrogen*. Online available at: https://www.agora-energiewende.de/en/publications/12-insights-on-hydrogen-publication/

Agora Energiewende, Wuppertal Institute, Futurecamp (2022). *Transforming industry through carbon contracts (Steel)*. Online available at: https://www.agora-energiewende.de/en/publications/transforming-industry-through-carbon-contracts-steel/

Agora Energiewende (2023). *Breaking free from fossil gas*. Online available at: https://www.agora-energiewende.de/en/publications/breaking-free-from-fossil-gas-1/

Agora Industry, Wuppertal Institute, Lund University (2021). *Global Steel at a Crossroads*. Online available at: https://www.agora-energiewende.de/en/publications/global-steel-at-a-crossroads/

Agora Industry (2022). *Mobilising the circular economy for energy-intensive materials*. Online available at: https://www.agora-energiewende.de/en/publications/mobilising-the-circular-economy-for-energy-intensive-materials-study/

Agora Industry (2023). *Global Steel Transformation Tracker*. Online available at: https://www.agora-energiewende.de/en/service/global-steel-transformation-tracker/

Australian Government (2021). *New low emissions technology partnership with the Republic of Korea*. Online available at: https://www.dcceew.gov.au/about/news/new-low-emissions-technology-partnership-with-the-republic-of-korea

Australian Government (2022). *Resources and Energy Quarterly*. Online available at: https://www.industry.gov.au/sites/default/files/minisite/static/ba3c15bd-3747-4346-a328-6b5a43672abf/resources-and-energy-quarterly-september-2022/documents/Resources-and-Energy-Quarterly-September-2022-Iron-Ore.pdf

Bataille et al (2021). *Global facility level net-zero steel pathways*. Online available at: http://netzerosteel.org/wp-content/uploads/pdf/net_zero_steel_report.pdf

BHP (2023). *BHP and Hatch commence design study for an electric smelting furnace pilot*. Online available at: https://www.bhp.com/news/media-centre/releases/2023/03/bhp-and-hatch-commence-design-study-for-an-electric-smelting-furnace-pilot

Bloomberg New Energy Finance (BNEF) (2022a). *2H 2022 Hydrogen Levelized Cost Update*.

BloombergNEF (BNEF) (2022b). *A Breakneck Growth Pivot Nears for Green Hydrogen*. Online available at: https://about.bnef.com/blog/a-breakneck-growth-pivot-nears-for-green-hydrogen/

Borneo Post (2022). *Green Steel Project to be built in Sipitang*. Online available at: https://www.theborneopost.com/2022/11/30/green-steel-project-to-be-built-in-sipitang/

Ember (2023). *Why the steel industry needs to tackle coal mine methane*. Online available at: https://ember-climate.org/insights/research/why-the-steel-industry-needs-to-tackle-coal-mine-methane/#supporting-material-downloads

Energy Transitions Commission (ETC) (2021). *Bioresources within a Net-Zero Emissions Economy*. Online available at: https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/

Global Energy Monitor (GEM) (2022). *Global Steel Plant Tracker*. Online available at: https://globalenergymonitor.org/projects/global-steel-plant-tracker/

Institute for Energy Economics and Financial Analysis (IEEFA) (2022a). *Iron ore quality a potential headwind to green steelmaking – Technology and mining options are available to hit net-zero steel targets*. Online available at: https://ieefa.org/resources/iron-ore-quality-potential-headwind-green-steelmaking-technology-and-mining-options-are

Institute for Energy Economics and Financial Analysis (IEEFA) (2022b). *Solving iron ore quality issues for low-carbon steel*. Online available at: https://ieefa.org/resources/solving-iron-ore-quality-issues-low-carbon-steel

Intergovernmental Panel on Climate Change (IPCC) (2018). *Global Warming of 1.5°C*. Online available at: https://www.ipcc.ch/sr15/

Intergovernmental Panel on Climate Change (IPCC) (2023). *AR6 Synthesis Report (SYR)*. Online available at: https://www.ipcc.ch/report/sixth-assessment-report-cycle/

International Energy Agency (IEA) (2020a). *Iron and Steel Technology Roadmap*. Online available at: https://www.iea.org/reports/iron-and-steel-technology-roadmap

International Energy Agency (IEA) (2020b). *Methane Tracker 2020*. Online available at: https://www.iea.org/reports/methane-tracker-2020

International Energy Agency (IEA) (2021). *Net Zero by 2050*. Online available at: https://www.iea.org/reports/net-zero-by-2050

International Energy Agency (IEA) (2022a). *World Energy Outlook 2022*. Online available at: https://www.iea.org/reports/world-energy-outlook-2022

International Energy Agency (IEA) (2022b). *Iron and Steel Tracking Report*. Online available at: https://www.iea.org/reports/iron-and-steel

International Energy Agency (IEA) (2022c). *Global Hydrogen Review*. Online available at: https://www.iea.org/reports/global-hydrogen-review-2022

International Energy Agency (IEA) (2022d). *Global Methane Tracker 2022*. Online available at: https://www.iea.org/reports/global-methane-tracker-2022/overview

International Energy Agency (IEA) (2022e). *Hydrogen Tracking Report*. Online available at: https://www.iea.org/reports/hydrogen

International Energy Agency (IEA) (2022f). *Hydrogen Projects Database*. Online available at: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

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

International Energy Agency (IEA) (2023). *Energy Technology Perspectives 2023*. Online available at: https://www.iea.org/reports/energy-technology-perspectives-2023

International Energy Agency (IEA), International Renewable Energy Agency (IRENA), UN Climate Change High Level Champions (2022). *Breakthrough Agenda Report 2022*. Online available at: https://www.iea.org/reports/breakthrough-agenda-report-2022

International Iron Metallics Association (IIMA) (2021). *Global Iron Ore - Outlook for DR grade iron ore: issues and challenges for the industry*. Online available at: https://www.metallics.org/assets/files/Public-Area/Presentations/FM-IO_210318.pdf

International Renewable Energy Agency (IRENA) (2022a). *Geopolitics of the Energy Transformation: The Hydrogen Factor*. Online available at: https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

International Renewable Energy Agency (IRENA) (2022b). *World Energy Transitions Outlook: 1.5°C Pathway*. Online available at: https://www.irena.org/publications/2022/mar/world-energy-transitions-outlook-2022

Iron Brand Equity Foundation (IBEF) (2022). *Iron & Steel Industry in India*. Online available at: https://www.ibef.org/industry/steel

Liebreich (2022). *The Clean Hydrogen Ladder*. Online available at: https://www.linkedin.com/pulse/clean-hydrogen-ladder-v40-michael-liebreich

McKinsey & Company (2021). *The DRI dilemma: Could raw material shortages hinder the steel industry's green transition?* Online available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-dri-dilemma-could-raw-material-shortages-hinder-the-steel-industrys-green-transition

McKinsey & Company (2022). *Closing Europe's green-metallics gap*. Online available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/closing-europes-green-metallics-gap

Metso Outotec (2021). *Circored Fine Ore Direct Reduction – a proven process to decarbonize steelmaking*. Online available at: https://www.mogroup.com/insights/blog/mining-and-metals/circored-fine-ore-direct-reduction-a-proven-process-to-decarbonize-steelmaking/

Midrex (2022a). *World Direct Reduction Statistics*. Online available at: https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2021.pdf

Midrex (2022b). *The Iron Ore Challenge for Direct Reduction On Road to Carbon-Neutral Steelmaking*. Online available at: https://www.midrex.com/tech-article/the-iron-ore-challenge-for-direct-reduction-on-road-to-carbon-neutral-steelmaking/

Mission Possible Partnership (MPP) (2021). *The Net Zero Steel Sector Transition Strategy*. Online available at: https://www.energy-transitions.org/publications/the-net-zero-steel-sector-transition-strategy/

Mission Possible Partnership (MPP) (2022). *Making Net Zero Steel possible*. Online available at: https://missionpossiblepartnership.org/wp-content/uploads/2022/09/Making-Net-Zero-Steel-possible.pdf

Organisation for Economic Co-operation and Development (OECD) (2022). *The ASEAN Steel Industry Development: Investment and Green Industry Challenges*. Online available at: https://search.oecd.org/industry/ind/Item_6.3_SEAISI.pdf

Paul Wurth (2022). *Coke Oven Batteries*. Online available at: https://www.paulwurth.com/en/technology/cokemaking/coke-oven-batteries/

POSCO (2022). *POSCO starts to design the HyREX demonstration plant*. Online available at: https://newsroom.posco.com/en/posco-starts-to-design-the-hyrex-demonstration-plant/

Primetals (2022). *Primetals Technologies, Fortescue und voestalpine evaluieren gemeinsam eine bahnbrechende Anlage für grüne Eisenerzeugung*. Online available at: https://www.primetals.com/de/presse-medien/news/primetals-technologies-fortescue-und-voestalpine-evaluieren-gemeinsam-eine-bahnbrechende-anlage-fuer-gruene-eisenerzeugung

RMI (2022). *Hydrogen Reality Check: We Need Hydrogen — But Not for Everything*. Online available at: https://rmi.org/we-need-hydrogen-but-not-for-everything/

Science Based Targets (SBTi) (2022). *Steel science-based target setting guidance*. Online available at: https://sciencebasedtargets.org/resources/files/SBTi-Steel-Guidance-draft.pdf

Thyssenkrupp (2023). *thyssenkrupp Steel awards a contract worth billions of euros to SMS group for a direct reduction plant: one of the world's largest industrial decarbonization projects gets underway*. Online available at: https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/thyssenkrupp-steel-awards-a-contract-worth-billions-of-euros-to-sms-group-for-a-direct-reduction-plant--one-of-the-worlds-largest-industrial-decarbonization-projects-gets-underway-163184

Vogl et al (2021). *Phasing out the blast furnace to meet global climate targets*. Online available at: https://www.cell.com/joule/pdfExtended/S2542-4351(21)00435-9

Wörtler et al (2013). *Steel's Contribution to a Low-Carbon Europe 2050*. Online available at: https://www.bcg.com/publications/2013/metals-mining-environment-steels-contribution-low-carbon-europe-2050

WV Stahl (2021). E*mployment in the Steel Industry*.

Publications by Agora Industry

IN ENGLISH

12 Insights on Hydrogen – Argentina Edition

Argentina as a hub for green ammonia
A forward-looking development strategy for addressing the global energy and climate crises

Transforming industry through carbon contracts (Steel)
Analysis of the German steel sector

Power-2-Heat
Gas savings and emissions reduction in industry

International climate cooperation for energy-intensive industry
A (realistic) proposal

12 Insights on Hydrogen

Mobilising the circular economy for energy-intensive materials (Executive Summary)
How Europe can accelerate its transition to fossil-free, energy-efficient and independent industrial production

Mobilising the circular economy for energy-intensive materials (Study)
How Europe can accelerate its transition to fossil-free, energy-efficient and independent industrial production

Getting the Transition to CBAM Right
Finding pragmatic solutions to key implementation questions

Global Steel at a Crossroads
Why the global steel sector needs to invest in climate-neutral technologies in the 2020s

Publications by Agora Industry

IN GERMAN

Power-2-Heat
Erdgaseinsparung und Klimaschutz in der Industrie

Klimaschutzverträge für die Industrietransformation (Stahl) – Update
Aktualisierte Analyse zur Stahlbranche

Klimaschutzverträge für die Industrietransformation (Zement)
Analyse zur Zementbranche

12 Thesen zu Wasserstoff

Mobilisierung der Kreislaufwirtschaft für energieintensive Materialien (Zusammenfassung)
Wie Europa den Übergang zu einer fossilfreien, energieeffizienten und energieunabhängigen industriellen Produktion vollziehen kann

Klimaschutzverträge für die Industrietransformation (Gesamtstudie)
Kurzfristige Schritte auf dem Pfad zur Klimaneutralität der deutschen Grundstoffindustrie

Klimaschutzverträge für die Industrietransformation (Stahl)
Analyse zur Stahlbranche

298/03-I-2023/EN

About Agora Industry

Agora Industry is a division of Agora Energiewende that develops strategies and instruments for climate-neutral industrial transformation – in Germany, the EU and globally. Agora Industry works independently of economic and partisan interests. Its only commitment is to climate action.

Agora Industry
Anna-Louisa-Karsch-Straße 2 | 10178 Berlin, Germany
P +49 (0)30 700 14 35-000
F +49 (0)30 700 14 35-129
www.agora-industry.org
info@agora-industrie.de