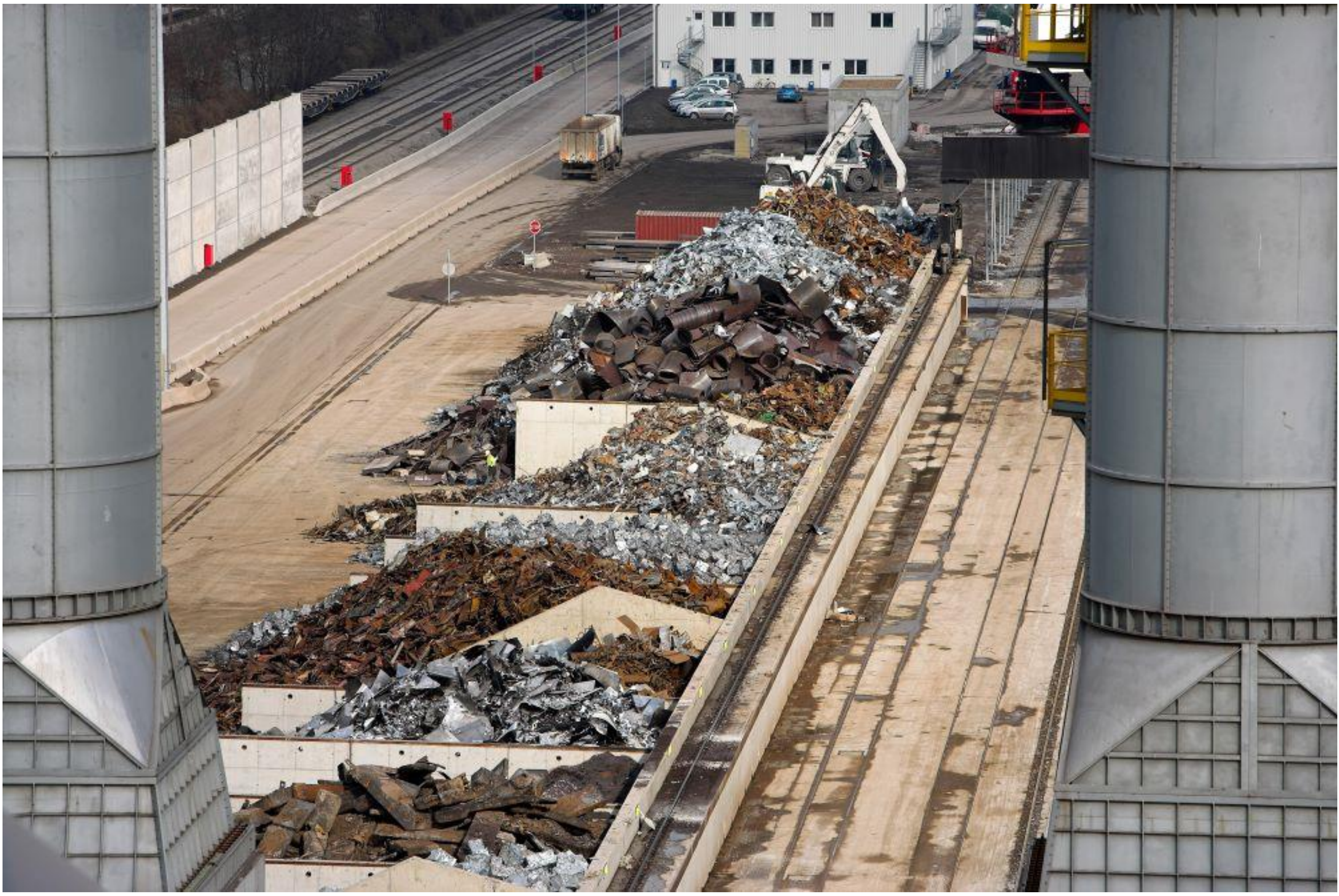
Starting from scrap

The key role of circular steel in meeting climate goals

sandbag
smarter climate policy



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With thanks to Alexander Fleischanderl (Primetals Technologies), Jeremy Jones (CIX), Dr Zushu Li (Advanced Steel Research Centre, University of Warwick), Matthias Pastl and his team (Voestalpine) and other industry experts who provided precious input for this research. Thanks also to Prof. Carlo Mapelli (Politecnico di Milano, former President of the Italian Association for Metallurgy) and Dr Daryna Panasiuk (Research Center for Advanced Science and Technology, University of Tokyo) who were consulted for the report.

Image credits

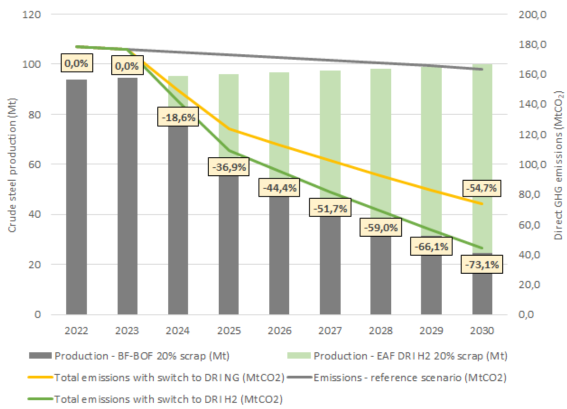
A scrap yard (credits: © primetals.com)

Summary / Factsheet

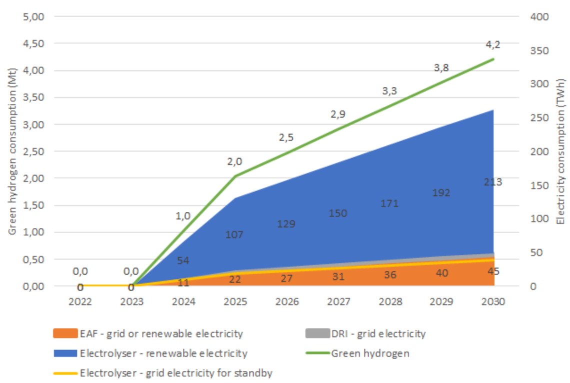
- 97% of the EU's direct emissions from the steel industry come from integrated steelmaking (BF-BOF route) used for higher quality products, while electric arc furnaces (EAF) tend to produce long and specialty steel products. However, in North America EAFs are more commonly used for flat products as well.
- 74% of blast furnace capacity will have to be relined (renovated) this decade.
- BF-BOF steel mills typically use 20% scrap (which reduces their carbon footprint) but the technology does not allow to use significantly more.
- All those BF-BOF steel mills could be replaced with EAFs fed by the same proportion (20%) of scrap, achieving 55% emission reductions by 2030, but that would increase annual fossil gas consumption (in 2030) by 18.2 bn cubic meters, or hydrogen by 4.2m tonnes in order to process primary iron ore into ore-based metallics (OBM) such as direct reduced iron (DRI).
- Electricity consumption will rise by 45 TWh to power the EAFs; it could rise by another 213 TWh to produce the hydrogen needed to process primary ore.
- EAFs can be virtually carbon-free if fed on zero-carbon electricity. They can cope with the intermittence of renewable energy, but the economics of running for fewer hours on cheaper renewable power vs. continuously on grid power are not always favourable. Running on renewables would also require access to both wind and solar electricity (and possibly some storage) to ensure e.g. 5000 operating hours per year (57%), down from 7600 (87%) with grid electricity.
- Manufacturing OBM using hydrogen requires uninterrupted access to hydrogen sources, although with some volume flexibility. Achieving this through renewable electricity would thus also require some optimisation work.
- Both OBM and hydrogen production require a small amount of uninterrupted grid electricity which cannot be provided by renewables.

Replacing aging blast furnaces with EAF fed with hydrogen DRI

GHG direct emission reductions



New hydrogen/electricity consumption

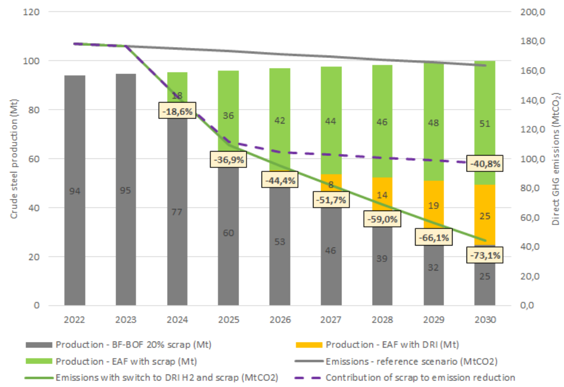


Source: Sandbag

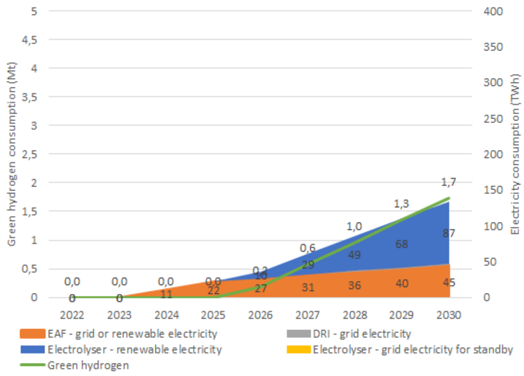
- Emission reductions in 2030 could reach 73% (scrap + DRI from H2), including 41% achieved from optimised scrap use.
- There is a risk that much of Europe's EAFs will use imported processed ore (DRI) if that product is not covered from a Carbon Border Adjustment Mechanism.
- Alternatively, by optimising the use of European steel scrap, the annual need for fossil gas (or hydrogen) can be reduced by 60%, down to 7.5 bn cubic meters gas (or 1.7m tonnes hydrogen) for the EU + UK. 126 TWh would be saved annually, compared with using only 20% scrap.
- Doing this first would also require less hydrogen storage capacity, and delay the need for green hydrogen by three years.
- Contrary to widespread belief, scrap quality does not make impossible to substitute BF-BOF steel mills with EAFs in the production of high-end steel, provided that scrap management is improved and that scrap impurities are diluted by the addition of some "virgin" iron like DRI.
- Optimising the use of scrap would mainly require better segregation of scrap categories which should happen as EAF steelmaking expands, and better assessment of scrap quality for which the technology is available and inexpensive.
- Additional savings of renewable electricity would be achieved through reuse in the construction sector, or through 'direct recycling' which consists of processing end-of-life steel objects without melting them in an EAF.

Replacing aging blast furnaces with EAF using optimised scrap distribution + H2DRI

GHG direct emission reductions



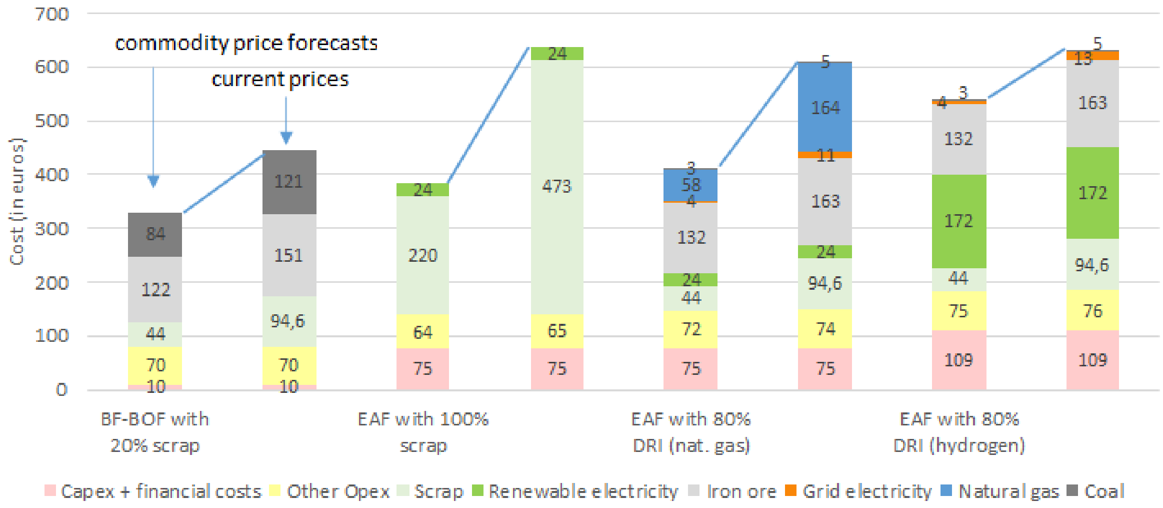
New hydrogen/electricity consumption



Source: Sandbag

- The difference in production costs of each process, and therefore abatement costs, are closely dependant on commodity prices.
- Although abatement costs are within the range of carbon prices recently seen in the EU ETS, the free allocation of emission permits as protection against carbon leakage largely cancels out the price signal created by that market.

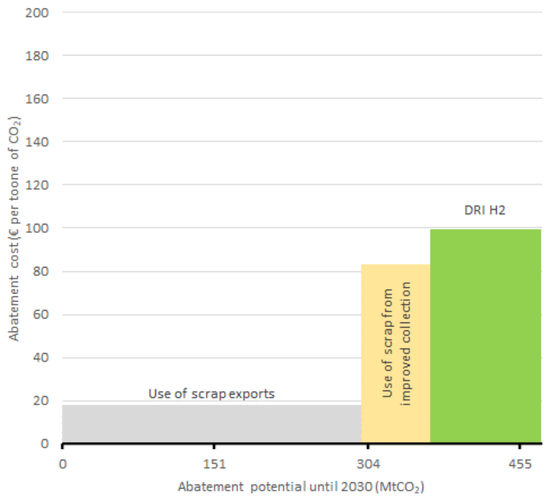
Cost of producing 1 tonne of steel using different processes, with two price assumptions



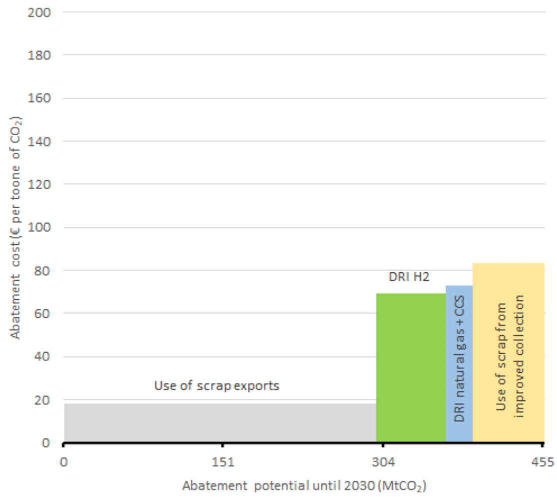
Source: Sandbag. BOF, EAF-DRI-natural gas and EAF-DRI-green hydrogen use 20% scrap.

Cost of abatement using commodity price forecasts from analysts

Using scrap + H2DRI



Using scrap + fossil gas with CCS + H2DRI



Source: Sandbag

Policy recommendations

- Decisions in product design must be made urgently to ensure the sustainability of scrap recycling. Designing products for easier recycle at end of life and easier removal of contaminants will ensure a better, higher quality scrap supply.
- The free allocation of emission permits under the EU ETS is an obstacle to a rapid transition to low-carbon steel.
- A reform of the ETS benchmarks would not resolve the problem of fair competition between high-carbon and low-carbon solutions.

- Most of the transition could happen within this decade. The replacement of free allowances with a CBAM would ensure total protection to plants selling to the EU market. A CBAM should cover ore-based metallics, as well as finished steel products.
- Adding hydrogen to the scope of the EU ETS (with a corresponding free allocation benchmark) would distort competition between secondary, recycled and hydrogen steel.
- The challenge is not about innovative technology but rather access to zero-carbon electricity and better practices in the scrap market. EU funding such as expected from the Climate Investment Fund (now the Innovation Fund) might be more suitable to address these EU-wide challenges than sponsor individual conversion projects.
- For hydrogen steel to be a low-carbon solution, the hydrogen produced must be zero carbon. This should be reflected in policies such as the Renewable Energy Directive (for its industry target), especially as part of the Delegated Acts on renewable fuels from non-biological origin (RFNBO).

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Introduction

The steel industry accounts for 8% of global greenhouse gas emissions (GHG) and 5.1% in the European Union (EU-27)[1], with a reputation of being a "hard-to-abate" sector. Enlarging the scope to include other materials increasingly used in steel production like alloys may even, according to some experts, push the GHG footprint of the sector to 11% of the world's total.

As the largest EU-based steelmakers (ArcelorMittal Europe, Salzgitter, Tata Steel Europe, ThyssenKrupp, voestalpine…) have pledged ambitious emission reduction targets – 80% or more – for 2050, and some intermediary targets are also starting to emerge for 2030, a lot of hopes are being put into new technology solutions such as hydrogen-based steel.

This is true of policymakers, as a report commissioned by the European Parliament in April 2021 on "carbon-free steel production" identified the entire EU primary steel production as "suitable for hydrogen", proposing a full switch by 2050 (of which only about 6% would happen by 2030 though) resulting in 296 TWh annual electricity consumption[2]. The report did not explore options involving circularity.

As most of the EU's steelmaking fleet will need renovating this decade, this unique window of opportunity, but also new constraints on energy use, should make us consider all options available including a wider recourse to circularity. As carbon pricing and subsidies such as carbon contracts for difference are part of the policy framework contemplated for Europe this decade, a detailed cost analysis is necessary to assess the effectiveness of potential financial levers.

This report follows others in suggesting the need for a wider recourse to circularity. This is the case of Material Economics, which described a 2050 scenario with a set of ambitious circularity policies causing steel production to decline, with 90% of it made from collected scrap. In an earlier paper, it presented a circularity scenario whereby 55m tonnes of virgin steel production are displaced by secondary steel from recycled scrap by 2030 and 75m tonnes by 2050[3] However, the consultancy's studies do not break down policy drivers, only stressing that the scenario's realisation is conditional upon "*the successful implementation of circularity levers*"[4]. Also, the papers' perimeter excluding exported steel products makes it difficult to compare with figures from other sources.

Another paper published by Agora Industry[5] with the support of Material Economics estimated possible gains from improving the quality of collected steel scrap. It founds that

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[1] EEA greenhouse gases – data viewer, European Environmental Agency, April 2021

[2] Carbon-free steel production – Cost reduction options and usage of existing gas infrastructure, EPRS, April 2021

[3] The circular economy: a powerful force for climate mitigation, Material Economics, 2018

[4] Preserving value in EU industrial materials. A value perspective on the use of steel, plastics, and aluminium, Material Economics, 2020

[5] Mobilising the circular economy for energy-intensive materials. How Europe can accelerate its transition to fossil-free, energy-efficient and independent industrial production, Agora Industry, 2022

"*much of these gains will not be able to be realised by 2030*[6]*"* giving instead an estimate of "up to 35m tonnes of virgin steel" replaced *"by 2040 and 2050".* This is only a fraction of Material Economics' estimates in its circularity scenario.

In a more top-down approach, the think tank E3G created a scenario whereby the steel sector reduces its emissions by 97% by 2050, which leads to a slightly lower production in Europe by 2030, from a mix of blast furnaces (some equipped with CCS) and electric arc furnaces using a mix of scrap (60m tonnes), direct reduced iron (DRI) from natural gas (31m tonnes) and DRI from hydrogen (9m) by 2030[7]. But this 'middle way' approach is presented without details on policy or market drivers.

The appendix compares those research papers and their findings.

[6] "because new capacity investments in EAFs and mini-mills to transform steel scrap into high-value products require scale up", according to the paper

[7] 1.5°C Steel: decarbonising the steel sector in Paris-compatible pathways, E3G, 2021

Steel production routes and feedstocks

Although steel production involves many industrial processes, for the purpose of this report, we will only consider upstream production up to the phase of liquid steel, also called *crude steel*. This means that downstream processes such as casting and rolling will not be discussed because their GHG emissions are low compared with liquid steel production.

The main crude steel production technologies are the blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF) routes. As it is older than the EAF route, the BF-BOF route remains dominant in volume both at global level (70% of total crude steel production) and in the EU (58%), though EAF-made crude steel accounts for a majority of output in many countries, e.g. the United States, Mexico, Turkey, Italy and Spain[8].

The BF-BOF route often includes all the transformation stages of raw materials (metallurgical coal into coke, iron ore and coke into pig iron, pig iron into steel) which is why it is nicknamed "*integrated steelmaking*". The EAF route can separate upstream and downstream processes by using already reduced iron, either in the form of steel scrap or ore-based metallics (OBM, that is pig iron, DRI or HBI – see table below).

The different types of iron feedstocks

Raw material	**Iron ore**	Rawest form of iron feedstock, direct output of mining activities
	Iron ore sinter or pellets	Agglomerated iron ore that facilitates its transport and processing
Ore-based metallics (OBM) – virgin material	**Pig iron**	Reduced iron with a high carbon content made in a blast furnace
	Direct reduced iron (DRI)	Iron reduced not in a blast furnace, but in another type of plant that can achieve reduction without reaching melting temperature, therefore saving a lot of energy
	Hot-briquetted iron (HBI) 	Compacted form of DRI that facilitates transport and storage
Recycled material	**Iron and steel scrap**	Iron and steel collected from manufacturing process losses and end-of-life products (building materials, vehicles, domestic appliances, machines, cutlery…) that need not to be reduced again

[8] Steel Statistical Yearbook 2020, World Steel Association, 2020

Steel products

In Europe, crude steel production routes are tightly associated to categories of steel products: *integrated steelmaking* with higher-grade “flat” products and *Electric Arc Furnaces* with “long” products. However, we will see that it does not have to be the case.

The many shades of steel

Although steel is an intermediate good and not a consumer product, it is not a homogeneous commodity. While there are thousands of different types of steel, including various alloys and grades of stainless steel, a frequent simplification retains two main categories: flat and long products.

Flat products

Hot rolled wide strip	Quarto plate
	
Main applications: automotive, tubes	Main applications: construction, shipbuilding

Long products

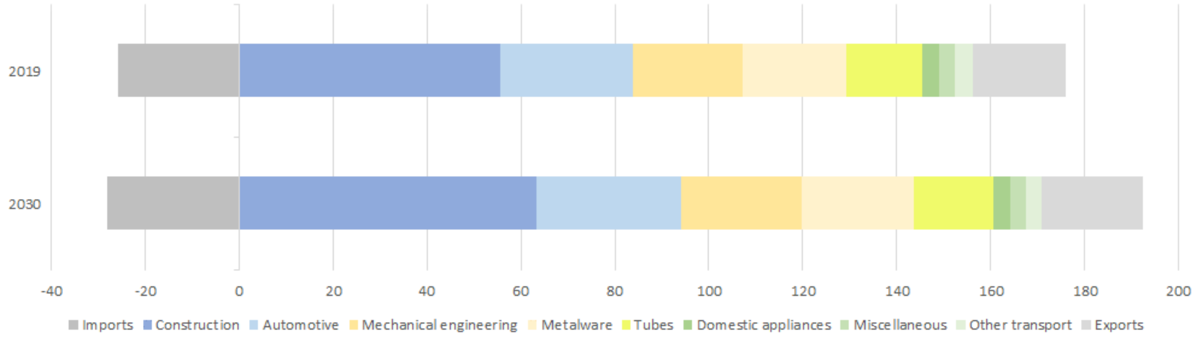
Heavy sections	Merchant bars	Rebars	Wire rod
			

Main applications: construction

1 Business-as-usual scenario – 2030

1.1 Demand and production

Projected EU+UK demand for steel in 2030 with no new policy or major shock



(millions tonnes of crude steel)	2019	2030
Domestic demand	**156.3**	**170.9**
Domestic production	**150.2**	**164.4**
- incl. from blast furnaces	92.3	100
- incl from electric arc furnaces	65.1	64

Our "business-as-usual" scenario is slightly lower than Eurofer's forecast, with domestic production at 164.4m tonnes in 2030 compared to 179.0m tonnes[9]. This is because Eurofer's scenario takes 2015 as a starting point and does not take into account the slowdown observed in 2018-2019 – the year 2020 is an outlier due to the pandemic. Our estimate is of approximately the same total increment as Eurofer's (+13/14m tonnes by 2030), but with no catch-up effect. The geographic scope is the former EU-28 (today's EU-27 + the United Kingdom) due to data availability limitations. Methodological details are given in appendix.

1.2 Greenhouse gas emissions

Direct* GHG emissions intensity of steel production routes in the former EU-28

tCO2e/t	Average 2016/2017	10% most efficient installations 2016/2017
BF-BOF route	2.06	1.64
EAF route	0.10	0.05

Sources: Sandbag, Ecofys[10] (*excludes "scope 2" emissions from electricity use)

[9] Low-carbon roadmap. Pathways to a CO2-neutral European steel industry, Eurofer, 2019

[10] Methodology for the free allocation of emission allowances in the EU ETS post 2012. Sector report for the iron and steel industry, Ecofys, Fraunhofer Institute for Systems and Innovation Research, Öko-Institut, 2009

We consider emissions from the BF-BOF route as the sum of emissions from coking, iron ore sintering and hot metal production, which made public by the European Commission over the 2016/17 period[11].

Direct GHG emissions of the EAF route are mainly due to the consumption of graphite electrodes (typically made from coal or crude oil derivatives) and the use of carbon for reduction purposes. EAFs can also use natural gas in order to facilitate heating and oxygen to remove impurities and excess carbon from the steel bath.

Although some steelmakers use some natural gas to reduce power consumption, emission reductions are higher if EAFs are fully electrified (0.6 MWh per tonne of liquid steel).

In our business-as-usual scenario for 2030:
- EU demand for steel will follow the projection presented above;
- long steel will continue to be produced predominantly through the EAF route and flat steel through the BF-BOF route;
- both routes will reduce their GHG emissions intensity through improved efficiency but without breakthrough technological change, so that the average GHG emissions intensity will level up to the 2017 best 10%[12];

the total direct GHG emissions of the EU steelmaking industry is expected to evolve as in the table and chart below.

Business-as-usual projections of total direct GHG emissions from steelmaking in the EU+UK

Mt CO_2eq	Direct GHG emissions 2017	Direct GHG emissions 2030	Cumulated emissions 2021-2030
BF-BOF route	186.5	163.8	1,719.5
EAF route	5.5	3.2	37.7
Total	192.0	167	1,757.2
Variation		-12.5%	

Source: Sandbag

1.3 Investment costs

In the coming years, steelmakers are expected to make major investment decisions as 74% of the blast furnace fleet will reach the end of their operating life during the decade[13]. While the business-as-usual scenario does not require additional production capacity, investments will nonetheless be needed to maintain existing steel mills. Considering that the first electric arc furnaces have started functioning in Europe in the 1960s and that their average lifetime is close to 70 years[14] with no need for relining unlike blast furnaces, it is possible to assume that

[11] Update of benchmark values for the years 2021 – 2025 of phase 4 of the EU ETS, European Commission, 2021

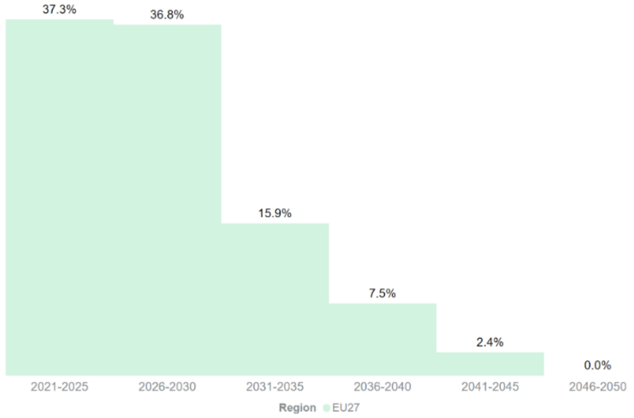
[12] The main improvement considered in this scenario would be a more efficient use of process off-gases, as proposed by leading engineering firms like Paul Wurth and Primetals Technologies.

[13] Global Steel at a Crossroads, Agora Industry, November 2021

[14] Ernst Worrell and Gijs Biermans, "Move over! Stock turnover, retrofit and industrial energy efficiency", *Energy Policy*, vol. 33 n°7, 2005

reinvestment decisions to be taken by 2030 concern only blast furnaces, and that the 74% share amounts to **70m tonnes of production capacity**.

Blast furnace capacity to reach end of operating life (EU27)



Source: Agora-Energiewende

Examples of recent relining operations

Year	Blast furnace	Annual Capacity (Mt crude steel)	Cost (€m)	Cost per mt of crude steel capacity (m€)
2014	Blast furnace 2 in Duisburg-Schwelgern, Germany (ThyssenKrupp)	4.38	200	45.7
2018	Blast furnace A in Linz, Austria (voestalpine)	3	180	60
2020-2021	Blast furnace B in Gent, Belgium (ArcelorMittal)	2.3	195	84.8
Selected assumption				**84.8**

A figure of 84.8 M€ per million tonnes of crude steel capacity production is retained as the Gent case is the most recent, state-of-the-art example. Therefore, **relining the aging facilities in a business-as-usual scenario would cost 6 billion euros**, not counting lost sales during the renovation works.

2 Greenhouse gas abatement options

The above section shows that the overwhelming share of direct GHG emissions coming from the steelmaking industry is linked with the BF-BOF route, therefore abatement solutions focus on it. They can be grossly split between three categories:

- installing carbon capture, usage and storage technologies (CCUS) in integrated steelworks;
- replacing blast furnaces with electric arc furnaces and using as feedstock various proportions of scrap and OBM (modern electric arc furnaces can run from 100% scrap to 100% DRI/HBI);
- reducing steel demand through improved material efficiency and further reliance on re-use practices and alternative materials.

2.1 BF-BOF and CCUS

Installing carbon capture, usage and storage technologies (CCUS) in integrated steelworks would certainly require less change as it would allow existing blast furnaces to keep running. Between 2004 and 2010, a large consortium involving major EU-based steelmakers (ArcelorMittal, ThyssenKrupp, voestalpine) and research institutes developed the ULCOS project – Ultra-Low CO_2 Steelmaking – with the objective of cutting BF-BOF emissions by 50%[15]. Among the studied technologies, CCS was selected by ArcelorMittal to be installed in its steelworks in Florange (France), but the project was eventually dropped together with the mothballing of this plant. Another outcome of ULCOS, the HIsarna technology, was planned to be deployed at Tata Steel's IJmuiden mill in the Netherlands until the company decided in 2021 to go for green hydrogen.

Despite these setbacks, new CCS-based technologies have been developed, some being now able to achieve emission reductions of up to 63% through carbon oxide conversion[16]. This limited potential is due to the focus of carbon capture on blast furnaces, where CO_2 emissions are both the largest and the most concentrated in integrated steelworks. Carbon capture at the stage of coking or iron ore sintering has been less explored in research[17].

At this stage, one of the most advanced projects of this kind is the Carbon2Chem technology developed by Thyssenkrupp and the UMSICHT Fraunhofer Institute[18]. Yet, it is still a pilot, and the industrial version of the mere process is still being researched. Provided that it is ready as hoped by its sponsors by 2025, only a demonstrator could start construction from then, which would make any commercial-scale emission abatement unlikely before the end of the decade.

[15] Ultra-Low CO2 steelmaking, European Commission
[16] Technology Assessment and Roadmapping (Deliverable 1.2), GREENSTEEL for Europe, 2021
[17] D. Leeson, N. Mac Dowell, N. Shah, C. Petit, P.S. Fennell, "A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources", *International Journal of Greenhouse Gas Control*, vol. 61, 2017
[18] Carbon2Chem® – Baustein für den Klimaschutz, Fraunhofer UMSICHT

Regarding cost, based on data provided by Agora Energiewende and the Wuppertal Institute[19] as well as Sandbag's previous work on calculations on hydrogen costs[20], we calculated that the CCUS component would add €280-300 per tonne of crude steel to the BF-BOF route.

2.2 Switch from BF-BOF to EAF with natural gas-made DRI

	Per tonne of steel	Total EAF-DRI
GHG Emissions until 2030	-1.19 tCO_2	-496.0m tonnes
Cost	€82.9* - €162.7**	€29.3bn* - €57.5 bn**
Natural gas use until 2030	+241.6 m^3	85.4 bn m^3
Renewable elec. use until 2030 (EAF)	0.6 MWh	212 TWh
Grid elec. use until 2030 (DRI production)	0.06 MWh	18.2 TWh
Renewables capacity needed	0.19 kW	14.5 GW

Based on like-for-like scrap charge. *At forecast prices. **At current market prices. Techno-economic assumptions are detailed in appendix.

DRI/HBI-fed EAFs is today the favourite technological choice made by the sector to reduce its GHG emissions, with over 15.9m tonnes of production capacity already announced (see appendix).

2.2.1 Abatement potential

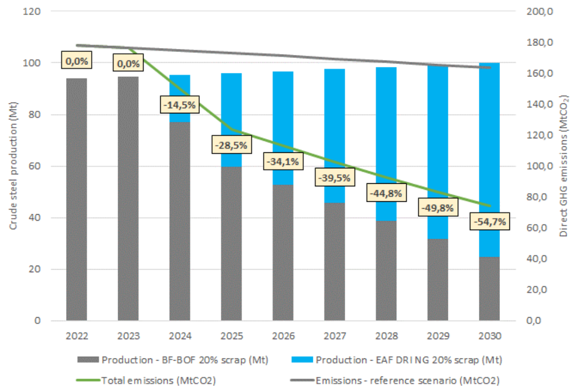
Our calculations are based on the technical parameters of ENERGIRON ZR, a state-of-the-art process developed by Tenova and Danieli, two frontrunning companies in steelmaking technologies. We chose it over competing processes because it generates less GHG emissions and is more often picked up for new plants in Europe, including Sweden's HYBRIT and Salzgitter's SALCOS project. It can be fuelled by natural gas or hydrogen without major modifications and includes in its basic version a CO_2 capture system that could reduce the carbon down to 0.159 tCO_2 per tonne of DRI, according to the manufacturers[21]. If the capture system is not activated, emissions are 0.415 tCO_2 per tonne of DRI. Needs for DRI in an EAF range between zero (with a 100% scrap charge) and 1.2 tonne per tonne of crude steel (with a 0% scrap charge). We assume here that CCS is not implemented.

Our ramping up assumption is simply based on the BF-BOF production capacity reaching end-of-life: new EAF-DRI (natural gas) lines come online as BF-BOF lines are closed down. Scrap formerly used in BF-BOFs is used instead in EAFs to reduce needs for DRI. Thanks to the use of 20% scrap, the carbon footprint is 0.45 tCO_2 per tonne of crude steel.

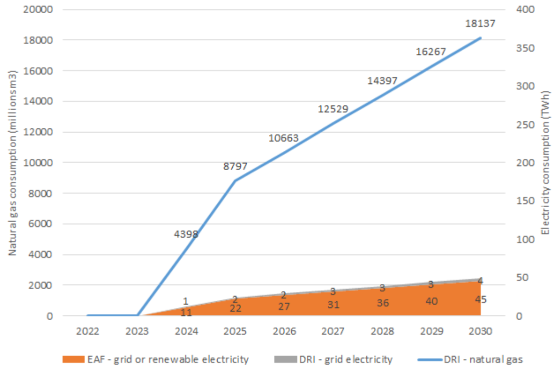
[19] Technology Assessment and Roadmapping (Deliverable 1.2), GREENSTEEL for Europe, 2021
[20] Samuel Gonzalez Holguera, Untangling the knots. Clearing the way to fast green hydrogen deployment, Sandbag, 2021
[21] Sustainable decrease of CO_2 emissions in the steelmaking industry by means of the Energiron direct reduction technology, Danieli, 2018

Effect of replacing aging blast furnaces with EAFs using natural gas DRI

GHG direct emission reductions



New natural gas and electricity use



Source: Sandbag

2.2.2 Feasibility

The above savings are for direct emissions only, and they come along with a sharp increase in electricity consumption. To prevent the increased power use from reversing the savings due to the burning of fossil fuels, EAFs need to be fed with additional renewable energy – given that new nuclear generation by 2030 is unrealistic. This is technically possible because unlike blast furnaces, EAFs can operate on a batch basis with a tap-to-tap time of about 60 minutes[22]. The downside is that EAFs will work for a smaller number of hours per year, so that more EAF capacity overall will be needed to deliver a given output.

Although it is often assumed that flat steel can is best produced in BF-BOF while the EAF route is better suited to lower-grade long products, in reality, the distinction between long and flat steel is more a matter of feedstock used. EAFs can fully substitute the BF-BOF route provided that they receive the adequate iron feedstock, and substituting BF-BOFs using 20% scrap with EAFs using the same quantity of scrap would not alter the quality of the steel produced.

Yet, as the BF-BOF and EAF routes operate on different feedstocks, replacing a blast furnace and an oxygen converter with an electric arc furnace involves upstream modifications such as the closure of coke ovens (if present), the installation of DRI production units and/or transport, storage and handling facilities for scrap and OBM if they are sourced externally.

Downstream, casting and rolling lines do not absolutely require changes but may be affected by the evolution of the energy system. Indeed, BF-BOF steel mills commonly recover process gases to generate electricity, often in large enough quantities to cover the needs of the entire installation and even to sell a surplus. An electric arc furnace produces much less of these gases and therefore, pushes for the adoption of more energy-efficient direct casting lines, though such lines are not specific to the EAF route and can also work in BF-BOF steelworks. Other aspects to be taken into account are size – common electric arc furnaces have a smaller capacity than BF-BOF systems – and at the end of the switch, the dismantling of blast furnaces. The highest in Europe, ThyssenKrupp's Schwelgern 2 in Germany, is 90 meters tall.

[22] Suez Steel's integrated minimal: from iron ore to finished product, Energiron, 2019

A shut down of blast furnaces and their replacement with one or several electric arc furnaces in the same plant has already been planned by several major steelmakers in the EU (ArcelorMittal, Salzgitter, SSAB, US Steel Kosice, voestalpine) and is now in the implementation phase or awaits public authorities' decision on financial support. There have also been historical precedents in Europe such as Germany's GMH, which decided back in the 1990s to close down its blast furnace and replace it with a 100% EAF, 100% scrap-based production, though not for the flat steel market.

Case study: US Steel Kosice

Since the ability to produce high-grade flat steel is often mentioned as an obstacle to the switch from BF-BOF to EAF steelmaking (see above "Steel products"), US Steel Kosice in Slovakia is a relevant case study. With three blast furnaces and four oxygen converters, it is currently one of the largest integrated steelworks in Central Europe with a maximum production capacity of 4.5m tonnes of crude steel per year, entirely for flat products. Subject to EU clearance for state aid and the required environmental permits, US Steel Kosice will start in 2023 a two-year shift of 3.1m tonnes production capacity (almost 69%) to EAF while keeping the same product mix and total capacity. Therefore, after completion of this project in 2025, two out of the three blast furnaces will be mothballed.

Concretely, the project will consist of acquiring and installing two electric arc furnaces, ladle furnaces and vacuum degassing equipments, as well as a new continuous endless casting and hot rolling line. The changes in feedstock and energy requirements will also require an extension of the scrap yard, a new high voltage substation, and a place to prepare HBI. The overall cost of the investment is estimated at 1.3 billion euros and does not include the dismantling of two blast furnaces, which will be covered by another project after the new EAF line starts functioning. In 2021, a previous cost assessment indicated 1.5 billion euros, suggesting overall decreasing costs. However, the amount of expected subsidy is unknown.

According to Sandbag calculations, US Steel Kosice's current average direct GHG intensity amounts to 1.93 tCO_2 per tonne of steel. After completion, the new production lines will emit 0.16 tCO_2 per tonne of EAF-made crude steel with a 50% scrap, 50% HBI mix. An additional 0.25 tCO_2 should be counted for HBI production (not on site) if based on natural gas. **Emissions would therefore amount to 0.16-0.41 tCO_2 per tonne of crude steel.** At the same time, the plant will use much more grid electricity (from 0.797 TWh per year currently to 3.199 TWh), increasing scope 2 emissions. Data provided by US Steel Kosice also show that the plant will use a lot of natural gas (approximately 9m^3 / tonne of crude steel) to feed burners and reduce electrical energy needs when heating and melting scrap and HBI. This probably explains why the footprint of the EAF (0.16 tCO_2 / tonne of crude steel) is higher than the best practice (0.05 tCO_2 / tonne of crude steel).

Most EU-based steelmakers with plans to switch to DRI-EAF with DRI own production capacity acknowledge that they will rely on natural gas until they will be able to ramp up sufficient "green" hydrogen own production or source it from elsewhere. GHG emission savings would nonetheless be significant compared with the BF-BOF route, and further fuel shift to hydrogen would not necessitate new investments. However, producing 75m tonnes of crude steel with the DRI-EAF technology and a 20% scrap charge would **consume 18.1 billion m^3 of natural gas**. This additional demand would represent 4% of the EU27's average annual gross inland consumption of natural gas in the past years (426 billion m^3)[23], it would challenge the EU's objectives of avoiding lock-in into natural gas and phasing out Russian gas imports "*well before 2030*"[24] in response to the Russo-Ukrainian war.

An electric arc furnace (credits: © primetals.com)

2.2.3 Cost of switch from BF-BOF to EAF

Detailed calculations of switch costs from BF-BOF to EAF are given in the appendix. They depend greatly on the price of commodities such as coal, gas and electricity. They also depend on the type of electricity used, either renewable (cheap but intermittent) or from the grid (reliable but more expensive). The assumption for renewable electricity is of an access to a mix of wind and solar power, with 5000 combined working hours per year (57%). This is less than the normal target of 7600 hours (86%) for high-efficiency EAFs running on grid electricity,

[23] Natural gas supply statistics, Eurostat, October 2021
[24] REPowerEU: Joint European Action for more affordable, secure and sustainable energy, European Commission, 8 March 2022

which translates into relatively higher capex, but cheaper opex thanks to cheaper intermittent electricity.

NPV[25] cost comparison over a 20-year lifetime of EAFs fed by grid vs. renewable electricity

	At current futures prices		At analyst forecast prices	
(bn €)	With grid electricity	With renewable electricity	With grid electricity	With renewable electricity
Capex	13.9	24.4	13.9	24.4
Opex	197.5	151.2	100.5	109.2
Total	211.4	175.6	114.4	133.6

Source: Sandbag, using prices detailed in the appendix

At current market prices, the overall cost of replacing the existing fleet of BF-BOF reaching their end of life with renewable electricity-fed EAFs running on the same amount of scrap topped up with DRI made with natural gas amounts to 57.5 billion euros. This translates into an abatement cost of €128.6 per tonne of CO_2.

If assumed price forecasts from analysts are applied, the overall cost falls to 29.3 billion euros. As for the abatement cost, it now amounts to €65.6 per tonne of CO_2.

	With futures prices	With price forecasts
Overall cost of switch (billions €)	57.5	29.3
Abatement cost (€ / tCO_2)	128.6	65.6

2.3 Switch from BF-BOF to EAF with "green" hydrogen-made DRI

2.3.1 Abatement potential

Green hydrogen DRI is often depicted as the ultimate GHG emission reduction solution, able to drive steelmaking close to climate neutrality. However, there is often confusion between renewable hydrogen, which should be produced from 100% renewable electricity, and hydrogen from electrolysis powered by grid electricity. In its definition of *renewable fuels from non-biological origin* (RFNBO), the European Union includes fuels that reduce 70% emissions, suggesting a carbon footprint that is far from negligible.

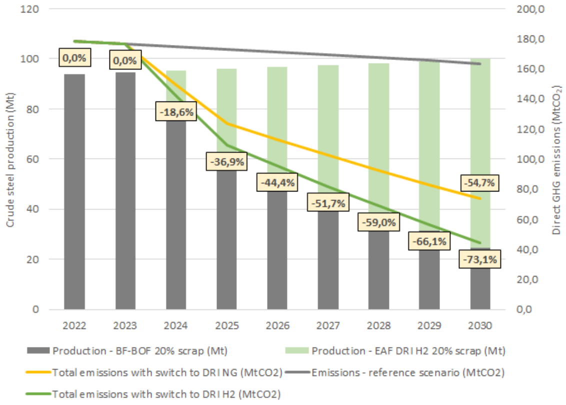
As the type of fuel used to produce DRI has almost no impact on steelmaking equipment, the ramp-up potential for a switch to green hydrogen DRI is tied to the availability of green

[25] With 6% discount rate

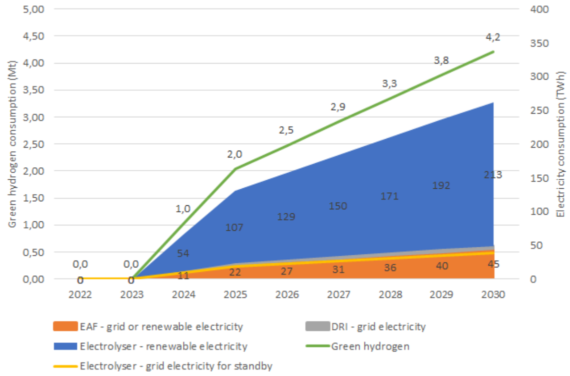
hydrogen. Total green hydrogen requirement for DRI plants to switch directly to hydrogen is as per the chart below[26].

Effect of replacing aging blast furnaces with EAF fed with hydrogen DRI

GHG direct emission reductions



New hydrogen/electricity consumption



Source: Sandbag

2.3.2 Feasibility

DRI plants would consume 4.2 million tonnes of green hydrogen in 2030, which represent a sizable share of the 10 million tonnes of green hydrogen domestic production capacity target set by the European Commission's Hydrogen Strategy for 2030. This poses a number of challenges, as the EU's domestic production will likely be closer to 5-6m tonnes, import sources are far from secured and several other sectors will compete for this hydrogen including more profitable ones such as the fertilisers and refining industries.

In addition, DRI furnaces typically run around the clock, so they would require a continuous source of hydrogen. However, they are also proven to be flexible enough to adjust output to fuel availability – down to 50% capacity according to manufacturers[27]. Whether flexibility is achieved through lower DRI output, hydrogen storage, external sourcing of hydrogen or DRI import, will depend on economic conditions and locally available solutions such as large hydrogen storage facilities and transmission pipelines.

Currently, the most advanced DRI-EAF projects in Europe based on green hydrogen are H2 Green Steel and HYBRIT. Interestingly, the former is carried out by a new company, not a historical steelmaker, making it quite atypical in a sector dominated in the EU by decade-old incumbents.

H2-DRI projects in the EU

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[26] 1 tonne of crude steel 100% made from DRI requires 1.2 tonne of DRI whose production itself consumes 70 kg of hydrogen; assuming 20% scrap charge, this makes 0.96 tonne of DRI per tonne of crude steel; green hydrogen consumption becomes 56 kg per tonne of crude steel.

[27] Suez Steel's integrated minimill: from iron ore to finished product, Energiron, 2019, and Ironmaking With Alternative Reductants, AIST Association for Iron & Steel Technology, 2020

Project	Company	Location	Targeted production capacity (Mt)	Investment (M€)	Planned completion
H2 Green Steel[28]	H2 Green Steel	Boden (Sweden)	5.0 (steel)	2 500	2030 (start in 2024)
H2 Green Steel Iberian Peninsula[29]	H2 Green Steel and Iberdrola (power and gas)	under study (Spain or Portugal)	2.0 (DRI)	2 300 (DRI plant and 1 GW electrolysis capacity)	2025 – 2026
HYBRIT[30]	SSAB (steelmaker), LKAB (mining) and Vattenfall (power generation)	Gällivare (Sweden)	1.3 – 2.7 (HBI, part of it planned to feed SSAB existing steel mills being converted from BF-BOF to EAF)	≈ 2 000 (HBI plant and electrolysers)	2030 (start in 2025)
ArcelorMittal Sestao[31]	ArcelorMittal	Gijón and Sestao (Spain)	1.6 (steel), 2.3 (DRI)	1 000 (DRI plant + EAF), hydrogen will be supplied by HyDeal España	2025

Risk of carbon leakage

It is no coincidence that the most advanced projects are located in Sweden, as this country enjoys both large reserves of high-grade iron ore appropriate for DRI production and stable renewable energy sources (hydropower and wind to a lesser extent). The uncertain replicability of these conditions in the EU's largest steelmaking countries suggests that some existing integrated steelworks planning to replace BF-BOF systems with EAFs may decide **not to produce DRI on-site, but to source it externally, including from non-EU countries**. This way, they would push associated emissions outside their direct scope, possibly creating a situation of carbon leakage. On the other hand, two factors limit this risk. First, relying on external HBI means that this feedstock will have to be re-heated, whereas DRI produced on-site, if used immediately, is already hot. This can translate into an energy consumption difference of 0.159 MWh per tonne of crude steel[32]. Second, if the European Commission's proposed Carbon Border Adjustment Mechanism (CBAM) is adopted, it will cover all OBMs (pig iron, DRI, HBI), reducing incentives to import them from countries with high-emission plants and no adequate carbon pricing scheme.

[28] H2 Green Steel will produce 5M tons of CO_2-free steel, mobilize 2.5B€ investments and create 10,000 jobs, EIT InnoEnergy, 23 February 2021
[29] H2 Green Steel and Iberdrola announce €2.3 billion Green hydrogen venture, H2 Green Steel, 2021
[30] Olle Olsson and Björn Nykvist, Bigger is sometimes better: demonstrating hydrogen steelmaking at scale, Stockholm Environment Institute, 2020
[31] ArcelorMittal signs MoU with the Spanish Government supporting €1 billion investment in decarbonisation technologies, ArcelorMittal, 13 July 2021
[32] Valentin Vogl, Max Åhman and Lars J. Nilsson, "Assessment of hydrogen direct reduction for fossil-free steelmaking", *Journal of Cleaner Production*, vol. 203, December 2018

2.3.3 Cost

Techno-economic assumptions are the same as in section 2.2.4. In terms of investments, in addition to the EAFs and DRI plants already presented above, electrolysers must be installed to produce green hydrogen, as well as compression and storage equipment. Cost assumptions are listed in the table below. Access to renewable electricity is key, and we assume that a mix of wind of solar energy ensures 5000 hours of utilisation rate for the electrolysers, as per industry standards.

Cost assumptions for green hydrogen production

	2022	2030
Electrolyser cost	500 €/kW	103 €/kW
Electrolyser efficiency, including stack degradation	61.9%	66.00%
Electrolyser utilisation rate	57% (5000 hours per annum)	57% (5000 hours per annum)
Compression cost	0.07 €/W of capacity	0.07 €/W of capacity
Storage cost	700 €/kg of hydrogen stored	700 €/kg of hydrogen stored
Storage duration	12 hours	12 hours
Fixed annual Opex (electrolyser)	2% of Capex	2% of Capex
Fixed annual Opex (compression and storage)	1.5% of Capex	1.5% of Capex
Plant lifetime	25 years	25 years

Source: Sandbag

In order to replace BF-BOF capacity reaching end-of-life, hydrogen annual production capacity would have to ramp up to 4.2m tonnes, and electrolyser capacity to 44.4 GW. This represents a net present value of 18.4 billion euros in capex.

Cost of switching from BF-BOF to EAF with green hydrogen-made DRI

	With futures prices		With market analysts 2030	
	Northern Europe	Southern Europe	Northern Europe	Southern Europe
Total (€bn)	35.5	12.6	42.8	15.9
Per tonne of CO_2 (€)	87.5	69.2	105.7	87.4

Source: Sandbag

Scrap being charged in an EAF (credits: © primetals.com)

2.4 Better use of existing scrap

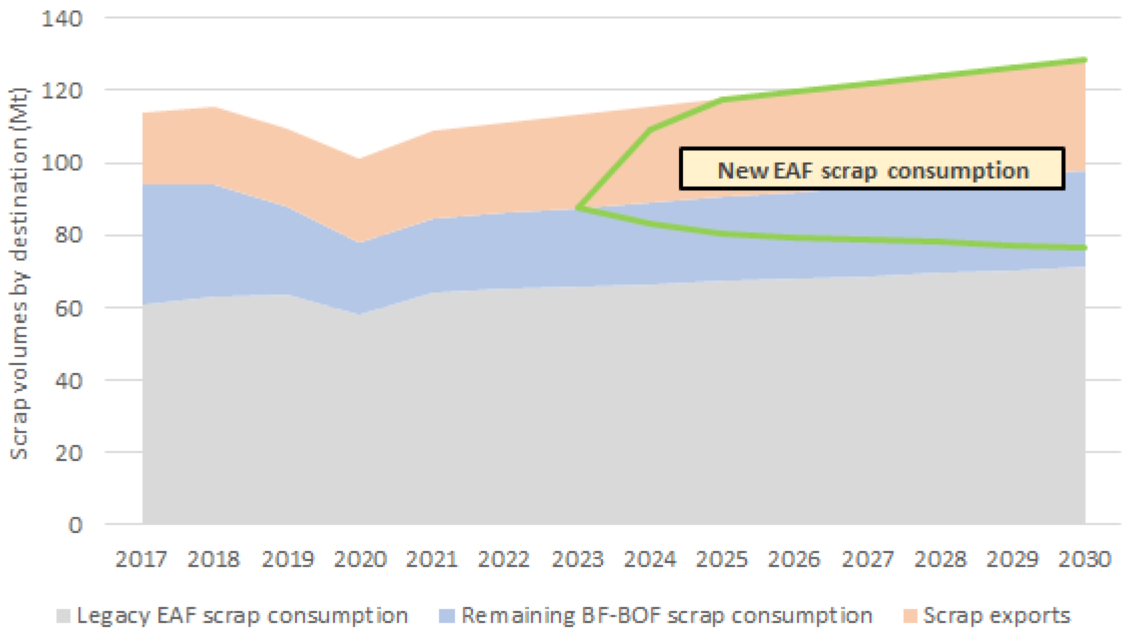
So far we only assumed that new EAFs will use the same scrap as currently used by the closed down blast furnaces they replace. Here we assume the new EAFs will also use the scrap that is currently being exported outside of Europe.

2.4.1 Abatement potential

One tonne of scrap used in an EAF avoids the use of 1.8 tonne of CO_2, compared to a tonne of steel made from a blast furnace. In 2020, 24m tonnes of scrap was exported from the EU28, and this is likely to increase to 31m tonnes in 2030. This scrap is currently exported by lack of domestic demand from European EAFs for the type of products that they are designed to make, as only the most modern BF-BOF can accept more than 30% of scrap[33]. Industry sources contacted by Sandbag explain that there are also cost issues: while scrap is useful as a coolant and an additional source of iron up to an average of 20% of the mix, further increasing the share of scrap increases energy consumption because it excessively decreases the temperature of pig iron and therefore, requires additional heating. With no domestic market in a business-as-usual scenario, scrap should therefore increasingly be exported over the decade as scrap collection rises, based on a constant collection rate.

[33] Greening converter steelmaking, Primetals Technologies, 2020

Collected end-of-life steel by use type (actual data until 2020, forecasts thereafter)

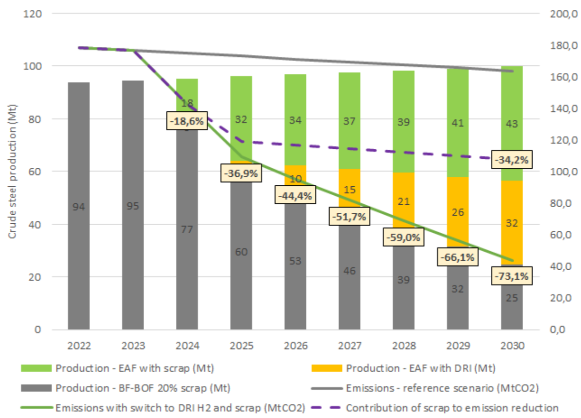


Source: Sandbag

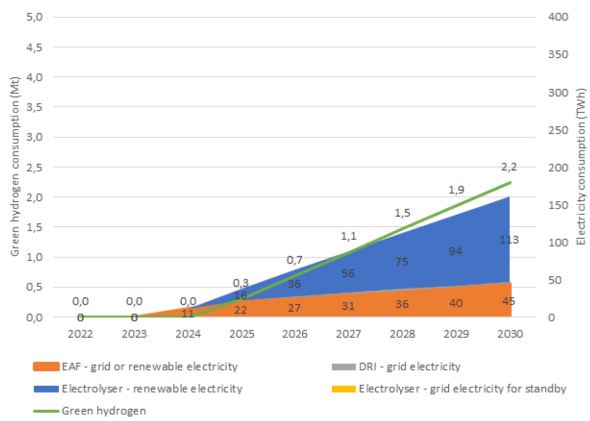
This exported scrap could, however, entirely be used by new European EAFs replacing old BFs. As illustrated above, the entire exported scrap volume could be absorbed by new EAFs in just two years as EAFs ramp up in Europe. By cutting DRI-made steel from 75m to 32m tonnes, this would achieve nearly half of the full decarbonisation hoped for with HDRI, with -34.2% emissions compared to -73.1%. It would do so much faster and create much less 'hidden' carbon footprint from green hydrogen production. It would also nearly halve the need for hydrogen, down from 4.2m to 2.2m tonnes in 2030, and electricity (from 270 to 150TWh) compared to a switch without using additional scrap.

Effect of replacing aging blast furnaces with EAF using currently exported steel scrap + HDRI

GHG direct emission reductions



New hydrogen/electricity consumption



Source: Sandbag

2.4.2 Feasibility

2.4.2.1 Matching scrap quality with products

The use of scrap poses a quality problem. In fact, research shows that the steel market can be split between four categories of products which require different levels of purity (P1 to P4) as there are scrap types of different qualities (Q1-4), so an increase of scrap use could be absorbed with minimal reshuffling between EAF facilities. According to Dworak and Fellner (2021) "*instead of exporting the excess scrap of lower purity (Q3 and Q4), diluting it with primary steel sources (e.g., pig iron, directly reduced iron) might be a suitable alternative*". At the same time, P1 and P2 steel produced from primary steel sources exceeds purity requirements.

Any type of steel can be produced by EAFs, but usually not with 100% scrap, although the share of OBMs can be kept quite low if the scrap quality is high. Arvedi, the only European steelmaker that produces flat steel through the EAF route, uses 1.2 Mt of pig iron and 0.5 Mt of HBI per year on top of 2 Mt of scrap[34]. In the US, where the EAF route is dominant, the production of flat steel requires imports of pig iron, HBI and prime scrap, and pig iron is estimated to account for 20%-25% of the feedstock mix in EAFs producing flat products[35]. Nucor's product specifications indicate that for high-grade steels like sheets and pipes, the average scrap content is 55-60%[36]. Blending scrap and OBM has therefore enabled EAF "pure players" such as Italy's Arvedi and Nucor and SDI[37] in the United States to compete with BF-BOF steelworks and produce high-grade flat steel like deep drawing steel, characterized by strict purity requirements (< 0.15% tramp, < 0.04% copper).

Average content of impurities in different types of iron feedstock in EU28

Type of iron feedstock	Average impurity (% by weight)	Share in total volume of scrap	Currently used for
Q1 scrap grade	0.13	21%	P3-4 products
Q2 scrap grade	0.21	10%	P3-4 products
Q3 scrap grade	0.30	35%	P3-4 products
Q4 scrap grade	0.40	34%	P3-4 products or exported
"Virgin" iron (pig iron, DRI)	0.01	NA	P1-2 products

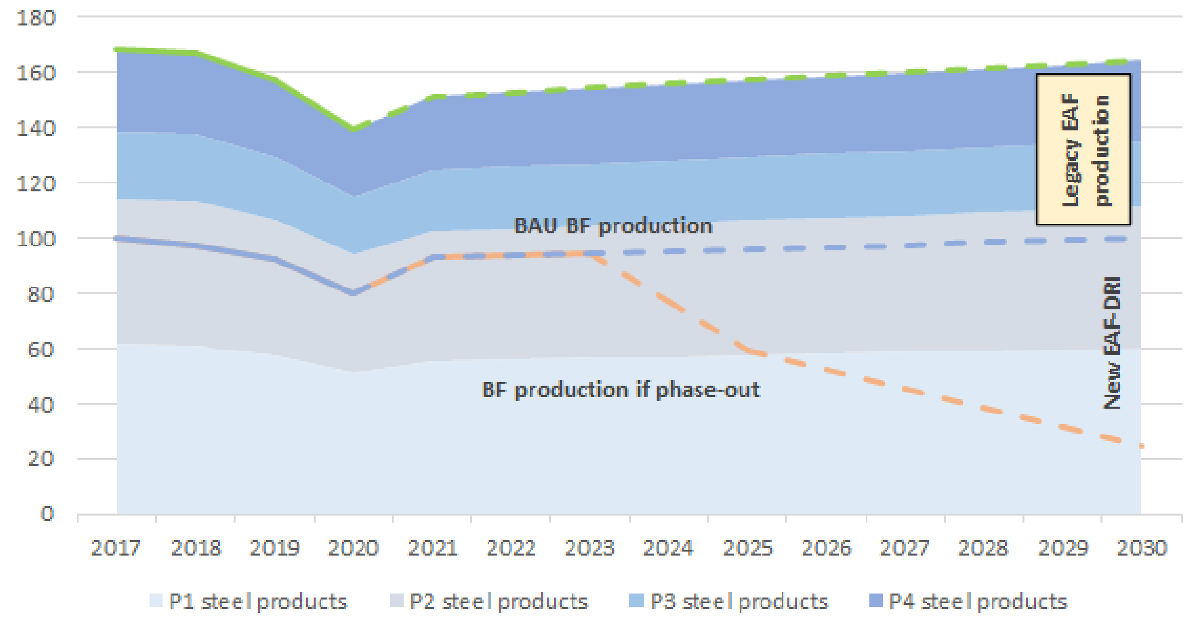
Sources: Dworak and Fellner (2021)[38], Jeremy Jones for Sandbag

For the scrap currently exported to be consumed domestically (assumed to be Q4), it needs to be directed to existing long-product EAFs (P4), substituting purer scrap (Q1-2) which in turn becomes available for flat steel in new EAFs. The first new EAFs should then focus on steel products with purity requirement P2, running on 100% high-purity scrap (Q1-2), while the

[34] Sustainability report Acciaieria Arvedi ed. 2020, Arvedi, 2021
[35] Nicholas Tolomeo, Michael Fitzgerald and Joe Eckelman, US steel sector thrives as mills move up quality ladder, S&P Global, 9 May 2019
[36] 2020 Recycled Content of Nucor Steel Mill Products, Nucor, March 2021
[37] Steel Dynamics Product Guide, 2019
[38] Sabine Dworak and Johann Fellner, "Steel scrap generation in the EU-28 since 1946 – Sources and composition", *Resources, Conservation and Recycling*, vol. 173, 2021

remaining BF-BOFs continue to meet demand for the highest purity steel P1 (see below chart). The following EAFs can produce the top-end steel (P1) by mixing lower-purity scrap but blending it with DRI. This would not alter the quality of steel products significantly, as shown in the following chart.

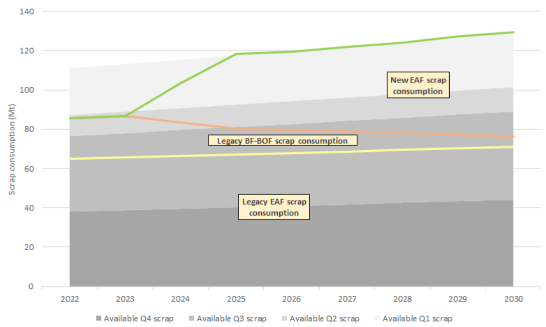
Optimal phase-in of new EAFs per product type to use all available scrap



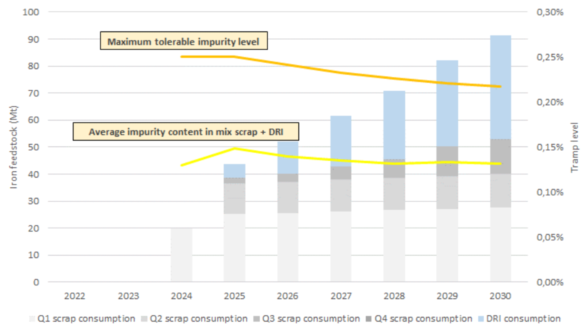
Source: Sandbag

With addition of currently exported scrap:

Optimal scrap use by production route



Feedstock quality for new EAFs



Source: Sandbag

2.4.2.2 Segregating scrap

Part of the reason why steel scrap is misallocated is that its market is not well segregated enough. For example, in Italy the weight of steel from out-of-use passenger vehicles is around 500k tonnes per year, whereas the amount of shredded scrap sold is 1 million tonnes. This is because recyclers shred together high-grade material with others that they cannot sell[39], to

[39] This practice has sometimes been associated with fraud and corruption, like in the "Dirty Steel" (Acciaio sporco) case revealed in 2016: some employees of a steel mill in charge of scrap quality check have turned a

produce a shredded material that is 0.3%-0.35% copper. That takes away the ability to use the good quality scrap for the application that will need it.

A solution to this would be to have **better segmented categories of scrap** with price differences that disincentivise the blending of steel, but this better segregation might appear naturally as EAF steelmaking expands to flat products. Although at the moment, in the EU, categories are such that there are materials with high and low copper content in the same category, in North America where 70% steelmaking is EAF-based, a lot more classifications were developed by necessity.

Scrap classifications

In the EU, the standard steel scrap classification as set by the European Ferrous Recovery and Recycling Federation (EFR) includes 11 specifications based on thickness, size, density and maximum content of residuals, in particular copper. As an example, E8, a type of new scrap, should contain pieces smaller than 3mm thick and a maximum total residual content of 0.300%. In comparison, E3, a common type of old scrap, sets a maximum copper content of 0.25% with pieces not exceeding 1.5 x 0.5 x 0.5 m[40].

The US classification formulated by the Institute of Scrap Recycling Industries (ISRI) relies on similar criteria, but contains more categories because some are exclusive to particular products, for instance cans or automobile slabs[41]. On top of these guidelines, individual steel mills set their own requirements based on their production needs[42].

2.4.2.3 Assessing scrap quality

According to Jeremy Jones (CIX), a world expert of EAF steelmaking, and Carlo Mapelli, professor at Politecnico di Milano and former President of the Italian Association for Metallurgy, a major obstacle to a better distribution of scrap use is that scrap quality check relies mostly on imprecise visual inspection, therefore pushing steelmakers to over-specify their scrap purchases to mitigate the lack of precision in scrap quality.

Equipment to improve material sorting and handpicking efficiency before scrap is melted is available and used by certain scrap processors and steelmakers. With such machines that often rely on optical recognition and artificial intelligence, scrap processors can better identify scrap quality grades, as well as achieve higher scrap quality grades and collect other precious materials like copper.

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blind eye on low-quality deliveries shipped as higher-grade material – Terni, acciaio 'sporco': chi sono gli arrestati, umbriaOn, 2016

[40] EU-27 Steel Scrap Specification, EFR, 2007

[41] Scrap Specifications Circular, ISRI, 2021

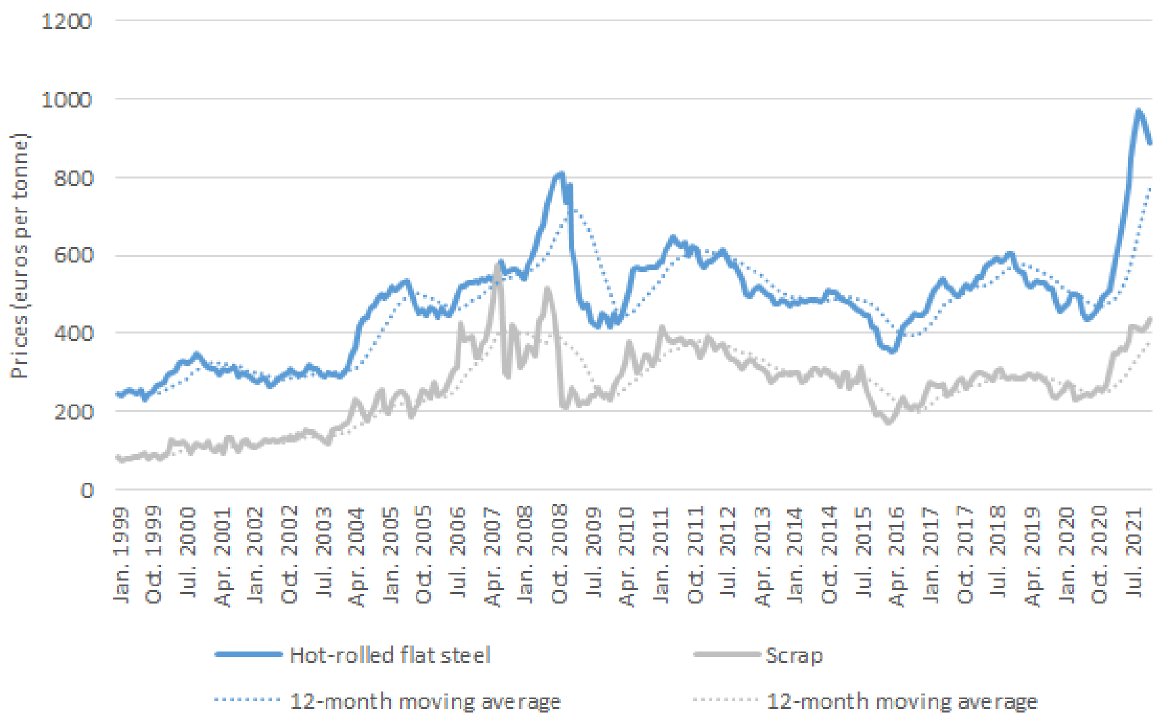
[42] See examples of Steel Dynamics Scrap Specifications or CMC.

For steelmakers, better knowledge of the real composition of scrap helps ensure that they pay the right price for scrap and reduce production costs by using a feedstock mix adequate to the expected steel grade and by decreasing energy consumption ("dirtier" scrap tends to take more time and energy to melt). Although this would still fall short of an exact analysis of the scrap content which requires melting, it would nonetheless be a major improvement compared with the current situation.

Industry sources indicate that such an investment would cost approximately 6-10 euros per tonne of crude steel with a payback period as short as 6 months thanks to better scrap pricing and more optimal scrap use. A report by the European Steel Technology Platform (ESTEP) confirms that "*not paying sterile fraction* [6 – 20% of the input] *as ferrous material through a better material characterization before material reception at the scrap yard, can represent costs saving up to 42€/t*", whereas "*the presence of 5% in iron oxide, silica or lime in scrap represents 7€/t, 40€/t or 10€/t respectively in extra process costs that can be avoid with improved knowledge of scrap and with its upgrade.*"[43]

2.4.3 Cost

Flat steel import-export and scrap export prices over time

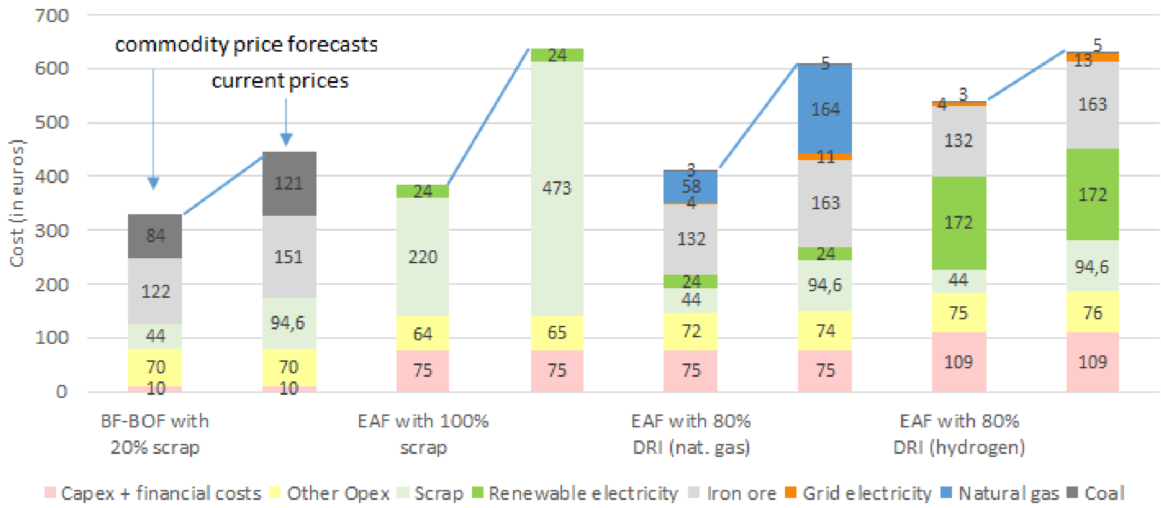


Source: Sandbag, using Comext database (for steel: average import and export values for H2 7208 "Flat-rolled products of iron or non-alloy steel, of a width >= 600 mm, hot-rolled, not clad, plated or coated")

[43] Improve the EAF scrap route for a sustainable value chain in the EU Circular Economy scenario, ESTEP, 2021

Rerouting currently exported scrap involves no additional collection or transport cost as this scrap is already collected and would simply go to steel mills instead of ports. However, steel mills would have to expand their existing facilities to receive and store this additional flow of scrap. Based on a recent project carried out by ArcelorMittal in Fos-sur-Mer (France), we find a capex cost of 10m euros corresponding to a capacity increase of 0.3m tonnes of scrap per year, that is €33.3m per Mt of scrap.

Cost of producing 1 tonne of steel using different processes and input costs



*using 20% scrap. Source: Sandbag

Cost of switching from BF-BOF to EAF with better use of existing scrap

	With futures prices	With market analysts 2030
Total (€bn)	29.8	5.3
Per tonne of CO2 (€)	100.3	17.9

Source: Sandbag

Would less scrap exports lead to carbon leakage?

While the use of EU-sourced scrap for steel domestic production rather than for exports would certainly reduce emissions in EU-based steelmaking, two former ArcelorMittal engineers interviewed by Sandbag for this study have objected that such a change would simply displace emissions as current non-EU consumers of EU-sourced scrap, in particular Turkey, would have to replace the lost supply of iron. This argument is based on a Scrap Availability Assessment Model developed in 2013 and which considers global scrap supply as little elastic because it is mostly a function of past steel production and because recycling rates grow slowly[44]. Its consequence is that the end of EU scrap exports would need to be compensated elsewhere by the production of "virgin" iron. This reasoning is also supported

[44] Johannes Morfeldt, Wouter Nijs, Semida Silveira, "The impact of climate targets on future steel production – an analysis based on a global energy system model", *Journal of Cleaner Production*, vol. 103, 2015

by the European Recycling Industries' Confederation, EuRIC, which underlines that the environmental benefits of scrap use occur "*wherever the scrap is used*"[45] and therefore, that scrap exports should not be restricted.

Indeed, the EU is the largest scrap exporter in the world, but the global significance of these exports – 24m tonnes in 2020, possibly 31m tonnes in 2030 – should be relativised against the world's total steel production of 1,879m tonnes in 2020. A second element is the changing role of China: according to the same Scrap Availability Assessment Model, "*EU available low-quality scrap will be of less importance after 2020*", and China will take over as the world's first generator of scrap because the huge volumes of steel used for its economic boom starting in the 1980s will begin to reach end-of-life[46]. The country is set to produce 340m tonnes of scrap annually by 2030, which is 160m more than in 2015[47] and double the current size of global scrap trade. Although it is unclear what share of this scrap will be consumed in China or exported, it could face similar difficulties to Europe in absorbing its own production. It follows that the alleged carbon leakage resulting from ending EU scrap exports would be both uncertain and limited in impact.

2.5 Use scrap from increased collection

So far we have proposed changes to the use of already collected scrap, but not to the quantity of available scrap collected from end of life steel. In this section we explore the possibility of increasing the use of domestic scrap in steelmaking beyond the volumes currently exported.

2.5.1 Maximum theoretically recoverable steel

The amount of available scrap depends on the *theoretically recoverable* scrap volume (i.e. all products reaching their end of useful life) and the share of that amount which is actually recovered, i.e. the collection rate. We explain further down our estimation of the theoretically recoverable amount; from that number, we deduced the 'business-as-usual' collection rate using the average collected amounts, over 2011-19: 82%, i.e. marginally lower than the 85% estimated by Worldsteel experts[48].

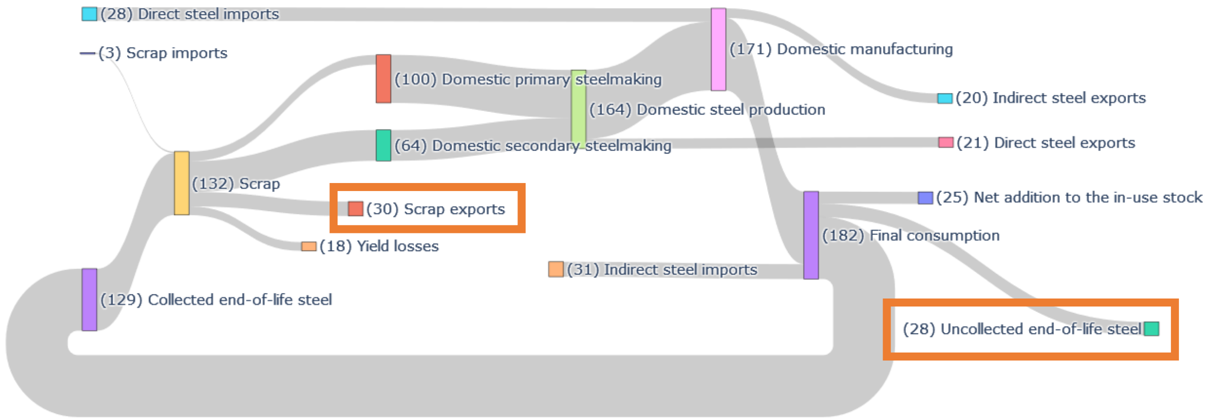
Material flow analyses show that in developed regions like the EU, most of the steel produced every year (both virgin material- and scrap-based) simply replaces steel embedded in goods that reach end of life, for example cars or domestic appliances.

The below bar-chart illustrates how in almost all sectors except for construction, steel volumes in the in-use stock have been relatively stable since the 1990s. Although some of the drivers

[45] EuRIC Circular Metals Strategy, EuRIC, February 2021
[46] Maria Xylia, Semida Silveira, Jan Duerinck & Frank Meinke-Hubeny, "Weighing regional scrap availability in global pathways for steel production processes", *Energy Efficiency*, vol. 11, 2018
[47] Tsunami, spring tide, or high tide? The growing importance of steel scrap in China, McKinsey, March 2017
[48] Life cycle inventory (LCI) study. 2020 data release, World Steel Association, May 2021

are changing with time (slower population growth expected, less substitution with plastics or aluminium) this stable trend is likely to continue into the current decade.

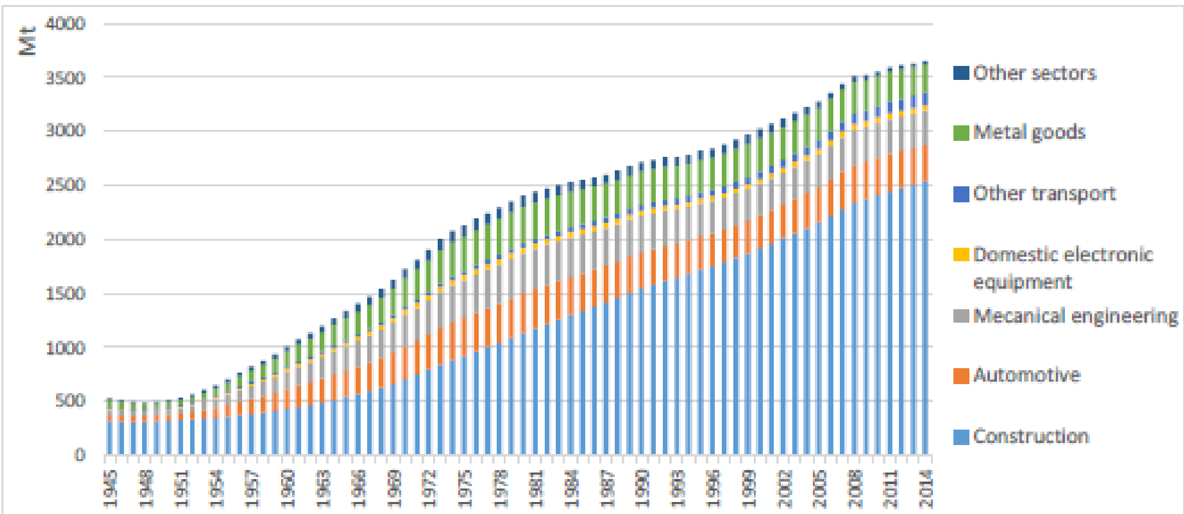
Business-as-usual flow of steel in the EU-28 in 2030



Source: Sandbag

A notable exception is the construction sector, for which the in-use steel stock has grown on average by 25m tonnes per year in the last two decades. Similarly, although the drivers are now different (slower population growth but higher demand for infrastructure such as railways and wind turbines), we can assume **a continuing annual in-use stock increase of 25m tonnes per year** over the decade. The demand for in-use stock reduces the amount of scrap that will theoretically be collectable: domestic consumption minus net addition to the in-use stock, which trends towards 157m tonnes in 2030. As a result, the maximal possible gain we could hope for by increasing collection rate (from 82% to 100%) is **28m tonnes of additional scrap**.

In-use stock of iron and steel in the former EU-27 (today's EU + UK minus Croatia)



Source: Daryna Panasiuk, *Dynamic material flow analysis for estimation of iron flows, stocks and recycling indicators in EU-27*, PhD defended at the University of Technology of Troyes, 2019

2.5.2 Maximum scrap use

Raising the share of scrap in steelmaking poses a quality problem, but to some extent, it can be addressed. The following table shows that, in order to produce steel from 100% scrap, there is a shortage of purer scrap (Q1 and Q2 grades) in relation to demand for the corresponding steel products, whereas there is a surplus of Q3 and Q4 grade scrap.

Meeting steel demand with available scrap (using 2017 data)

Corresponding steel product	Demand (Mt)	Scrap grade	Available qty	Upgrade with DRI
P1: most flat products (cold rolled coils) – deep drawing quality, interstitial-free steel	64.1	Q1	23.5	N
P2: tubes, plates, hot rolled products in construction, wire rod (other than construction)	54.3	Q2	10.6	N
P3: hot rolled bar, plates (construction), wire rod (construction)	25.6	Q3	38.2	Y
P4: heavy section, light section, rail section, reinforcing bar, hot rolled bar (construction)	31.0	Q4	37.6	Y

Source: Dworak and Fellner (2021). Conversion from scrap to crude steel equivalent accounts for the fact that 1.1 tonne of scrap is needed to produce one tonne of 100% scrap-based long steel, and 1.07 tonne of scrap for one tonne of flat steel.

Dworak and Fellner show that since the early 2000s, Q1 and Q2 scrap, which are technically suitable for the production of flat steel in EAFs, has not been consumed this way, for: two reasons: first, the number of EAF mills equipped with the downstream casting and rolling lines to produce flat steel is currently very small in the EU; second, the statistical availability of purer scrap at an aggregate level should not conceal the fact that it may be challenging for steelmakers to actually source it (see paragraph **Erreur ! Source du renvoi introuvable.** on feasibility).

Based on figures presented in the tables above, the average impurity level of collected scrap was 0.29% in 2017, only slightly higher than the average tolerable impurity level of steel demand (0.27%). When accounting for the 65m tonnes "virgin" iron, that was added into the system, the impurity content of the feedstock used was in fact 0.20%, i.e. significantly overspecified.

To avoid overspecification, a more optimal allocation should be done as follows:

- each scrap grade is mapped in priority to the production of the corresponding steel grade;
- the phase out of BF-BOF begins with less demanding steel grades, making possible for the first new EAFs to come online to use a higher share of scrap.

In this new fleet of EAFs, what would be the effect of using 28m tonnes of additional scrap by pushing collection efforts up to the theoretical maximum? Assuming that this scrap is Q4-grade (because higher-quality scrap would have motivated better collection efforts) and that it would come in substitution of DRI, the left-hand chart below shows two problems:

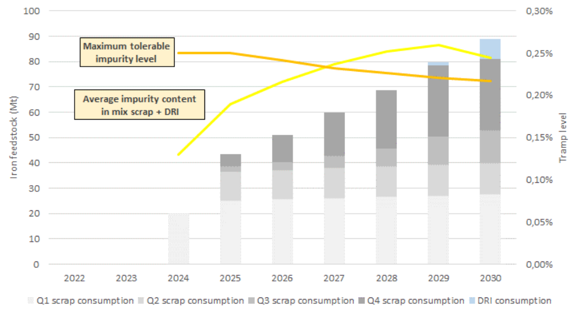
- first, whereas the average maximum tolerable impurity level for the new EAFs decreases together with the replacement of more high-end BF-BOF steel production, the average impurity content in the iron blend quickly rises due to the addition of low-quality scrap, so that already in 2027, it exceeds the tolerable rate;

- second, as additional EAFs continue to come online throughout the decade and drive up demand for scrap or DRI, in 2029, the new scrap source coming from improved collection is exhausted, making necessary to use DRI in order to provide enough iron.

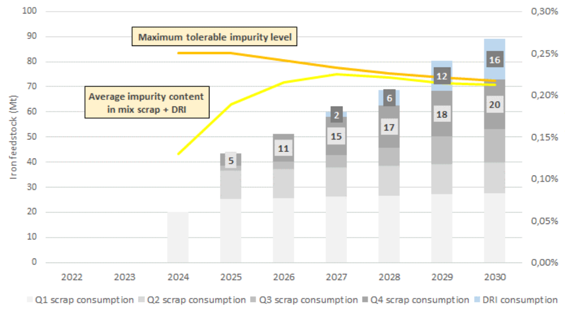
It follows that even if more scrap could be sourced in the EU through better collection practices, it could not all be used due to quality reasons, so that a certain amount of virgin iron, e.g. DRI, is **unavoidable – 17%** of the iron feedstock for the new fleet of EAFs in 2030. This amounts to a **maximum useful Q4 scrap volume of 20m tonnes**.

Quality of feedstock for the new EAFs

Using maximum scrap collection



Using scrap to meet quality requirements

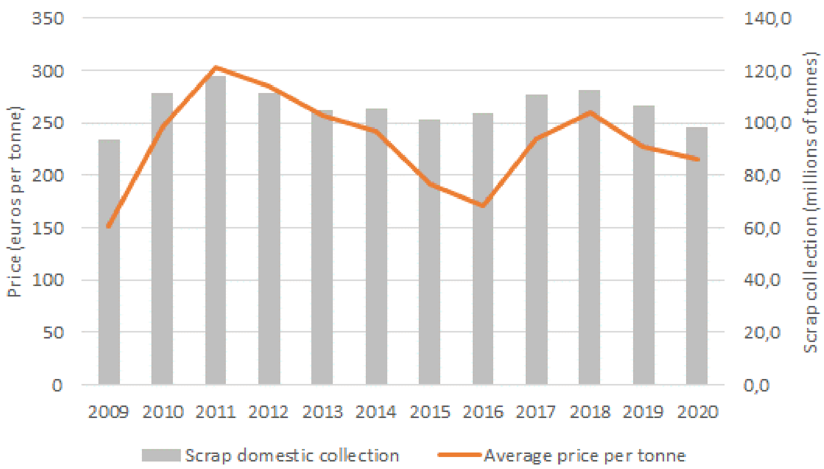


Source: Sandbag

2.5.3 Cost – affordable collection

Although there is no real-life example of a country achieving a 100% recovery rate across all sectors, fluctuations are observed in scrap collection rates. Although a more thorough study would be needed to assess the price elasticity of scrap collection, a range of +/-8m tonnes was observed in the last few years, with some degree of correlation with the price: it corresponded to variations in scrap prices by about €100 per tonne. Given the emission avoidance achieved by 1 tonne of scrap (about 1.8t of CO_2), this suggests that 8m additional tonnes of scrap could be collected at a cost under €56 per tCO2. This is well below the 20m tonnes maximum useful scrap level and would leave steel quality well within acceptable levels.

Scrap price and collection amounts



Source: Sandbag based on the Bureau of International Recycling, the Federal Association of German Steel Recycling and Disposal (BDSV) and Eurofer statistics

Cost of switching from BF-BOF to EAF with increased collection

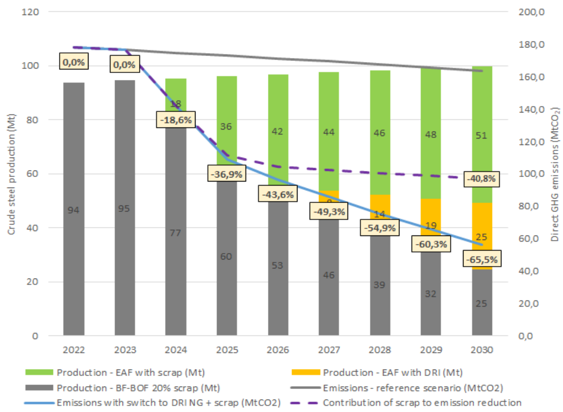
	With futures prices	With market analysts 2030
Total (€bn)	**11.3**	**5.7**
Per tonne of CO2 (€)	**166.4**	**83.3**

2.5.4 Abatement potential

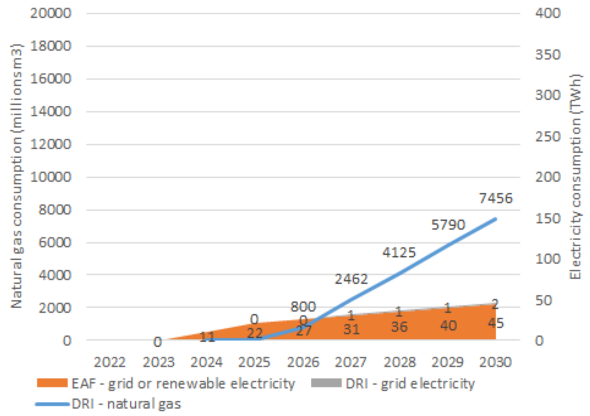
If this 8m tonnes additional scrap from improved collection substitutes natural gas-made DRI, cumulated DRI needs over the decade fall from 131m tonnes to 82m tonnes, and cumulated avoided emissions amount to 20.3 $MtCO_2$. 12.3 billion cubic meters of natural gas are also saved, leading to financial savings of 2.1-6.0 billion euros depending on whether futures gas prices (€0.68 per cubic meter) or market analysts' forecast prices for 2030 (€0.24 per cubic meter) are applied with a discount rate of 6%.

Effect of replacing aging blast furnaces with EAF using currently exported steel scrap + increased collection + natural gas DRI

GHG direct emission reductions



New natural gas and electricity consumption

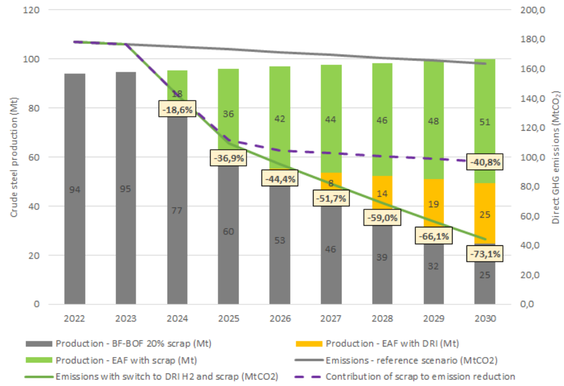


Source: Sandbag

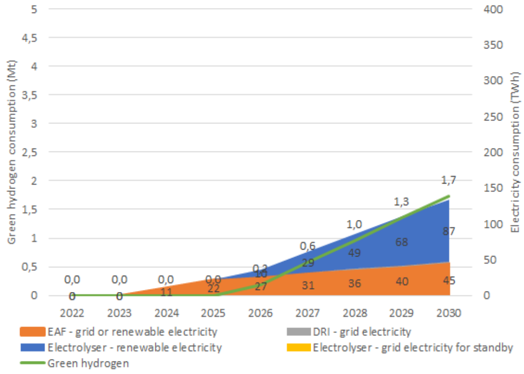
As green hydrogen-made DRI production causes no direct GHG emission, replacing it with scrap from increased collection (+ 8m tonnes) does not lead to further GHG emission decrease. However, cumulated hydrogen consumption would diminish from 7.6m to 4.8m tonnes (-2.8m tonnes). Based on Sandbag's previous work on green hydrogen production and a discount rate of 6%, we find cumulated **renewable electricity savings of 243 TWh** and total financial savings (investments and maintenance of electrolysers, compression and storage costs, electricity costs) of 5.7-6.9 billion euros. depending on whether electrolysers are supplied with cheaper Southern renewable electricity or more expensive Northern one.

Effect of replacing aging blast furnaces with EAF using currently exported steel scrap + increased collection + HDRI

GHG direct emission reductions



New hydrogen/electricity consumption



Source: Sandbag

2.6 CCS fitted on DRI plant

2.6.1 Abatement potential

From section 2.3 onwards, we have assumed that the production of DRI used by European EAF facilities would be decarbonised through the use of ‘green’ hydrogen. An alternative is for them to use natural gas, as in section 2.2, but to capture the CO_2 emitted.

Compared with a GHG intensity of 0.415 tCO_2 per tonne of DRI without CCS, adding a CCS component **cuts GHG intensity by 62%** down to 0.159 tCO_2 per tonne of DRI according to a manufacturer. The relative low rate of capture is explained by the fact that it applies to emissions from the reduction system, but not flue gases from the preheating process[49].

CCS is a controversial method, notably because of uncertainty over long-term safety[50]. The Intergovernmental Panel on Climate Change (IPCC), the most authoritative scientific body on climate change, recognizes that “*there is limited experience with geological storage*” and that leakages are possible, but adds that “*the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years*”[51]. Regarding transport, it considers that “*there is no indication that the problems for carbon dioxide pipelines are any more challenging than those set by hydrocarbon pipelines in similar areas, or that they cannot be resolved.*”

[49] Achieving Carbon Free Emissions via the ENERGIRON DR Process, Danieli and Tenova, 2010
[50] Sanne Akerboom, Svenja Waldmann, Agneev Mukherjee, Casper Agaton, Mark Sanders and Gert Jan Kramer, “Different This Time? The Prospects of CCS in the Netherlands in the 2020s”, *Frontiers in Energy Research*, vol. 9, 2021
[51] IPCC Special Report on Carbon Dioxide Capture and Storage, 2005

However, these assumptions do not address all concerns connected with CCS. First, leakages can occur at different points, for example abandoned wells where they would be larger[52]. Second, in relation to the use of natural gas, CCS captures CO_2 at the location of natural gas transformation, but does not tackle potential upstream GHG emissions at the extraction and transport stages of natural gas – so-called "fugitive methane" –, although they may not be systematic.

Another limiting factor for CO_2 storage is geography, as storage projects[53] in the pipeline and potentially available for steelmaking emissions are located in the North Sea. Given the lack of transport infrastructure, only few DRI plants across the EU will have access by 2030 to a CO_2 storage facility, unless most plants are built in areas with access to a CO_2 storage facility, with DRI then shipped to other steel mills.

Concentrating DRI plants in few places away from most EAF facilities is not impossible. It can be more economical or practical in terms of access to natural gas and iron ore. For example, the DRI plant co-owned voestalpine and ArcelorMittal in Corpus Christi (Texas, USA) is a standalone installation with no steel production on-site but that supplies EAFs elsewhere in the USA, and soon in the EU once EAFs for flat steel production will be installed. The planned DRI plant in Dunkirk (France) is designed to supply not only local steelmakers like Ascoval, but also steel mills in Germany, the Czech Republic and Romania[54]. However, outsourcing DRI production from EAF sites also increases electricity consumption because it obliges the EAF plants to re-heat DRI after its transport.

Overall we believe some degree of concentration around CO_2 storage sites could happen but a large share of DRI production will tend to be built at or near EAF facilities: of 30m tonnes of DRI needed annually to meet Europe's demand after all 'affordable' scrap is used as per 2.5.3, we assume that 7.5m could be produced within the reach of a carbon transport and storage site: that would be 2.5m tonnes DRI capacity in each of DMX in Dunkirk, Carbon Connect Delta near Ghent and UK East Coast Cluster. (We have not considered the CCS Athos project because it was cancelled after Tata Steel chose green hydrogen for its IJMuiden steel mill). This leaves a potential connectable DRI production of 7.5m tonnes per year. The technology would capture 1.9m tonnes of CO_2 annually and 8.5 $MtCO_2$ over the decade. This figure ignores possible leakages that may occur during CO_2 transport and storage as well as potential fugitive emissions connected with natural gas extraction and transport.

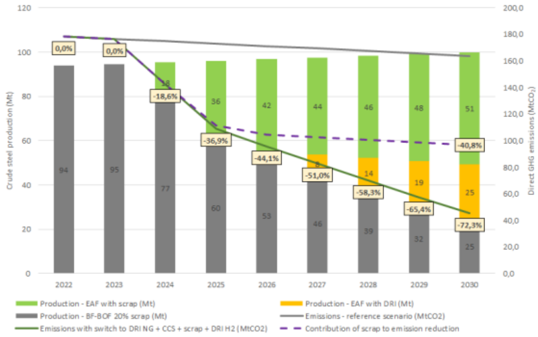
[52] Juan Alcalde, Stephanie Flude, Mark Wilkinson, Gareth Johnson, Katriona Edlmann, Clare E. Bond, Vivian Scott, Stuart M. V. Gilfillan, Xènia Ogaya & R. Stuart Haszeldine, "Estimating geological CO_2 storage security to deliver on climate mitigation", *Nature Communications*, vol. 9, 2018

[53] Europe Carbon Capture Activity and Project Map, CATF

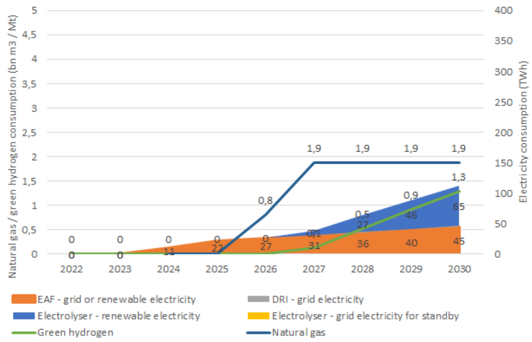
[54] Aurélie Barbaux, Pourquoi Liberty Steel choisit Dunkerque pour produire de l'acier vert avec de l'hydrogène, L'Usine Nouvelle, 22 February 2021

Effect of replacing aging blast furnaces with EAF using CCS-equipped natural gas DRI where available and green hydrogen DRI elsewhere

GHG direct emission reductions



New hydrogen/electricity consumption



Source: Sandbag

2.6.2 Feasibility

CO2 capture systems are off-the-shelf solutions available commercially. In the case of Energiron ZR technology (which we used for our calculations), it simply consists of activating an in-built CO_2 capture system.

Existing examples of capture technologies working at industrial scale around the world show that carbon dioxid recovered through the DRI production process is currently not directed towards long-term storage, but resold as a feedstock for the production of dry ice, food or beverages, or for “enhanced oil recovery”[55].

Long-term carbon storage involves specific infrastructure and adequate transport means, e.g. pipelines or ships. Although the regulation of geological, long-term storage of carbon dioxide has been covered by an EU directive since 2009, there are currently three commercial large-scale facilities in operation in Europe – Sleipner and Snøhvit in Norway and MOL Szank in Hungary[56]. The Norwegian sites are operated by Equinor, Norway’s largest state-owned energy company, in order to store excess CO_2 from natural gas, while Szank is used by Hungary’s main oil and gas company for enhanced oil recovery. Their combined absorption capacity of about 1.65 $MtCO_2$ per year represents less than 1% of the annual direct emissions of the EU steelmaking industry.

The NGO Clean Air Task Force (CATF) reported that Europe’s absorption capacity may reach around 41 $MtCO_2$ per year in 2030 if all announced projects are eventually carried out and completed according to schedule. Although DRI plants will be in competition with other industrial installations to have their CO_2 emissions stored, captured emissions from DRI production represent a small share of planned new storage capacity, so that this should not be a limiting factor.

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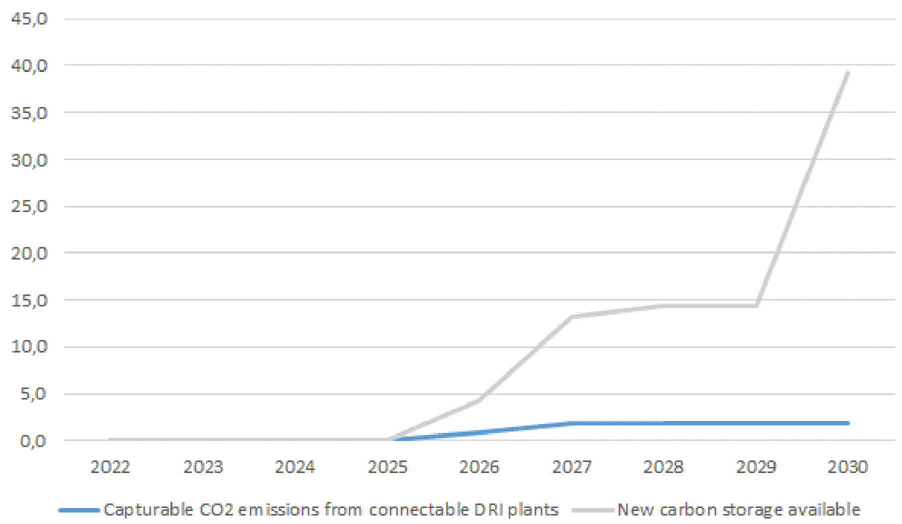
55 Green steel production through hydrogen-based Energiron DRI process, Danieli, 2021

56 CCS Facilities, Global CCS Institute

Planned new CO_2 storage capacity in Europe and captured emissions from potential DRI production (Mt per year)



Sources: CATF and Carbon Limits, Sandbag

2.6.3 Cost

Based on a study commissioned by the Dutch Ministry of Economic Affairs and Climate Policy and carried out by Xodus, a consultancy, the average transport and storage cost for industrial projects are €47 per tonne of CO2[57] from an industrial cluster to a storage site in the North Sea.

Cost of switch from BF-BOF to natural gas DRI + CCS where available

	With futures prices	With market analysts 2030
Total (€bn)	3.7	1.9
Per tonne of CO2 (€)	142.5	73.2

Source: Sandbag

2.7 Switch from BF-BOF to EAF with “blue” hydrogen-made DRI

“Blue” hydrogen is made from natural gas through steam methane reforming but with a CCS component. On top of concerns relative to safety and availability of permanent carbon storage (see above), blue hydrogen DRI production would consume even more natural gas because of conversion losses. This probably explains why it is rarely mentioned in EU-based steelmakers’ decarbonation plans, which rather privilege a direct switch from natural gas to green hydrogen.

[57] Porthos CCS – transport and storage (T&S) tariff review, Xodus, 2020

2.8 Improve scrap quality

In section 2.5.2 we found that, although the scrap currently collected (and exported) could easily be absorbed by new EAF facilities, quality issues limit the amount of scrap that could be used if collection rates happened to rise above current levels. One solution often suggested is to improve the level of scrap quality.

Scrap contamination occurs in two steps:

- first, end-of-life steel and other elements are shredded together without sufficient separation, notably from vehicles;
- then when this scrap is melted, metallic tramp elements become embedded in the steel and can no longer be removed.

As certain categories of steel products can tolerate a relatively high level of residues, separation is not always carried out to the maximum possible, or different grades of scrap are even mixed together. This suggests that better management could allow to use scrap to produce higher grades of steel.

According to Jeremy Jones and Carlo Mapelli, a combination of sorting machines and handpicking can, in an optimal configuration, reduce Cu content to 0.1%[58] (equivalent to commercial-grade steel with tramp level up to 0.2%). This is still too high for the manufacture of most flat products, except for construction plates and certain types of advanced high-strength steel (AHSS). As for technologies enabling the removal from liquid steel of tramp elements, in particular copper, are currently nowhere in use in industry and are very unlikely to be technically and commercially available by 2030.

2.9 Downstream measures

As steel is an intermediate good, demand for it, end-of-life collection and possible re-use are first and foremost in the hands of downstream, steel-intensive industries, especially the construction and automotive sectors that are projected to continue in 2030 to account together for over half of the EU steel consumption.

2.9.1 Re-use

A way of reducing demand is by re-using objects before they enter the waste stream, thereby giving them a new life without remelting. This is already widespread in the construction sector, where second-hand steel sections represent 5%-10% of Europe’s construction steel market[59].

[58] Zhijiang Gao, Seetharaman Sridhar, Erik Spiller, et al., “Applying Improved Optical Recognition with Machine Learning on Sorting Cu Impurities in Steel Scrap”, *Journal of Sustainable Metallurgy*, vol. 6, 2020
[59] Evaluating re-use potential: Material profiles and vision for project workflow, Arup, 2021

Alternative building materials like timber can also be used in construction projects, including civil engineering works like bridges. Buildings in Europe contain on average 20% steel of the total mass of materials[60], and at least some of it could be replaced by timber, as demonstrated by the headquarters of the Swedish company Sjöklint Agenturer[61].

According to a widely cited study published by the European Forest Institute[62], wood construction could take up a market share of 20% of buildings in Europe by 2030. For non-residential buildings, it is currently estimated at 1% on average in the EU, with wide differences between countries, and is realistically assumed to be able to reach 5% in 2030[63]. A linear growth of this market share until 2030 would lead to cumulated steel consumption reduction of 5.5m tonnes over the decade.

Demand-side measures in the construction sector do not bring significant GHG direct emission reductions because construction steel is already made to a large extent through the scrap-based EAF route, although the electricity savings would be material – up to 0.6 MWh per tonne of crude steel. More impact would be achieved by cutting the demand for higher-end steel products, which tend to require higher shares of primary feedstock.

This could be the case of the automotive industry, where widespread re-use would reduce the demand for primary material. However, it could prove challenging as newer vehicles tend not to allow the re-use of spare parts because of blocking devices. The increasing complexity of new cars, with proprietary high-strength steels and advanced polymers and plastics, also makes re-use more challenging, especially since cars that will enter the market in the next years, in particular alternative fuel vehicles, are expected to be quite different in terms of composition from existing cars.

Isolated cases exist, such as carmaker Renault scaling up re-use operations, not only in recovering and reselling spare parts, but also by reconditioning vehicles. The latter would be a major development because it makes possible to re-use elements such as the body, the chassis and suspensions, which account for over half of the total weight of a car with a predominant share of steel.

2.9.2 Direct recycling

Whereas re-use is only possible for old products that meet the specifications of a new use, an alternative is to reprocess end-of-life products without melting them. Direct recycling consists of heating and rolling e.g. a rail and use it as material for a new type of use, as if it were a billet of metal.

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[60] 2018 Global Status Report. Towards a zero-emission, efficient and resilient buildings and construction sector, Global Alliance for Buildings and Construction, 2018

[61] David Malone, One of Europe's largest office and warehouse buildings is made entirely of wood, Building Design Construction, 24 June 2020

[62] Elias Hurmekoski, How can wood construction reduce environmental degradation?, European Forest Institute, 2017

[63] Elias Hurmekoski, Long-term outlook for wood construction in Europe, 2016

This process uses considerably less electricity than EAFs while still allowing flexibility for new uses.

2.9.3 Product design

Overall scrap quality tends to decrease over time as, thanks to process efficiency improvements, the volume of manufacturing-derived, cleaner scrap (busheling, prime scrap, prompt scrap) has been falling, whereas the amount of post-consumer, end-of-life scrap, characterized by lower purity, has been rising together with the accumulation of steel in developed countries' stocks. This trend of increasing copper levels in scrap must be reversed in order to keep steel recycling sustainable.

Copper that is embedded in the steel itself is extremely difficult to remove. However, most of the contamination occurs in the form of "free copper", i.e. the presence of pieces of copper during the shredding of metallic objects containing steel mixed with small pieces of other metals. This problem should worsen as electric cars grow to dominate the automotive industry with typically three times more copper content compared to ICE vehicles.

It is therefore imperative that the automotive industry ensures that automobiles can be efficiently recycled. According to Jones (2019)[64], this may require designing for recyclability implementing strategies such as centralized wiring harnesses that can be easily removed prior to shredding end-of-life vehicles.

2.9.4 A false solution: substitution with aluminium

The automotive industry is the second largest steel consumer in the EU, and what is more, it is the largest user of flat steel that is currently made predominantly in GHG-intensive blast furnaces.

Aluminium is a metal that features a comparatively low density and for this reason, it is often described as a possible alternative to steel in order to lightweight vehicles and reduce fuel consumption. Indeed, for similar use and material properties, 1 kg of aluminium can replace 2 kg of steel[65], and in the 2010s, some cars like the Audi A8 have been designed with an all-aluminium body, although the use of aluminium raises technical challenges to reach the desired shape.

The lower band of the direct carbon intensity of primary aluminium production is 1.6tCO_2 per tonne of aluminium and has limited potential for further decrease with current processes due to the unavoidable consumption of carbon anodes. In addition, GHG indirect emissions from electricity production are very high (14 MWh per tonne of aluminium[66]) and unlike EAF steelmaking, must run continuously.

[64] Jeremy Jones, Assessment of the Impact of Rising Levels of Residuals in Scrap, AISTTech 2019
[65] Driving better material choices for automobiles. The impact of low CO2 footprint aluminium on life cycle emissions, Rusal, 2018
[66] EU Strategies on Energy Sector Integration & Hydrogen,Position on the European Commission's Policy Roadmaps, European Aluminium, June 2020

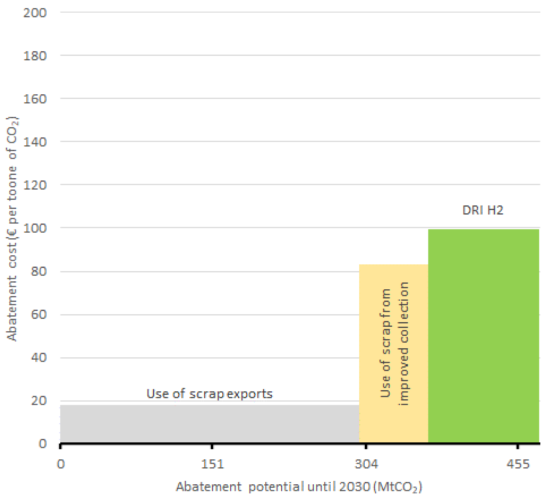
Compared to steel from EAFs with DRI, even made from natural gas, aluminium would result in a net increase of direct GHG emissions. Also, the density gap between aluminium and steel is expected to become narrower thanks to the development of advanced high-strength steels (AHSS), so that some direct GHG emission savings can be expected from lightweighting, even without material substitution.

3 Total abatement and incentives

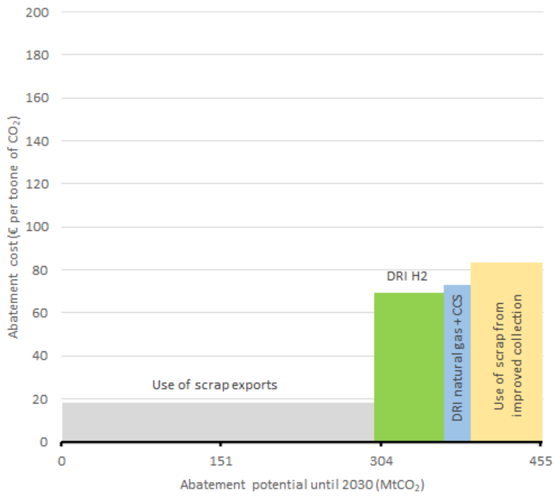
The previous chapter aimed to clarify options on the table for Europe's steel industry, their emission reduction potential, feasibility and cost. The following charts summarises some of the findings by presenting those options in their merit order of cost.

With forecast commodity prices

H2DRI route

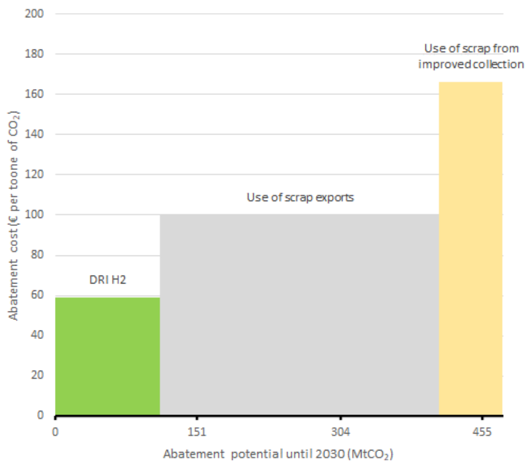


CCS + H2DRI route

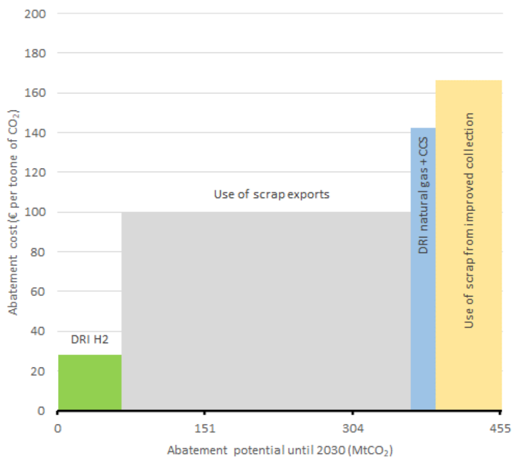


With current futures prices

H2DRI route



CCS + H2DRI route



Abatement costs are highly dependant on commodity prices, so as the markets are experiencing high volatility, the merit order of different abatement measures can change significantly. At times of very high natural gas prices, feeding into grid power prices, hydrogen-based solutions using much cheaper renewable energy appear very competitive. Scrap prices play an important role, making solutions based on secondary steel more or less competitive.

The role of policy instruments will be key in setting incentives for a successful, cost-effective low-carbon transition, as the current framework creates many inefficiencies.

3.1 Free allocation and CBAM

Most of the costs of transitioning towards low carbon steel production fall within the range of carbon prices recently seen in the EU ETS, which suggests that market forces should be sufficient to incentivise the transition. However, the price signal created by the EU ETS is largely cancelled by **the free allocation of emission allowances to steel plants, which tends to lock in existing production methods**. This is because each production process receives a number of allowances in relation to its carbon intensity, for example a 1.288 (worth about €90 each) per tonne of steel for a blast furnace, compared to only 0.05 allowance, as per the ETS benchmarks.

A reform of those benchmarks is scheduled, but not until 2026. If benchmarks were "product-based" rather than "process-based", it could help both processes (BF-BOF and EAF) compete more fairly. However, this would come with a number of problems, as different grades of steel have different limits of impurities, with some grades less easy to produce without primary processed ore. So the reformed benchmarks would need to take into account those grades of steel, but that would **incentivise the over-specification of steel quality**, by reducing the market price difference between low-impurity and high-impurity steel and thereby creating another lock-in.

A reform of the benchmarks would also fail to cover activities of re-use and direct recycling, thereby perpetuating the competitive distortion between production-based savings and circularity-based savings.

Rather than a benchmark reform, the phasing out of free allocation would much better competitive issues and achieve emission reductions at the lowest cost. The **replacement of free allocation with a carbon border adjustment mechanism (CBAM)** would ensure this, however the transition between the two should be **much faster** than proposed by the Commission. An immediate replacement would not negatively affect producers selling to the domestic market, thanks to the new protection brought by the CBAM.

A **CBAM should cover ore-based metallics (OBM)** such as direct reduced iron, to avoid carbon leakage through the import of such feedstock as electrification develops, as shown in section 2.3.2.

3.2 Electricity and Hydrogen

Adding **hydrogen from water electrolysis to the scope of the EU ETS** (with a corresponding free allocation benchmark) would not be satisfactory. This would be equivalent to a process-based benchmark in the case of steelmaking, as hydrogen is not the finished product, instead of a product-based benchmark, and would distort the competition between scrap-based and hydrogen-based steel.

EAFs can run on (intermittent) renewable power. However, only a mix of wind and solar power would keep operating hours above levels that could make the investment competitive, compared to using more expensive grid electricity. In absence of continuous source of cheap carbon-free electricity, **access to both wind and solar energy for each plant** is key.

As well as the carbon price, some incentives could be created using the Climate Investment Fund (currently called "Innovation Fund"). However, as the biggest challenges identified are related to access to carbon-free electricity and reorganisation of the scrap market, and not on-site infrastructure, **the Climate Investment Fund would be more effective if used to support coherent EU-wide policies** in this respect, than project-based initiatives.

Electrolysers can also mostly run on intermittent electricity, although the production of OBM requires a continuous source of hydrogen, which would require some hydrogen storage. There is a risk that hydrogen producers will use carbon-intensive grid electricity to boost their bottom-line, especially as they receive **compensation for indirect carbon costs** in relation to their electricity use, as per the EU ETS.

To avoid this from happening, the targets set to the use of hydrogen under the Renewable Energy Directive (RED) should ensure that the electricity used is renewable. The **Delegated Acts on Renewable Fuels from Non-Biological Origin (RFNBO)**, recently proposed by the European Commission, will need to reflect this.

APPENDIX

Scenarios comparison between studies

a) Studies mentioning circularity

Comparison between studies on the possible structure of EU steel production in 2030

	BF-BOF	scrap EAF	DRI-EAF	Total production (Mt)
Material Economics (2018, 2020)	40	90	0	130 (excluding exports)
Agora Industry / Material Economics (2022)	n/c minus 16	n/c plus 16	n/c	n/c
E3G (2021)	50	60	40	≈ 150
Sandbag BAU	100	64	0	164
Sandbag – maximise affordable scrap use	25 (substitutable with DRI-EAF)	114	25	164

b) Other studies focused on a switch to H2-DRI-EAF steel production technology

Estimates of additional hydrogen and electricity demand linked to a complete switch to H2-DRI-EAF steel production technology

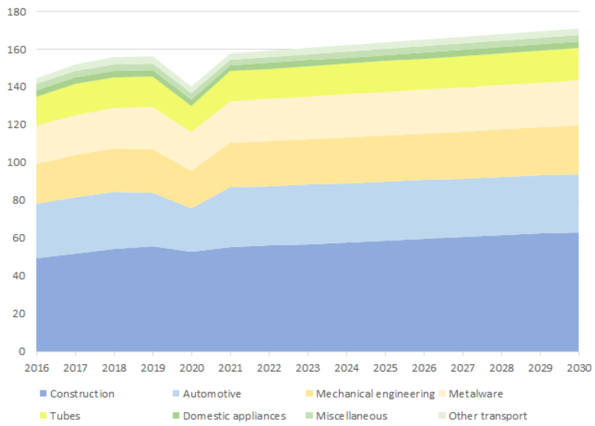
Study	Total investment (M€)	Scope	H2 demand (Mt)	Electricity demand per Mt of crude steel (TWh)	Cost per t of annual production capacity (€)
CRU (2021)[67]	105,000	DRI production, EAFs, electrolysers and downstream equipment in the EU+UK (98 Mt of crude steel production capacity)	> 4.5	3.21	1,071
VITO for the European Parliament (2021)[68]	180,000	DRI production, EAFs, electrolysers and renewable energy sources in the EU+UK (94 Mt of crude steel production capacity)	6.6	3.14	1,900
H2FUTURE (2021)[69]	N/A	DRI production, EAFs and electrolysers in the EU+UK (98.1 Mt of crude steel production capacity)	5.6	3.47	N/A

[67] Paul Butterworth, The cost of decarbonising European steel is high, CRU, 13 December 2021
[68] Juan Correa Laguna, Jan Duerinck, Frank Meinke-Hubeny and Joris Valee, Carbon-free steel production: Cost reduction options and usage of existing gas infrastructure, VITO NV for the Secretariat of the European Parliament, 2021
[69] Amaia Sasiain Conde and Katharina Rechberger, Report on exploitation of the results for the steel industry in EU28, H2FUTURE, 2021

FfE (2020)[70]	N/A	DRI production, EAFs and electrolysers in the EU-UK (77 Mt of crude steel production capacity)	8.6	6.62	N/A
Roland Berger (2020)[71]	30,000	DRI production, EAFs and electrolysers in Germany only (30 Mt of crude steel production capacity)	N/A	4	1,000
Mayer, Bachner, and Steininger (2019)[72]	113,500	DRI production, EAFs and electrolysers in the EU-28 (102 Mt of crude steel production capacity)	N/A	4.41	1,113
Vogl, Åhman, and Nilsson (2018)[73]	N/A	DRI production, EAFs and electrolysers	N/A	3.5	574

Methodological notes

EU-28 steel consumption by steel-using sector, in millions of tonnes (projected beyond 2020)



Methodology: steel consumption by sector is estimated using the Steel-Weighted Industrial Production (SWIP) index and therefore, it may not perfectly match real consumption. Figures for the years 2016-2020 come from the different editions of Eurofer, *European Steel in Figures*, while figures for the years 2021-2030 are extrapolated from 2019 data, since 2020 was an exceptional year. In line with forecasts produced in independent studies by worldsteel (presentation before the Global Forum on Steel Excess Capacity, *Global Steel Market Overview*, 2018), PwC (*Steel in 2025: quo vadis?*, 2015) and BCG (*Steel's contribution to a low-carbon Europe 2050*, 2013), a compound annual growth rate (CAGR) of 0.9% is applied to the 2019 total steel consumption, and on this basis, consumption by sector is calculated using their average respective shares for the years 2016-2019. Shares for mechanical engineering, metalware, tubes, domestic appliances, other transport and miscellaneous are assumed to remain identical until 2030, whereas shares for construction and automotive are assumed to change from 35/20% respectively to 37/18%, in line with 2016-2019 trends explained by the development of energy infrastructure (e.g. windmills) and decreasing steel intensity in cars.

[70] Tobias Hübner, Andrej Guminski, Simon Pichlmair, Moritz Höchtl, and Serafin von Roon, European Steel with Hydrogen, FfE, 2020
[71] The future of steelmaking – How the European steel industry can achieve carbon neutrality, Roland Berger, 2020
[72] Jakob Mayer, Gabriel Bachner, and Karl W. Steininger, "Macroeconomic implications of switching to process-emission-free iron and steel production in Europe", *Journal of Cleaner Production*, vol. 210, February 2019
[73] Valentin Vogl, Max Åhman and Lars J. Nilsson, *op. cit*.

Cost calculations

1 Cost of switch from BF-BOF to EAF

Investments, announcements and plans related to conversion from BF-BOF to DRI-EAF in the EU

Company	Plant	Production capacity to be shifted to DRI-EAF (Mt)	Estimated cost (million euros)	Planned completion year	Status
ArcelorMittal	Gijón / Sestao (Spain)	1.6	1 000	2025	On-going implementation
SSAB	Oxelösund (Sweden)	1.2	n/c	2026	On-going implementation
Thyssenkrupp	Duisburg (Germany)	n/c[74]	2 000 – 8000	2030	On-going implementation
Salzgitter	Salzgitter (Germany)	2	1 250	2025	Awaiting final investment decision
US Steel	Kosice (Slovakia)	3.1	1 300	2025	Awaiting final investment decision
ArcelorMittal	Dunkirk (France)	2	n/c	2027	Awaiting final investment decision
ArcelorMittal	Gent (Belgium)	2.5	1 100	n/c	Awaiting final investment decision
ArcelorMittal	Bremen and Eisenhüttenstadt (Germany)	3.5	1 000 – 1 500	n/c	Awaiting final investment decision
Voestalpine	Donawitz and Linz (Austria)	2 EAF (undisclosed capacity)[75]	1 000	2027 (first phase)	Awaiting final investment decision (in 2023)
SSAB	Raahe (Finland) and Lulea (Sweden)	n/c	n/c	By 2030	Plan
Liberty Steel	Galati (Romania)	4.0[76]	n/c	n/c	Plan
SHS (Saarstahl, Dilinger)	Völklingen and Dillingen (Germany)	n/c	n/c	n/c	Plan
Tata Steel	Ijmuiden (Netherlands)	n/c	n/c	n/c	Plan[77]
	Total	> 15.9			

[74] The four existing blast furnaces are to be replaced but it is unclear whether production capacity will be fully maintained – Transformation of the steel industry can become a successful model for the transition to climate neutrality, thyssenkrupp, 28 June 2021

[75] HBI will be at least in part sourced from voestalpine's HBI production plant in the United States.

[76] HBI is expected to be sourced in majority from a to-be-built 2.5-million-tonnes local DRI plant, and partly from a 2-million DRI plant planned in Dunkirk (France) for the needs of Ascoval, However, it is unclear whether the existing blast furnaces would be closed down as a result of new EAF capacity – Ekaterina Bouckley, GFG Alliance plans to revamp Romanian Galati plant into 'green' steelmaker, S&P Global, 11 June 2020

[77] Tata Steel opts for hydrogen route at its IJmuiden steelworks, Tata Steel, 15 September 2021

1.1 EAF – investment costs

Based on existing projects or assessment studies aiming at setting up EAF production capacity, we assume an investment cost of €210m per Mt of annual crude steel production capacity.

Project / study	Total investment cost (M€)	Scope	Capacity (Mt)	Cost per Mt of annual crude steel production capacity (M€)
US Steel Kosice	1 300	Acquisition and installation of 2 EAFs, new casting and rolling line	3.1	420
SSAB Oxelösund[78]	≈ 500[79]	Acquisition and installation of one EAF	1.2	417
Vogl, Åhman and Nilsson (2018)[80]	N/A	Limited to the acquisition of EAFs	N/A	184
eclareon (2021)[81]	N/A	Limited to the acquisition of EAFs	N/A	210
Selected assumption (EAF alone)				210[82]

Unlike coal-based iron ore reduction in blast furnaces, direct reduction of iron pellets or fines does not need to reach the melting point of iron and is therefore more energy-efficient and less GHG-intensive. It is also suitable for smaller production volumes, making it a good solution to feed EAFs. While modern DRI processes are very flexible in terms of fuels – they can use natural gas, coal, hydrogen… –, they are less tolerant than blast furnaces in terms of iron and tend to require higher-grade pellets.

The high ambitions of EU-based steelmakers in the DRI-EAF technology poses a number of challenges. Today's global DRI production is about 108m tonnes per year, but close to zero in the EU – the only functioning plant, run by ArcelorMittal in Hamburg (Germany), has an annual capacity of 0.6m tonnes[83] using natural gas. It is however expected to switch to hydrogen by 2030[84].

[78] Presentation of the Year-end report, SSAB, 28 January 2022
[79] 5 billion SEK, an average exchange rate of 1 SEK = 0,10 EUR is assumed.
[80] Valentin Vogl, Max Åhman and Lars J. Nilsson, "Assessment of hydrogen direct reduction for fossil-free steelmaking", *Journal of Cleaner Production*, vol. 203, December 2018
[81] Boris Valach, Accelerate shift towards green steel, Eclareon GmbH, 2021
[82] eclareon's figure matches US Steel Kosice, considering that around 200 M€ per annual crude steel production capacity should be subtracted from 420 in order to cover acquisition costs of the casting and rolling line (Competitive advantages of Arvedi ISP ESP technology, Arvedi, and Francesco Facchini, Giorgio Mossa, Giovanni Mummolo, and Micaela Vitti, "An Economic Model to Assess Profitable Scenarios of EAF-Based Steelmaking Plants under Uncertain Conditions", *Energies*, vol. 14, 7395, 2021).
[83] ArcelorMittal Hamburg Turns 50 – Leading Another Ironmaking Renaissance, Midrex Technologies, 30 March 2021
[84] German Federal Government commits its intention to provide €55 million of funding for ArcelorMittal's Hydrogen DRI plant, ArcelorMittal, 7 September 2021

As for the GHG emission savings of the DRI-EAF technology, they depend very much on the fuel used, which in turn raises the questions of physical availability and affordability.

Key resource use for primary steel technologies

per tonne of crude steel	**BF-BOF (current best available)**	**100% DRI-fed EAF + DRI plant fuelled by natural gas without CCS**	**100% DRI-fed EAF + DRI plant fuelled by "blue" hydrogen**	**100% DRI-fed EAF + DRI plant fuelled by "green" hydrogen**
GHG intensity (tCO_2)	1.64	0.55 (-67%)	0.11 (-93%)	0.05 (-97%)
Iron ore (t)	1.22	1.66	1.66	1.66
Coal (t)	0.47	0.02	0.02	0,02
Natural gas (m^3stp)	0	301	316	0*
Electricity (MWh)	0 (self-production)	0.68**	0.77	4.06

Sources: European Commission (BF-BOF GHG intensity), H2Future[85] (BF-BOF resource use), CE Delft[86] (blue hydrogen), Sandbag[87] (hydrogen production), Danieli[88], Tenova[89], Tenova / Danieli[90] (DRI and EAF best available technologies)

* Full electrification assumption, although today's common practice is to use some natural gas in EAFs in order to reduce electricity use

** Assumption that furnaces use cold HBF, which need preheating: 0.60 for EAFs and 0.08 for DRI

1.2 EAF – Overall switch costs

The overall cost of switching from BF-BOF to EAF fed with scrap and DRI made with natural gas is the difference between investments in BF-BOF relining and investments in EAFs and DRI plants plus the difference in operating expenses (raw materials and energy, labour, maintenance) between the BF-BOF and the EAF-DRI-NG routes.

Techno-economic assumptions (per tonne of annual crude steel production capacity)

[85] Amaia Sasiain Conde and Katharina Rechberger, Report on exploitation of the results for the steel industry in EU28, H2FUTURE, 2021
[86] Lucas van Cappellen, Harry Croezen, and Frans Rooijers, Feasibility study into blue hydrogen. Technical, economic & sustainability analysis, CE Delft, 2018
[87] Samuel Gonzalez Holguera, Untangling the knots. Clearing the way to fast green hydrogen deployment, Sandbag, 2021
[88] Dario Pauluzzi, Ashton Hertrich Giraldo, Alberto Zugliano, Daniella Dalle Nogare, and Alessandro Martinis, CFD Study of an Energiron Reactor Fed With Different Concentrations of Hydrogen, Danieli, 2020 AISTech Conference Proceedings
[89] Pablo Duarte and Jorge Becerra, Decrease of GHG emissions through the Carbon Free Emissions ENERGIRON DR Scheme in Integrated Mills, Tenova HYL, 2011
[90] Premium Quality DRI Products from ENERGIRON, Tenova and Danieli, 2019

	CAPEX (M€ per tonne of annual crude steel production capacity)	Lifetime (years)	Operation and maintenance costs
BF-BOF relining	-85	20	3.2% CAPEX
EAF	210	20	3.5% CAPEX
ENERGIRON DRI plant	300	20	3.5% CAPEX
Difference	+425		

Sources: Vogl, Åhman and Nilsson (2018), Danieli (2019), IEA (2019), Eclareon (2021)

	Futures prices[91] (euros)	Market analysts 2030[92] (euros)	Sources
Iron ore / pellets (per tonne)	123*	100	Vogl, Åhman and Nilsson (2018), World Bank, Federal Reserve Bank of St. Louis, CME
Scrap (per tonne)	430	200	OECD, BDSV, LME
Premium for increased scrap collection (per tonne of scrap)	100	100	Sandbag estimate
Coal (per tonne)	260*	180	Mayer, Bachner, and Steininger (2019), OECD, IEA, SGX
Natural gas (per m^3)	0.68	0.24	World Bank Commodities Price Forecast 2021, ICE
Limestone and fluxes (per tonne)	90	90	Vogl, Åhman and Nilsson (2018)
Graphite electrodes (per tonne)	4 000	4 000	Vogl, Åhman and Nilsson (2018)
Grid electricity (per MWh)	174	60	Sandbag (2021), EEX

* Assuming an exchange rate of 1 USD = 0.92 EUR

We assume that the cost of electricity is the levelized cost of electricity from renewables plus an extra 20% for connection[93].

We also assume a different cost of renewable electricity in Northern and Southern Europe due to different conditions of solar irradiance and wind potential. For each region, a combination of solar and wind power is assumed to be able to provide electricity 5000 hours per year, so that the total EAF production capacity to be installed by 2030 amounts to 132 Mt. This impacts Capex, labour, and operation and maintenance costs, but not input consumption which depends on actual output, not capacity.

[91] Based on futures commodity contracts with delivery over 2024
[92] Retrieved on April 25th, 2022
[93] Samuel Gonzalez Holguera, *op. cit.*.

Additionally, we assume that regional locations (Northern or Southern Europe) of the new EAFs will match the current geographical distribution of BF-BOF capacity. Based on the list of blast furnaces[94] provided by researchers of the EU-supported H2FUTURE project, we find that 69% of BF-BOF capacity is located in Northern European countries, and 31% in Southern European countries[95]. As a simplifying hypothesis, we consider that the phase down of BF-BOF happens at the same pace in the North and the South.

2 Increased scrap collection

Assumptions used for the flow chart in section 2.5.1.

Sources and assumptions	
Domestic steel production ("virgin" and "recycled")	Sandbag BAU 2030 scenario described above, Eurofer for shares of BF-BOF and EAF
Scrap imports	Linear flat trend of the years 2011-2019
Scrap exports	Based on forecast surplus of low-quality scrap (details in the next section)
Direct steel imports and exports	Calculated as constant shares of EU steel supply and production
Indirect steel imports and exports	Covers automotive, metalware and mechanical engineering which cover 90% of indirect steel trade, figures based on average steel content[96] and trade past trends or forecasts when available
Net addition to the in-use steel stock	See above explanations about the in-use steel stock
Yield losses	6 Mt from the EAF yield rate (1.1 tonne of scrap for 1 tonne of crude steel), the rest (12 Mt) in the oxygen converter of the BF route becomes slag[97]

[94] Amaia Sasiain Conde and Katharina Rechberger, *op. cit*.
[95] Our "Northern Europe" group includes Belgium, the Czech Republic, Denmark, Estonia, Finland, Germany, Ireland, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Slovakia, Sweden and the United Kingdom. The "Southern Europe" group includes Austria, Bulgaria, Croatia, Cyprus, France, Greece, Hungary, Italy, Malta, Portugal, Romania, Slovenia and Spain.
[96] Indirect trade in steel, World Steel Association, 2015
[97] Jonathan M. Cullen, Julian M. Allwood and Margarita D. Bambach, Mapping the global flow of steel: from steelmaking to end-use goods, 2012