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Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology

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This report describes work undertaken by ERM on behalf of IEAGHG. The principal researchers were: Silvian Baltac, Sébastien Haye, Anisha Harris, Ignacio Rabsiun Aramburu, Yamini Panchaksharam, Tom Butler. Supporting Authors: Jacob Jones, Charlie Readman.

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Further information can be obtained by contacting IEAGHG at: ***Email:*** *mail@ieaghg.org* ***Phone:*** *+44 (0)1242 802911*
Address: *IEAGHG, Pure Offices, Hatherley Lane, Cheltenham, GL51 6SH, UK*

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The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its mandate is to promote energy security amongst its member countries through collective response to disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy. The IEA Technology Collaboration Programmes (TCPs) facilitate international collaboration on energy related topics.

CLEAN STEEL:
AN ENVIRONMENTAL AND TECHNOECONOMIC OUTLOOK OF A DISRUPTIVE TECHNOLOGY

This study primarily presents a comparative analysis of steelmaking pathways to cost-effectively decarbonise a steel mill, taking a life-cycle perspective on associated environmental impacts. The roll-out of clean steel technologies is envisioned to have a significant implication for support infrastructure. Therefore, a secondary objective of the study is to gain insights into the primary energy and infrastructure implications associated with large-scale deployment of different steel decarbonisation pathways. Clean steel production will likely be more expensive than steel produced today; this poses additional economic strains on steel producers and consumers. Consequently, a third objective is to estimate the price premium that clean steel could command in existing and future markets. Further, this study formulates recommendations for key stakeholders to support the sector and outlines recommendations for further work.

Key Messages

- To achieve deep decarbonisation, disruptive measures and innovative steelmaking processes will be necessary. Although enhancements in energy efficiency or increased scrap utilisation in basic oxygen steelmaking can diminish emissions, these measures alone will not suffice to achieve the substantial emissions reductions required to align with climate objectives.
- The solution for steelmaking facilities to transition to cleaner steelmaking could vary substantially by geography even within Europe. It finds that sites in Northwestern Europe are likely to be better suited for adopting carbon capture and storage (CCS) technologies due to developing of CO_2 Transport and Storage (T&S) projects. Sites in Central or Southern Europe may find transitioning to hydrogen-based routes more attractive due to existing hydrogen pipelines.
- While all pathways show a reduction in fossil global warming potential (GWP)[1] impact, it is evidenced that alongside dealing with residual direct emissions, decarbonisation of the supply of materials/energy and treatment of wastes will be required to drive down total GWP of crude steel production.
- When considering use of renewable electricity within the steel mill and at the pellet plant, as well as for the production of hydrogen, H-DRI with bioenergy could deliver significant reductions in fossil GWP of about 80% compared to basic oxygen steelmaking. NG-DRI with CCS also shows strong potential for high levels of reduction.
- Transitioning to hydrogen-DRI does not yield the same level of reductions when all the embedded emissions linked to upstream raw materials and waste treatment are accounted for. In fact, considering the fossil GWP, the H-DRI pathway exhibits a higher fossil GWP compared to NG-DRI. This discrepancy is primarily driven by a substantially greater electricity input (six times higher) in the shaft furnace, as opposed to NG-DRI routes, and a higher coal consumption (ten times higher) in the Electric Arc Furnace (EAF).
- Lifecycle fossil GWP impacts of crude steel can be significantly lower if using onsite renewable or an equivalent net zero source electricity, which could be secured through Power Purchase Agreements.
- Nevertheless, the findings also indicate that achieving completely emissions-free steel production is not feasible. Residual emissions within the steelmaking facility and across the supply chain must be addressed.

[1] In the LCA, the GHG footprint is referred to as the Global Warming Potential (GWP) Impact

- The findings indicate that current carbon pricing mechanisms fail to offer sufficient incentives to favour pathways with lower greenhouse gas (GHG) emissions intensity.
- Today, basic oxygen steelmaking without emission reduction measures remains the most economically advantageous option in terms of levelised production costs, even when factoring in carbon pricing. However, maintaining the status quo does not come without financial implications. Addressing and reducing emissions are becoming integral aspects of corporate strategies and procurement processes. Failing to decarbonise will likely result in a diminishing market share and reduced revenue in the future.
- In the short term, all pathways experience a decrease in production costs as energy and commodity prices gradually settle from their current record highs. By 2050, the Blast Furnace-Basic Oxygen Furnace (BF-BOF) + Bioenergy with CCS (BECCS) and Natural Gas-Direct Reduced Iron + Electric Arc Furnace + CCS (NG-DRI+EAF+CCS) routes demonstrate the lowest breakeven prices. At that point, only the BF-BOF+hydrogen (H_2) pathway exhibits a higher breakeven price for steel compared to the base case BF-BOF (unabated) pathway.
- As time progresses, the disparity in production costs diminishes, and by 2050, unabated basic oxygen steelmaking becomes one of the costlier steel production pathways.
- For the range of cost inputs, all pathways could potentially achieve lower levelised production costs compared to the BF-BOF baseline cost, except the hydrogen-DRI (H-DRI) pathways.
- This study has identified that high energy costs in Europe may adversely affect the cost structure for steel producers transitioning towards H-DRI pathways. Steel producers could potentially lower production costs by importing hot briquetted iron (HBI) to charge it into an electric arc furnace. Extending the analysis to other regions, bringing in wider geopolitical factors which may influence the roll out of technologies across the globe, is required to identify regions where transitioning to H-DRI presents a competitive advantage.
- The study suggests that steel consumers with a shadow carbon price of €100/tCO_2 would be willing to pay a maximum of 30% premium for clean steel compared to conventional steel. However, should the decarbonisation of other components in the value chains of final products also lead to increased costs, the overall rise in expenses could surpass initial estimates. This might result in end consumers exhibiting a reduced willingness to pay.
- Achieving decarbonisation within the steel sector is contingent upon substantial supporting infrastructure, which currently represents a pivotal bottleneck.
- If all steel mills were to adopt H-DRI-based pathways, they could potentially account for 30% of the anticipated increase in renewable generation capacity in the EU by 2030.

Background of Study

Steel stands as a fundamental pillar of our contemporary global economy, serving as a ubiquitous industrial commodity on a global scale. It plays an indispensable role, both in visible and concealed aspects of the modern world, encompassing crucial applications ranging from infrastructure and transportation to industrial machinery and packaging. Notably, steel production has surged significantly in the 21st century, with an impressive output of nearly 2 billion tonnes of raw steel in 2020. This trajectory is poised to continue upward by 2050, propelled by sustained economic growth and urbanisation, even as advanced economies approach a saturation point in their steel inventories.

Despite being an essential material in modern society, steel production stands as one of the leading contributors to global carbon emissions, accounting for approximately 7% of the total energy-related CO_2 emissions. This elevated carbon footprint in iron and steel manufacturing can be attributed in part to its heavy reliance on coal and coke as primary energy sources, reducing agents and providers of permeability to the blast furnace burden.

Recognising the increasing significance and urgency of decarbonising the steel industry, IEAGHG commissioned Element Energy to investigate the environmental and technoeconomic implication of various potentially transformative technologies for reducing carbon emissions in steel production. There is a growing array of technology choices emerging for decarbonising steelmaking, encompassing various carbon capture and storage (CCS) configurations, smelting reduction methods, and hydrogen-based direct iron reduction processes. Each of these technologies possesses unique cost structures, environmental footprints, and differing impacts and requirements within the broader system. This study provides a comparative examination of these diverse pathways for steel production, with a specific focus on assessing their suitability and feasibility within Northwestern Europe.

The primary production route of steel comprises three phases: raw material preparation, ironmaking, and steelmaking. Initially, iron ore is mined and goes through beneficiation to prepare it for ironmaking. In this phase, a mix of lump ore, sinter, and pellets undergoes chemical reduction to produce iron by removing oxygen from the iron oxides. There are two major methods for this process:

Firstly, the Blast Furnace (BF) method uses coke as the reducing agent to produce pig iron, which is then converted into steel in a Basic Oxygen Furnace (BOF). This coal-based process, often denoted as BF-BOF, has been the most common and carbon-intensive pathway globally for the past 50 years.

In the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route for steel production, metallurgical coal plays a multifaceted role.

- It acts as a heat source crucial for maintaining the high temperatures required in the BF
- It acts as a reducing agent for the iron ore
- It provides permeability to the blast furnace burden
- It is a source of carbon for the final product (steel is an alloy of carbon and iron).

These quadruple roles of metallurgical coal, combined with the substantial global demand for steel, underscore its integral importance in the BF-BOF steelmaking process.

Secondly, the shaft furnace method uses natural gas as the reductant to transform iron ore into metallic iron in a solid state, producing Direct Reduced Iron (DRI). This DRI, often combined with scrap, is then melted in an Electric Arc Furnace (EAF) to produce steel. Known as the DRI–EAF process, this natural gas-based route involves direct reduction in a shaft furnace followed by steelmaking in an EAF.

Scope of study

Nine pathways are detailed in our techno-economic and lifecycle assessment (refer to table 1), selected from a comprehensive list of primary steel production methods. This includes the conventional Blast Furnace-Basic Oxygen Furnace (BF-BOF) process, which serves as the base case in this study. Emerging alternatives aim to either modify or replace this traditional method. These encompass variations of the BF-BOF process integrated with Carbon Capture and Storage (CCS) and Bio-Energy with Carbon Capture and Storage (BECCS), both of which aim to capture CO2 emissions from the blast furnace. The latter approach includes biomass as an additional energy source. Furthermore, the integration of Top Gas Recovery (TGR) with the BF-BOF process represents a significant advancement in the industry’s shift towards a low carbon pathway. By enhancing the traditional BF-BOF process with TGR, CCS, and BECCS, these emerging technologies offer a promising route to decrease the carbon footprint of steel production. Another notable innovation is the BF-BOF process with hydrogen injection, which employs hydrogen to reduce CO2 emissions. Amongst the broad spectrum of pathways available for steel production, this analysis excludes those with limited technical maturity, although they are referenced in the report. The pathways included in the assessment were chosen due to their advanced technical readiness, potential for commercial adoption by 2030 and suitability for integration into European integrated sites. To facilitate clear presentation of findings, each pathway has been assigned a reference name for easy identification.

Table 1. Technology routes included in study

<table>
<tr><th>Base case</th><th>Technology pathway</th><th>Reference name</th><th>TRL [2]</th></tr>
<tr><td rowspan="4">BF-BOF</td><td>BF-BOF</td><td>BF-BOF</td><td>-</td></tr>
<tr><td>BF with TGR-BOF + CCS</td><td>BF-BOF+CCS</td><td>6</td></tr>
<tr><td>BF w/TGR-BOF + BECCS</td><td>BF-BOF+BECCS</td><td>6</td></tr>
<tr><td>BF-BOF with hydrogen injection in blast furnace</td><td>BF-BOF+H_2</td><td>7</td></tr>
<tr><td rowspan="5">NG-DRI + EAF</td><td>NG-DRI + EAF</td><td>NG-DRI+EAF</td><td>-</td></tr>
<tr><td>NG-DRI + EAF + CCS</td><td>NG-DRI+EAF+CCS</td><td>8-9</td></tr>
<tr><td>H-DRI + EAF</td><td>H-DRI+EAF</td><td>6-7</td></tr>
<tr><td>H-DRI + EAF with bioenergy</td><td>H-DRI+EAF+bio</td><td>6</td></tr>
<tr><td>NG-DRI + Electric smelting + BOF</td><td>NG-DRI+Smelt+BOF</td><td>8</td></tr>
</table>

Defining the boundary limits for the integrated steel mill and other steel production methods is crucial for determining energy needs, direct CO_2 emissions, and the cost per unit of steel manufactured. In this study, we have established the functional unit as one metric ton of crude steel with a carbon content of 0.1%. Consequently, equipment related to downstream processes like reheating furnaces and hot rolling mills has been excluded from consideration.

For the technoeconomic analysis (TEA), upstream processes were not included within the boundary limit when accounting for energy use and direct greenhouse gas (GHG) emissions. As a result, the energy and material flows stemming from the production of purchased pellets and burnt dolomite were not accounted for. It is important to note that although certain integrated steel mills include pellet plants, this is not characteristic of most steel mills that rely on pellet imports. Energy and material flows from these upstream processes are accounted for as part of the lifecycle assessment (LCA).

The system boundary selected for the LCA is cradle-to-gate up to the point of crude steel production, which includes:

- All of the steelmaking processes and on-site ancillary services that are required
- All necessary inputs and outputs per process including materials, energy inputs, emissions, wastes and co-products
- All related upstream processes, i.e., raw material acquisition, and waste treatment

The downstream processing of crude steel is contingent upon the final product or application, and it remains consistent regardless of the upstream steelmaking method. Consequently, the study did not include downstream processing of crude steel, product utilisation, or the end-of-life stages. Figure 1 provides a concise overview of the cradle-to-gate system boundary.

[2] TRL: technology readiness level, a scale from 1 to 9 used to measure technology maturity.

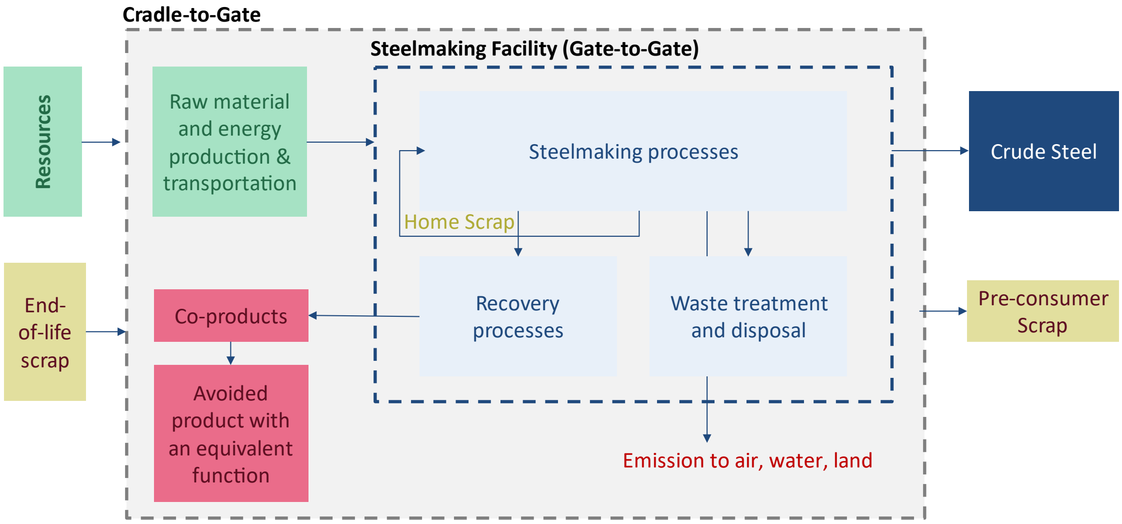

Figure 1: System Boundary for Cradle-to-Gate, adapted from World Steel Inventory

In the cradle-to-gate system, a cut-off approach is used for all recycled products, including scrap. A cradle-to-gate with recycling system can also be adopted, under which the impacts of using steel scrap in the steelmaking process (e.g., associated with the municipal facilities) and the credits for end-of-life recycling, at a specified recycling rate, are included within the system boundary.

Findings of Study

Technoeconomic analysis:

The TEA assessment estimates the production cost of a tonne of crude steel for an integrated steel mill nearing the end of a blast furnace campaign, and hence facing an investment decision: relining the blast furnace and continuing operations, potentially including some modifications, or switching to an alternative pathway. The study thus, adopts the viewpoint of a brownfield site situated in Western Europe. Note, the capital cost structure is notably distinct from that of a greenfield steel site.

The BF-BOF steelmaking pathway delivers the lowest levelised cost across all the pathways, even after accounting for carbon pricing. Breakeven steel prices for the various steelmaking routes are presented in Figure 2. The base case BF-BOF route remains the cheapest production pathway, and with all BF-BOF variations exhibiting lower costs than any of the DRI routes. Pathways incorporating carbon capture and storage (CCS) show a relatively moderate increase in production costs compared to the base case, ranging from 5% to 18%. The H-DRI pathways, on the other hand, exhibit the highest breakeven prices, 44% greater than the base case (including carbon price). The results expose that current carbon pricing is not a sufficient incentive towards pathways with a lower GHG emissions intensity.

The findings indicate that current carbon pricing mechanisms fail to offer sufficient incentives to favour pathways with lower greenhouse gas (GHG) emissions intensity. While certain pathways are nearing cost parity with traditional integrated steelmaking and would require minimal additional support, for H-DRI pathways, given their current state of technology readiness, additional policy support is crucial to ensure their future viability based on merit.

The BF-BOF pathway incurs its highest costs primarily in raw materials. In pathways that utilise hydrogen, the predominant cost factor is energy. Specifically, energy and reductants account for 40%, 42%, and 43% of production expenses, excluding carbon costs, in the BF-BOF+H2, H-DRI+EAF, and

H-DRI+EAF+bio pathways, respectively. The cost gap between the BF-BOF pathway and H-DRI+EAF could close before 2040, depending on the hydrogen sourcing strategy and evolution of costs. H-DRI could be economically competitive in other regions with a higher potential for low-cost hydrogen and electricity.

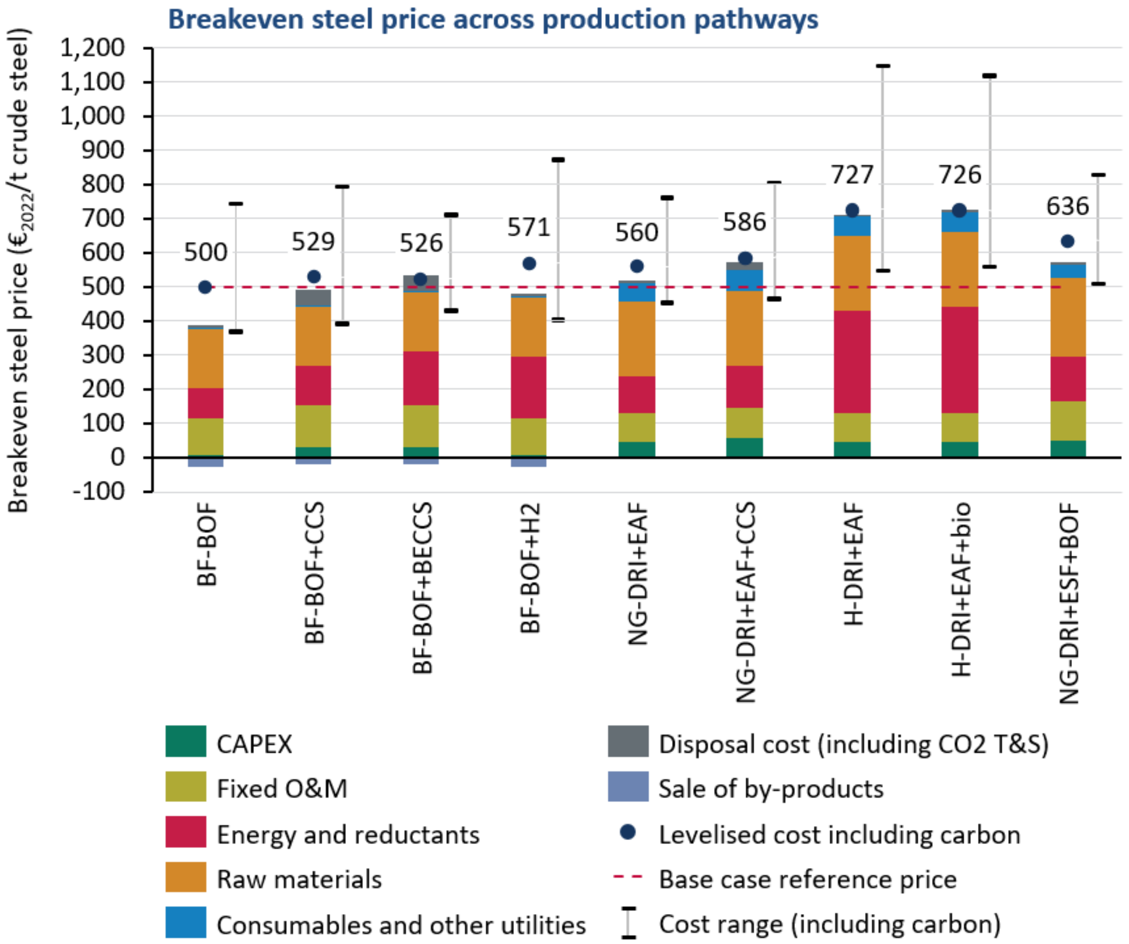

Figure 2. Breakeven steel price across production methods

Sites strategically located to secure affordable raw materials may experience a decline in cost competitiveness if they lack access to cheap energy sources. Simultaneously, the dependence on pathways where energy comprises a significant portion of total production costs exposes steel producers to the potential hazards of price volatility. Although price volatility is a universal concern for all commodities, energy prices tend to exhibit greater fluctuations compared to other commodities.

Direct Reduced Iron (DRI) is a lower-temperature alternative to traditional blast furnace methods, producing iron without the need for carbon-rich coke, instead using hydrogen-based gas mixtures, which potentially could be fully replaced by green hydrogen in the future. The process separates the iron reduction and melting stages; melting is achieved using electric furnaces powered by electricity, possibly from renewable sources, pointing towards the possibility of near-zero emission steel production. Yet, significant challenges persist, including technical complexities and the need to introduce carbon at some stage since steel requires carbon. Moreover, the renewable energy demand for such operations is substantial, with a single DRI plant needing a power supply comparable to a small nuclear station, escalating significantly when including the electric furnace's energy needs. If all blast furnace plants were to be replaced by DRI, it would necessitate approximately 1,000 plants of similar energy requirements. H-DRI could be economically competitive in other regions with a higher potential for low-cost hydrogen and electricity.

Some pathways exhibit relatively low abatement cost but might not be aligned with deep decarbonisation of steel production. A direct comparison of production costs alone offers an incomplete picture, as pathways have different GHG emissions intensities. A comprehensive assessment, comparing steel production costs among various pathways and examining their emissions intensity over a lifecycle perspective was conducted and illustrated in Figure 3:

The three CCS pathways and the NG-DRI+EAF pathway demonstrate a breakeven carbon price below €200/t CO_2, which aligns to the upper limit of carbon price forecasts in Europe through 2050. However, both BF-BOF+CCS and NG-DRI+EAF pathways do not achieve substantial reductions in direct emissions. In the case of the modelled BF-BOF+CCS route, this is explained due to the CO content in the upgraded blast furnace process gas, after CO_2 separation, and due to the additional emissions sources in the integrated site that are not routed to a capture plant. In the case of hydrogen-based routes, the breakeven carbon price surpasses anticipated carbon prices up to 2050. Nevertheless, H-DRI could still emerge as the most cost-competitive pathway for achieving deep decarbonisation, especially when CCS routes are considered impractical.

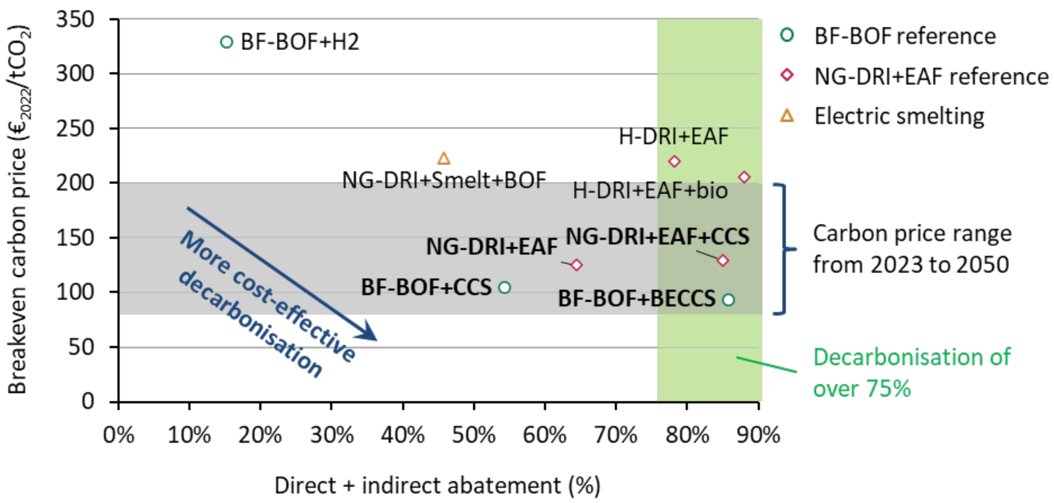

Figure 3: Breakeven carbon price and emissions intensity reduction for different steelmaking routes

Although according to this analysis, H-DRI appears to offer a less cost-effective approach to decarbonisation compared to NG-DRI+EAF+CCS or BF-BOF+BECCS, strategic considerations might favour the former option due to broader policy implications. The persistent dependence on natural gas for NG-DRI+EAF+CCS not only raises concerns about energy security but also underlines the potential indirect influence of peripheral policies, such as those regulating natural gas and biomass. These regulations may indirectly affect the technology merit order, making certain options more viable in the long term. Similarly, the availability of biomass, which is crucial for the BF-BOF+BECCS pathway, could be constrained by external policy factors, thereby impacting its feasibility. Therefore, while H-DRI currently requires ongoing policy backing and support to be financially viable, its attractiveness may increase as other policies evolve. This complex interplay of direct and indirect policy influences must be considered in the strategic planning for sustainable steel production.

Fossil emissions:

The results of the LCA show that transitioning from BF-BOF steelmaking can lead to a reduction in the fossil Global Warming Potential (GWP) impact of the crude steel[3] product, when accounting for embedded CO_2 emissions, such as those originating from upstream raw material processing as presented in Figure 4. However, it is evidenced that alongside dealing with residual direct emissions, decarbonisation of the supply of materials/energy and treatment of wastes will be required to drive down total GWP of crude steel production:

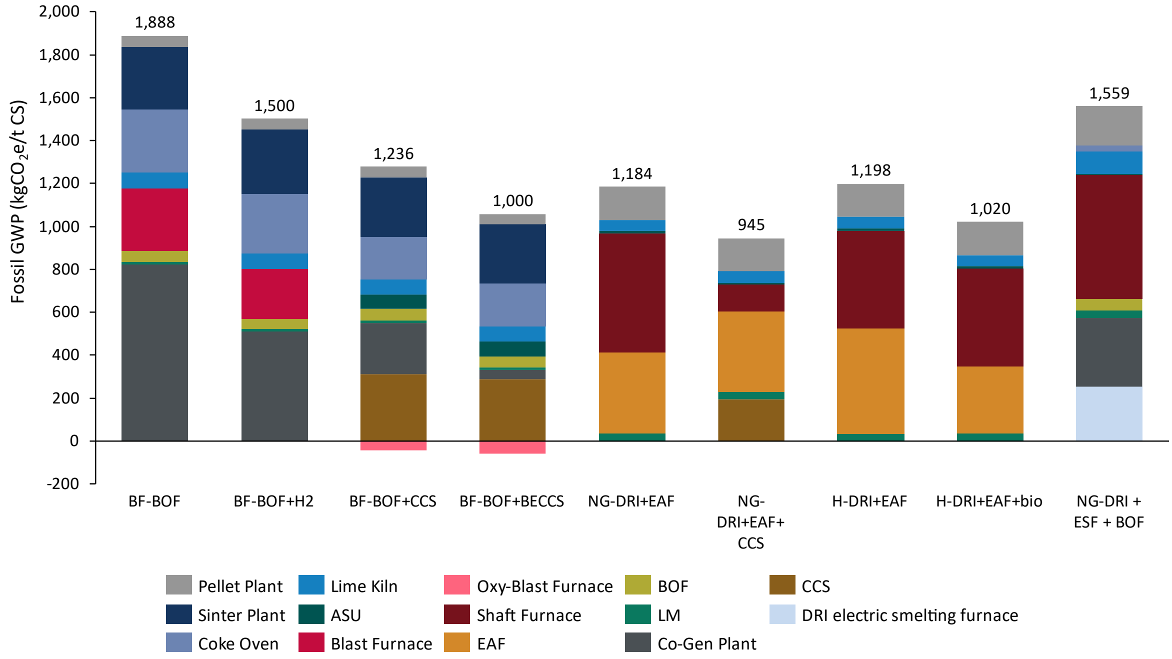

Figure 4. Fossil GWP for the steel decarbonisation pathways

- In the baseline BF-BOF steelmaking pathway, the primary source of fossil Global Warming Potential (GWP) emissions is the co-generation unit. The co-generation unit is responsible for substantial carbon dioxide emissions, largely attributed to the combustion of coal in connection with the input of blast furnace gas (BFG) and basic oxygen furnace gas (BOFG).
- In the BF-BOF with hydrogen injection pathway, the hydrogen (assumed to be renewable or an equivalent net zero source), displaces some of the pulverised coal injection (PCI) as an auxiliary reducing agent and heat source in the blast furnace, which drives the decrease in emissions arising from the blast furnace.
- For the BF-BOF-CCS route, the blast furnace is substituted with an oxy-blast furnace that incorporates top gas recycling (TGR) and chemical absorption capture. The utilisation of TGR leads to a reduced coke consumption, subsequently lowering emissions associated with coke oven operations. Additionally, the capture of process gases contributes to decreased direct CO_2 emissions originating from the oxy-blast furnace.
- By substituting PCI coal with charcoal (BF-BOF+BECCS), fossil GWP sees a reduction of approximately 240 $kgCO_2e$/t CS compared to BF-BOF+CCS. However, there is an increase in biogenic emissions to about 220 $kgCO_2e$/t Crude Steel (CS) due to the release of biogenic CO_2 that remains uncaptured. The biogenic emissions can be captured downstream of a co-generation plant.

[3] Crude steel refers to the first solid steel product upon solidification of liquid steel

- The well-established natural gas-DRI route presents a substantial decrease in fossil GWP compared to the BF-BOF route. Within the NG-DRI process, the primary contributor to fossil GWP is the shaft furnace, primarily due to its high natural gas consumption, exceeding 8,800 MJ/t CS. The transitional pathway, NG-DRI+Smelt (ESF)+BOF, is appealing to steel producers as it enables integrated Basic Oxygen Steelmaking (BOS) facilities to transition a portion of their production to the direct reduction route. Nevertheless, this smelting pathway entails substantial natural gas consumption in the shaft furnace of about 10,300 MJ/t CS.
- More dramatic fossil GWP reductions are achievable when including CCS on NG-DRI, approximately 50% compared to BF-BOF, due to the reduction in direct CO_2 emissions. As with the BOS CCS cases, there are additional emissions associated with an electric boiler required to generate sufficient steam for the CO_2 capture process.
- Transitioning to hydrogen-DRI does not yield the same level of reductions when all the embedded emissions linked to upstream raw materials and waste treatment are accounted for. In fact, considering the fossil GWP, the H-DRI pathway exhibits a higher fossil GWP compared to NG-DRI. This discrepancy is primarily driven by a substantially greater electricity input (six times higher) in the shaft furnace, as opposed to NG-DRI routes, and a higher coal consumption (ten times higher) in the Electric Arc Furnace (EAF). This implies that H-DRI becomes advantageous only when renewable electricity or an equivalent net zero source ~~sources~~ can be integrated into the steelmaking facility.

Price premium for clean steel

The green premium is the additional cost above that of the conventional equivalent, which consumers are willing to pay for clean steel due to its lower GHG footprint (Macnaughton and Poole, 2023). The emergence of this premium implies that the extra costs incurred in producing clean steel could potentially be passed on to customers. However, the extent to which this is feasible, whether green premiums can fully offset the additional production costs, and the timeframe for these premiums to materialise, are questions with no well-defined answers. A green premium for clean steel will likely develop if there is a mismatch in demand and supply leading to a shortage. In the long term, the green premium will likely fade out as supply catches up with demand. There is thus a ‘first mover advantage’ – the first movers will be able to claim large green premia until the market becomes saturated and supply meets demand.

Estimating the evolution of green premia is a complex task. An estimation would require a market assessment of supply and demand for clean steel over time. However, it is possible to estimate an upper boundary for green premia based on the abatement cost customers are willing to pay. Shadow carbon prices can provide insights into the extent of companies' willingness to pay for a green premium.

Steel produced under the conventional integrated route has a GHG footprint of 1.89 t CO_2/t Crude Steel (CS). For steel consumers with a shadow carbon price of €100/t CO_2, this would represent an additional cost of €189/t CS to be considered for procurement decisions. A shadow carbon price would also apply to the low emissions from clean steel. Assuming that clean steel meets the ResponsibleSteel’s Near Zero threshold[4], for a 20% scrap content the emissions intensity would be 0.33 t CO_2/t CS. This would add a cost of €33/t CS for procurement decisions. As a result, conventional steel would have a net shadow carbon price of €156/t CS. Compared to a global hot-rolled coil price of €530/t HRC, calculated from UN Comtrade data, this is equivalent to a green premium of 30%. This means that steel consumers

[4] The ResponsibleSteel standard Near Zero emissions intensity threshold accounts for direct CO_2 emissions and GHG emissions associated with the generation of electricity imported to the site and with imported materials.

with a shadow carbon price of €100/t CO_2 would be willing to pay an added maximum of 30% for clean steel compared to conventional steel. Naturally, this green premium varies with the shadow carbon price as illustrated in Figure 5:

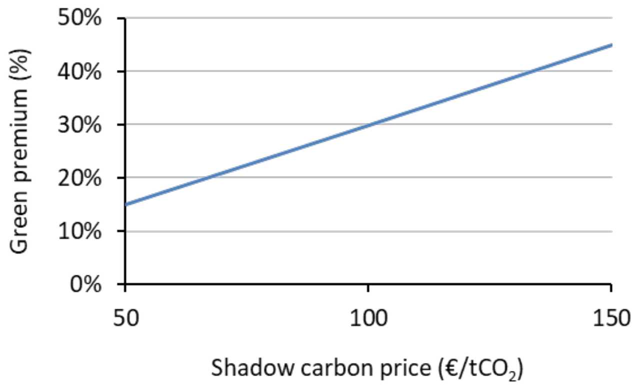

Figure 5. Price premium for clean steel

On its own, a 30% green premium is insufficient to reach cost parity between traditional integrated steelmaking and steelmaking that aligns with ResponsibleSteel's Near Zero threshold.

For H-DRI steel to become cost-competitive, it would necessitate a larger green premium. However, the majority of consumers are unlikely to be willing to pay such an elevated premium. As time progresses, the reduction in production costs for clean steel and the rise in production costs for conventional steel driven by escalating carbon prices will gradually decrease the cost gap. This may result in the green premium being adequate to bridge the remaining disparity.

While green premia can increase the cost of clean steel for customers, their impact on the end-product costs will be minimal (see Figure 6). Because the cost of steel represents only part of the end-product cost, the impact of green premia gets diluted down the value chain. The cost impact on each consumer of clean steel will be dependent on the percentage that steel costs represent in the end-product. For instance, for a car with a market price of €30,000 using 1.5 t of steel at a price of €530/t HRC, the cost of steel represents 2.6% of the market value of the final product. If the 30% green premium is passed on to consumers, the impact on the market price would be a 0.8% increase. The Energy Transitions Commission[5] have detailed similar small scale price increases for end users despite an increase in steel production costs, as illustrated in the figure as follows:

[5] A global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, https://www.energy-transitions.org/

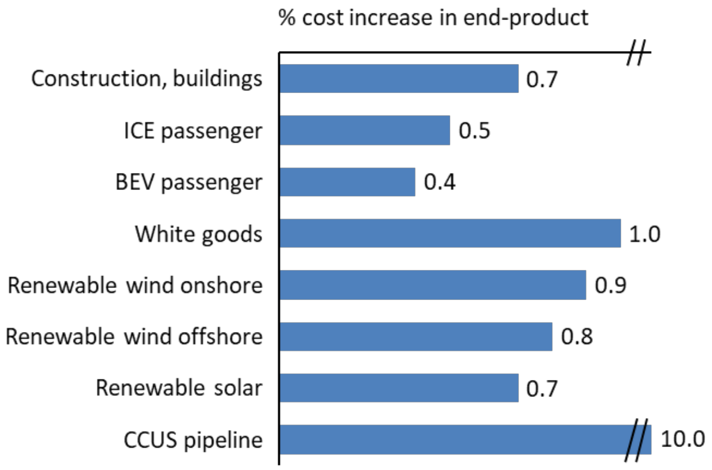

Figure 6. Cost increase in end-product

The actual impact on end-products is important. If steel consuming sectors are able to pass on costs to end consumers, they would not absorb the total cost of green premia. By passing on the green premium costs, some steel consumers may be ready to accept green premia in excess of what their internal carbon price dictates. Passing on green premia may only be possible for sectors with short value chains, where the steel consumer acts as a direct intermediary between the steel producer and the end user. If the value chains of other components of end goods also face higher costs because of their decarbonisation the total cost increase could well exceed the values and end consumers may show a lower willingness to pay.

Expert Review

Nine expert reviewers from across the industry and research organisations took part in the expert review process of this study. The feedback from external reviewers has been overwhelmingly positive regarding the report's quality and technical depth. Many commended its thoroughness and clarity, noting it as both insightful and accessible for non-expert readers. Specific points of improvement were also identified; one reviewer suggested a clarification in the description of 'integrated' steel production, emphasising that both the reduction and steelmaking processes occur at the same site. This suggestion was duly incorporated. Another reviewer sought clarity on what is encompassed by BECCS, particularly questioning if CO_2 removal during the biomass pyrolysis process for charcoal production was accounted for. In this context, BECCS was generically referenced. CCS was not modelled on the biomass pyrolysis, but emissions from this step were factored into the LCA.

Conclusions

A broad spectrum of alternative methods of steel production exist that have the potential to facilitate the decarbonisation of the steel industry. Some technologies that have the potential to achieve the most decarbonisation are presently at low readiness level. As a result, this study primarily emphasises technologies capable of reaching commercial viability by 2030, along with their suitability for integration into established integrated sites.

Among the selected technologies, the study demonstrates that all have the capability to lower emissions, including both direct and embedded emissions, when compared to the base case of unabated BF-BOF methods. Nevertheless, the findings also indicate that achieving completely emissions-free steel production is not feasible. Residual emissions within the steelmaking facility and across the supply chain must be addressed.

In comparison to BF-BOF, all the assessed pathways exhibit elevated production costs, with BF-BOF being the most cost-effective method for steel production. Generally, production costs tend to rise as decarbonisation efforts increase. Nevertheless, maintaining the status quo is not a financially neutral scenario. Effectively addressing and reducing emissions, both operational and embodied, are evolving into integral aspects of business and procurement. Failing to decarbonise in the future may result in a diminishing market share and revenue reduction.

Retrofitting CCS to an integrated BOS mill may entail only a minor incremental cost for steel production. However, without a substantial increase in the utilisation of charcoal, this approach is not compatible to achieving significant GHG emissions reductions necessary for deep decarbonisation. Nevertheless, CCS integrated into a DRI plant may remain an attractive option when contrasted with hydrogen-based methods, primarily because of the additional electricity and hydrogen required in hydrogen-based processes. Hence, pathways that rely heavily on hydrogen and electricity have the potential to attain reduced GHG emissions and decreased reliance on fossil resources. Nevertheless, the achievement of these outcomes greatly relies on the sourcing of low-carbon hydrogen and electricity. The sensitivity analysis indicated that over the long run, H-DRI+EAF with bioenergy has the potential to achieve the lowest fossil GWP as the electricity grid decarbonises. As we look ahead, the cost disparity will diminish as effective carbon pricing rises and energy cost (electricity and hydrogen) decrease, thus rendering H-DRI pathways progressively more attractive.

The availability of supporting infrastructure is synonymous with the transition to clean steel technologies. This study highlights the crucial role that infrastructure must fulfil for the successful implementation of alternative steel technologies.

- The current capacity of CO_2 storage projects under development in Europe would be enough to accommodate 24 years' worth of CO_2 storage if all steel mills in the EU switched to CCS-based pathways, provided that this storage is exclusively allocated to the iron and steel sector, which of course it cannot be.
- The steelmaking industry's hydrogen requirements within the EU may potentially consume up to 50% of the available hydrogen supply for emerging applications. This sector faces competition from other industries such as transportation and chemicals for access to hydrogen resources.
- Compared to traditional unabated integrated steel mills, all alternative steel technologies require greater amounts of electricity. To facilitate this transition, additional renewable energy generation capacity and grid enhancements will be necessary. If all steel mills were to adopt H-DRI-based pathways, they could potentially account for 30% of the anticipated increase in renewable generation capacity in the EU by 2030.
- Pairing bioenergy with H-DRI has the potential to achieve the most substantial decrease in fossil emissions. Replacing PCI coal with charcoal in all EU steel mills would necessitate 17 Mtpa of charcoal. Although this falls within the estimated capacity of forestry-based biomass, actual availability could be considerably lower due to factors like limited accessibility, underdeveloped supply chains, and competition from other uses.

The approach for steelmaking facilities to shift towards cleaner methods can differ significantly based on geographical location, even within Europe. In Northern Europe (the primary focus of this study), adopting CCS technologies may be more favourable, given the proximity of developing CO_2 storage projects. Conversely, sites in Central or Southern Europe might find transitioning to hydrogen-based pathways more appealing, due to the presence of established hydrogen pipelines. Nonetheless, in the absence of measures such as purchase price agreements (PPAs) and until there is widespread production of renewable or an equivalent net zero or low emissions source hydrogen, the siting of H-DRI projects will probably be determined by steel mills near the vicinity of evolving hydrogen projects. This is fundamentally influenced by the accessibility of affordable renewable electricity and techno-economic advances that will ensure its safe use. As a result, existing H-DRI projects are currently under development in Northern Europe.

The analysis has shown that green premia for steel taken alone might have a low impact on the final product cost all other things being equal (e.g., less than 1% impact for a car). However, if the value chains of other components of end goods also face higher costs because of their decarbonisation the total cost increase in the price of a car, for example, could well exceed the value of any green premia and end consumers may show a lower willingness to pay.

Recommendations

In light of these findings, it is recommended that future work focuses on 4 areas:

1. Expanding the scope of the analysis: Numerous technologies, including emerging options like electrolytic reduction or alternative CCS configurations, were omitted from the study. A more comprehensive evaluation, incorporating the application of learning rates to emerging technologies, can provide a more holistic view of future costs and their associated impacts. Furthermore, the LCA could be broadened to encompass additional environmental and social impact aspects. This expansion may unveil unforeseen environmental hot spots within the pathways. Further analysis of decarbonisation possibilities for both upstream mining and downstream processing of raw steel, areas not covered in this study, may also contribute to the identification of strategies for reducing embedded emissions and costs. Considering the substantial potential for biomass utilisation that has been identified, it is essential to conduct a comprehensive assessment of the actual availability of biomass for steel production and to examine the potential effects its use might have on process parameters.
2. Decoupling steel and iron production and its societal consequences: This study has shown that elevated energy expenses in Europe could have adverse effects on the cost dynamics for steel manufacturers transitioning to H-DRI pathways. Steel manufacturers might have the opportunity to reduce production expenses by importing HBI for use in electric arc furnaces. To pinpoint regions where transitioning to H-DRI offers a competitive advantage, it is imperative to broaden the analysis to include other geographical areas and consider broader geopolitical factors that might influence the adoption of these technologies globally. It is equally important to evaluate the potential consequences of separating steel and iron production in relation to both direct and indirect employment and the added value in various regions, particularly at the local level, and how this might influence the concept of a just transition.
3. Exploring commercial agreements and business strategies: Ensuring access to affordable and environmentally friendly sources of electricity and hydrogen, as well as the ability to command a green premium, are essential factors for steel producers embarking on the journey toward cleaner steel production methods. Examining the commercial agreements and business models that could support various pathways is essential. For example, future research can explore whether steel producers can secure access to more cost-effective electricity and hydrogen through involvement in demand-side response measures. To comprehensively grasp the influence of steel producers and customers in negotiating the green premium, further insight is required. This understanding will help assess the extent to which costs can be transferred to end-users.

4. Evaluating barriers and facilitators in the transition: The supporting infrastructure is pivotal in enabling the adoption of steel decarbonisation technologies. Furthermore, it is likely that additional policy backing will be necessary to facilitate the transition process. A better understanding of the impediments and catalysts associated with various technology pathways is essential, as this study has predominantly concentrated on economic and environmental indicators, providing only a partial perspective. It's also essential to investigate the pros and cons of various policy mechanisms designed to promote the implementation of decarbonisation technologies. This includes evaluating the potential impact of the Carbon Border Adjustment Mechanism (CBAM) on European steel production.

Clean Steel: an Environmental and Technoeconomic Outlook of a Disruptive Technology

Final Report

PREPARED FOR

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January 2024

Authors

This report was prepared by Element Energy and E4tech, who in June 2021 both joined the ERM Group, the largest sustainability consultancy, with a global footprint and over 7,000 employees worldwide.

We specialise in the intelligent analysis of low carbon energy, industrial decarbonisation, and low-carbon fuels. We provide consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport/fuels. In addition, we focus on both technical and strategic issues, and offer bespoke business and policy advice based on deep technical understanding, insightful analysis and industry knowledge.

Study Authors:

Silvian Baltac	Partner
Sébastien Haye	Principal Consultant
Anisha Harris	Managing Consultant
Ignacio Rabsiun Aramburu	Managing Consultant
Yamini Panchaksharam	Senior Consultant
Tom Butler	Consultant

Supporting Authors: Jacob Jones, Charlie Readman.

For comments or queries please contact: ccusindustry@erm.com

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The IEAGHG manager for this report was: Abdul'Aziz A. Aliyu

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Executive Summary

This study presents a comparative analysis of steelmaking pathways to cost-effectively decarbonise a steel mill, taking a life-cycle perspective on associated environmental impacts

Steel is an essential component of our modern global economy and steel is one of the most widely used industrial products across the planet. Production levels are set to keep rising by 2050 due to continued economic expansion and urbanisation, despite a saturation of the stock of steel in advanced economies. Although a vital material in modern society, steel manufacturing is one of the largest sources of carbon emissions globally, responsible for about **7% of total energy-related CO_2 emissions**. The high carbon-intensity of iron and steel production is partly explained by its large dependence on coal and coke as fuels and reducing agents. In integrated steelmaking facilities, there are several highly complex and highly energy intensive industrial processes which are the source of direct emissions. Additional embedded emissions arise in other parts of the iron and steel supply chains and product life cycle, including mining, transporting raw materials and finished products, and providing energy and electricity used in the different manufacturing steps.

In light of the growing importance and urgency to decarbonise the steel industry, IEAGHG commissioned this study to investigate the environmental and technoeconomic outlook of a broad range of potentially disruptive technologies for decarbonising steelmaking. Multiple technology options for steelmaking decarbonisation are emerging (including multiple CCS configurations, smelting reduction, and hydrogen-based direct reduction of iron), each with unique cost and environmental profiles and differing impacts and requirements on the wider system. The study provides a **comparative analysis** of these different steelmaking pathways, focusing on the applicability and suitability of the routes in Northwestern Europe. Therefore, key objectives of this study are:

- **to deliver a combined techno-economic and lifecycle assessment of a range of decarbonisation pathways for steelmaking**.
- to identify pathways for decarbonising steelmaking that are **both cost-effective and able to tackle all the main sources of emissions form a life-cycle perspective**.
- **to understand the primary energy and infrastructure implications** associated with large-scale deployment of the different decarbonisation pathways.

  to **estimate what price premium could be claimed** by clean steel on existing and future markets.

We have assessed nine primary steel production pathways – these cover both current and emerging pathways to decarbonise steel production

Steel can be produced from two main metallic inputs: iron ore and steel scrap. Primary steel production uses iron ore as its main metallic input whereas secondary steel production utilises a predominantly scrap-based input. The primary production route is the dominating route, with over 77% of global steel production following this process. Secondary production is around one-eighth as energy-intensive as primary production and uses electricity as the main energy input. Increasing the share of scrap-based production can bring down the global steel sector's emissions; however, this is limited by scrap availability. **Sectoral innovations are centred on decarbonising primary steel production, which is the focus of this report**. Primary steel production includes **basic oxygen steelmaking** (BOS) and the **direct reduced iron-electric arc furnace route** (DRI-EAF). Basic oxygen steelmaking, the combination of producing iron in a blast furnace (BF) and feeding this to a basic oxygen furnace (BOF), is the most common and carbon-intensive steelmaking pathway, taking place in integrated steel mills. BOS uses coal as its main energy input and represents virtually all primary steel production in Europe. DRI-EAF combines iron production in a shaft furnace and steel production in an electric arc furnace and is far less common than basic oxygen steelmaking. Currently, shaft furnaces use natural gas as their main energy input.

Disruptive measures and new steelmaking processes will be required for deep decarbonisation. While energy efficiency improvements or higher scrap use in basic oxygen steelmaking can reduce emissions, this alone will not lead to the deep reduction in emissions needed to meet climate goals. The distinct categories of technologies that could deeply reduce emissions from primary steel **are carbon capture and storage (CCS), the alternative reduction of iron ore, the use of sustainably sourced biomass-based feedstocks, or a combination of these.** Transition towards hydrogen-based direct reduction (H-DRI) is quickly gathering pace in Europe, with multiple announcements of new plants. Other steel producers, particularly outside Europe, are considering retrofitting their integrated steel mills with CCS technologies to enable the continued use of existing equipment.

Nine pathways are included in the detailed techno-economic and lifecycle assessment out of a long list of primary steel production pathways. Out of the many pathways to produce steel, those at low technical maturity are not included within the analysis but are mentioned in the Main Report. Included pathways were selected based on their technical maturity, potential to achieve commercial deployment by 2030, their applicability for European integrated sites, and their uniqueness. For ease of identification when presenting results, a reference name is assigned to each pathway.

Technology pathways included in assessment[1]

Base case	Technology pathway	Reference name	TRL[2]
BF-BOF	BF-BOF	BF-BOF	-
	BF with TGR-BOF + CCS	BF-BOF+CCS	6
	BF w/TGR-BOF + BECCS	BF-BOF+BECCS	6
	BF-BOF with hydrogen injection in blast furnace	BF-BOF+H_2	7
NG-DRI + EAF	NG-DRI + EAF	NG-DRI+EAF	-
	NG-DRI + EAF + CCS	NG-DRI+EAF+CCS	8-9
	H-DRI + EAF	H-DRI+EAF	6-7
	H-DRI + EAF with bioenergy	H-DRI+EAF+bio	6
	NG-DRI + Electric smelting + BOF	NG-DRI+Smelt+BOF	8

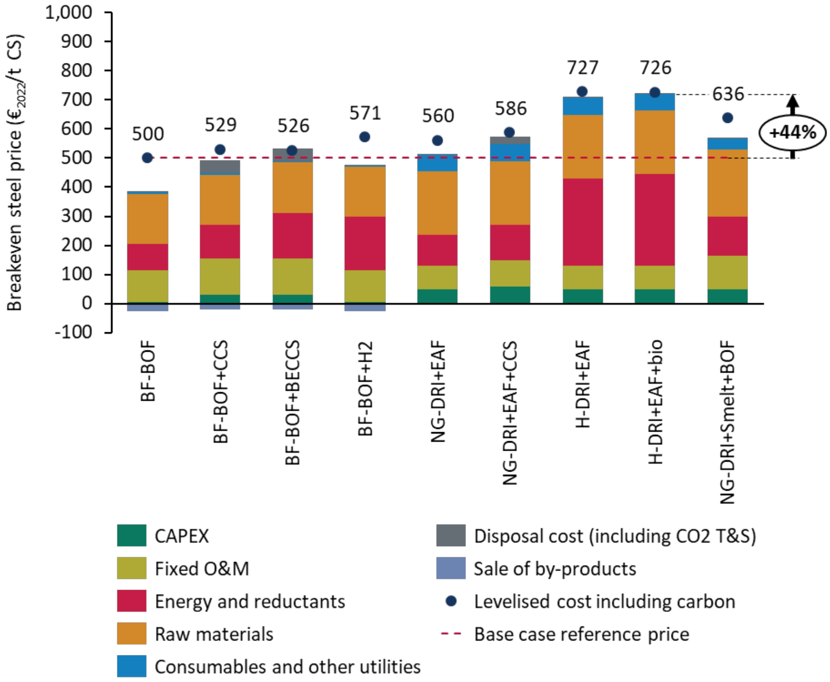
Incumbent basic oxygen steelmaking is more economical than clean steel pathways

The techno-economic assessment estimates the production cost of a tonne of crude steel for an **integrated steel mill nearing the end of a blast furnace campaign**, and hence facing an investment decision: relining the blast furnace and continuing operations, potentially including some modifications, or switching to an alternative pathway. Key performance indicators are obtained from a cash flow that combines performance data and costs.

Results show that unabated basic oxygen steelmaking results in the lowest levelised cost of production across all pathways, even after accounting for carbon pricing. Nonetheless, doing nothing is not a cost-neutral scenario. Managing and eliminating emissions is becoming a core part of business and procurement, and not decarbonising will in the future lead to loss of market share and revenue reduction. Pathways involving CCS imply a relatively modest production cost increase compared to the base case. Hydrogen-based direct reduction pathways, which assume the use of renewable electrolytic hydrogen, have the highest breakeven prices. **The results expose that current carbon pricing, combined with the free allocation of emission allowances, is not a sufficient incentive towards**

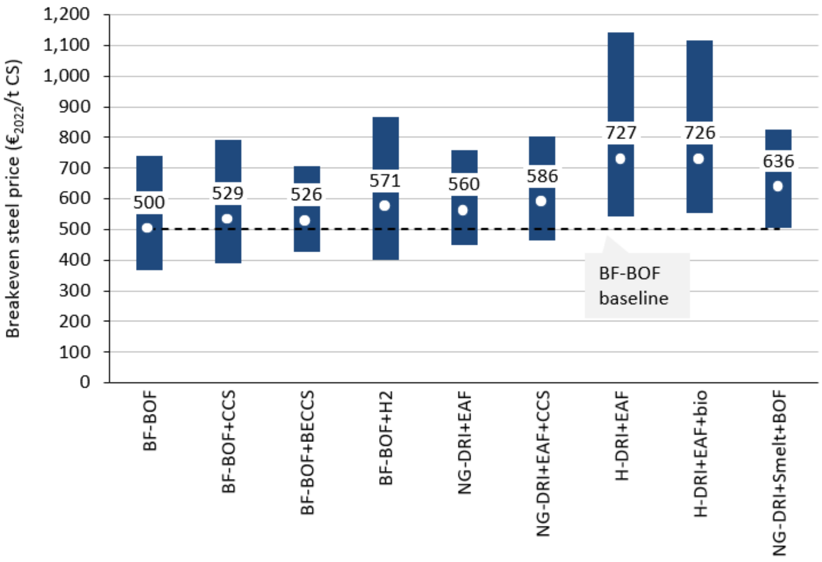
[1] TGR: top gas recycling; BECCS: bioenergy with CCS.
[2] TRL: technology readiness level, a scale from 1 to 9 used to measure technology maturity.

pathways with a lower GHG emissions intensity. While some pathways, such as BF-BOF+CCS or BF-BOF+BECCS, are close to reaching cost parity with conventional integrated steelmaking and would require little additional support, stronger policy support would be required for H-DRI pathways to reach cost parity. CAPEX represents a relatively small portion of the levelised costs. **Government funding or capital grants could unlock access to capital for a sector that has typically struggled to raise private capital, but it does not address the much larger operating costs expected under the H-DRI pathways.**



Breakeven steel price across production pathways

Results were tested upon varying the main cost input parameters, including energy costs, effective carbon prices, and the CO_2 transport and storage cost. The analysis reflects that under certain combinations low-carbon pathways could be cost-competitive with unabated basic oxygen steelmaking. For the range of cost inputs, **all pathways could potentially achieve lower levelised production costs compared to the BF-BOF baseline cost, except the H-DRI pathways**.

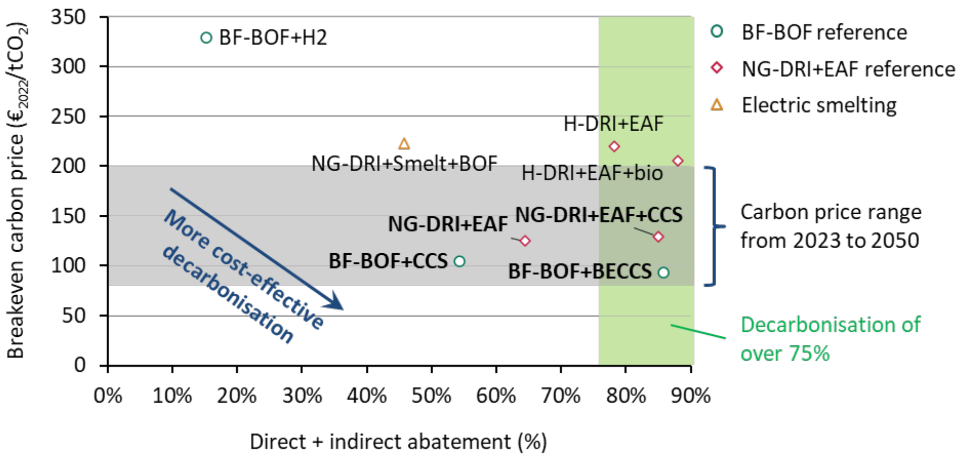


Ranges for production costs upon varying unit cost inputs

Some pathways present relatively low abatement cost but may not be compatible with deep decarbonisation of steel production

For some routes, the breakeven effective carbon price is within the range of future carbon price projections.[3] The three CCS pathways and natural gas-based DRI-EAF have a breakeven carbon price lower than €200/t CO_2. However, the modelled BF-BOF+CCS and NG-DRI+EAF do not deliver deep direct and indirect emissions reductions. For hydrogen routes, the breakeven carbon price is higher than expected carbon prices up to 2050. H-DRI could still be the most cost-competitive pathway delivering deep decarbonisation when CCS routes are deemed not to be feasible. Injection of hydrogen in a blast furnace is the least cost-effective pathway for GHG emissions reduction.

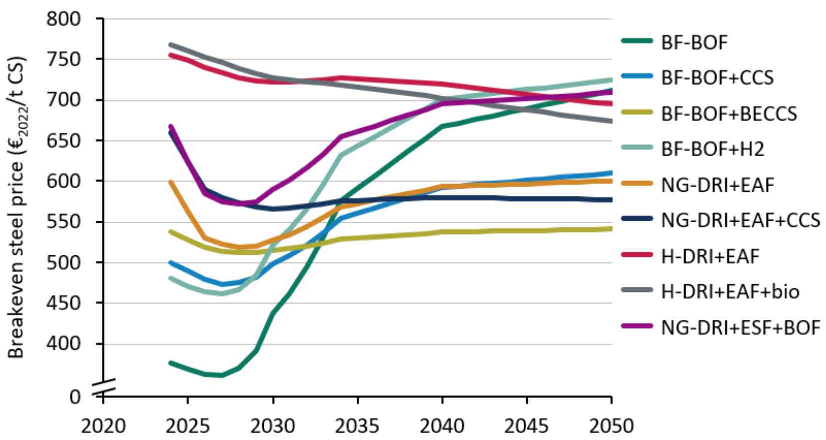
[3] The effective carbon price only applies to direct CO_2 emissions.



Breakeven carbon price and emissions intensity reduction for different steelmaking routes

The production cost gap closes over time and by 2050 unabated basic oxygen steelmaking is one of the most expensive steel production pathways

The gap between the breakeven steel price for unabated basic oxygen steelmaking and other routes closes as carbon costs increase and energy prices decrease. The levelised production costs of steel presented above do not reflect how the breakeven steel prices will vary together with variations in raw materials, energy and carbon costs over time. As those costs change over time, the production cost of a tonne of crude steel will evolve differently for each pathway. In the medium term, the phasing out of free allowances increases the breakeven price as sites have to pay for an increasing share of their emissions. The H-DRI routes see a gradual long-term decline as hydrogen price decreases over time. By 2050, the BF-BOF+BECCS and the NG-DRI+EAF+CCS pathways present the lowest breakeven price. By then, only the BF-BOF+H2 pathway results in a higher breakeven price for steel than the base case BF-BOF pathway.



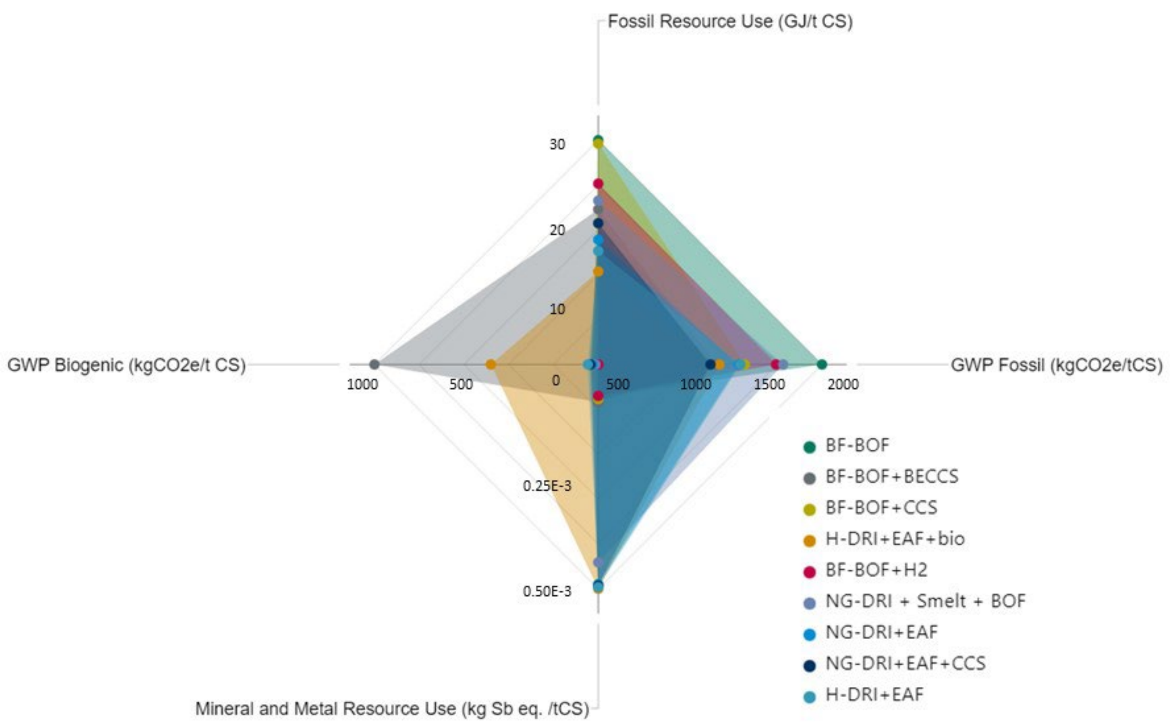
Breakeven price for steel for different steel production pathways over time

Transitioning to direct reduction pathways and incorporation of CCS can lead to lower environmental impacts across fossil GWP and fossil resource use when expanding analysis to include embedded emissions along the supply chain

Considering only direct emissions and the indirect emissions associated with hydrogen and electricity is not sufficient to evaluate pathways to a true net zero. The life cycle assessment, which has been conducted in line with the ISO 14040 series[4] and World Steel's Life Cycle Inventory, analyses and compares the environmental impacts of the different steelmaking pathways. In the LCA, all indirect emissions associated with material and energy inputs to the system and treatment of waste products have been included (termed embodied emissions). Infrastructure impacts are not included.

The LCA results show that transitioning from BF-BOF steelmaking to alternative steelmaking pathways can reduce the environmental impacts of crude steel when considering fossil GWP. However, the impact of embodied emissions means that the reduction is not as drastic as when only considering the direct emissions (and indirect emission for electricity and hydrogen) shown in the techno-economic assessment. Pathways relying on bioenergy naturally see a much greater impact when considering biogenic GWP, while results are more divided when considering mineral and metal use.

While all pathways show a reduction in fossil GWP impact, it is evidenced that alongside dealing with residual direct emissions, decarbonisation of the supply of materials/energy and treatment of wastes will be required to drive down total GWP of crude steel production. Retrofitting BF-BOF with BECCS has the most potential to reduce the fossil GWP of basic oxygen steelmaking, though this in turn is balanced by an increase in biogenic GWP. Switching to direct reduction pathways can achieve similar or greater reduction in fossil GWP, with NG-DRI + CCS and H-DRI with bioenergy capable of achieving the deepest levels of reduction. Embodied emissions associated with the supply of materials and energy limit the reduction potential, in particular the supply of grid electricity, coal and refractory lining in electric arc furnaces. For the results shown below, it was assumed renewable electrolytic hydrogen was supplied for any routes consuming hydrogen.



Environmental impacts of steelmaking pathways

Direct reduction pathways offer more substantial reductions in fossil resource use compared to basic oxygen steelmaking, as these pathways do not rely on the use of a coke oven: this is further

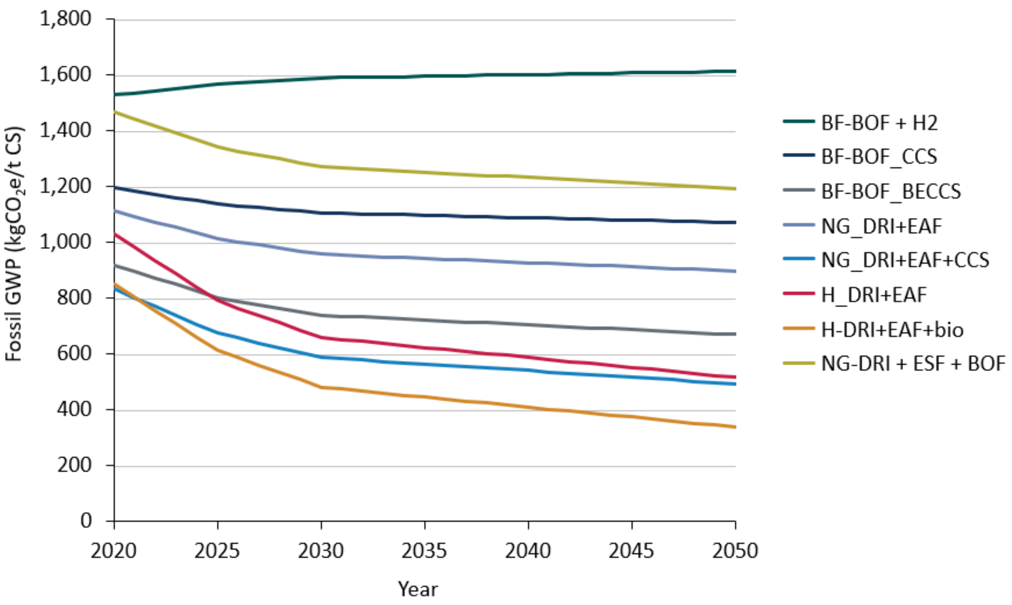
[4] Note, a critical review by a third party has not been performed, deviating from the framework.

emphasised in the H-DRI routes owing to the use of renewable electricity in hydrogen production, reducing the embedded fossil use in the shaft furnace. H-DRI and replacement of PCI with biomass-derived charcoal offers the most dramatic reduction, assuming availability of the latter. In the BF-BOF pathways, coal is assumed to be sourced from Australia; sourcing of coal from within Europe could drive down the fossil resource impact by as much as 55%.

There is limited difference in mineral resource impact across all BF-BOF pathways and the NG-DRI smelting furnace pathway**.** The sinter plant is the largest contributor to metals and minerals resource impact in the BF-BOF pathways due to the large input of sinter feed (similar to iron ore concentrate) and limestone. The impact of refractory lining in electric arc furnaces (and its disposal) drive the five times higher impact seen across the DRI routes.

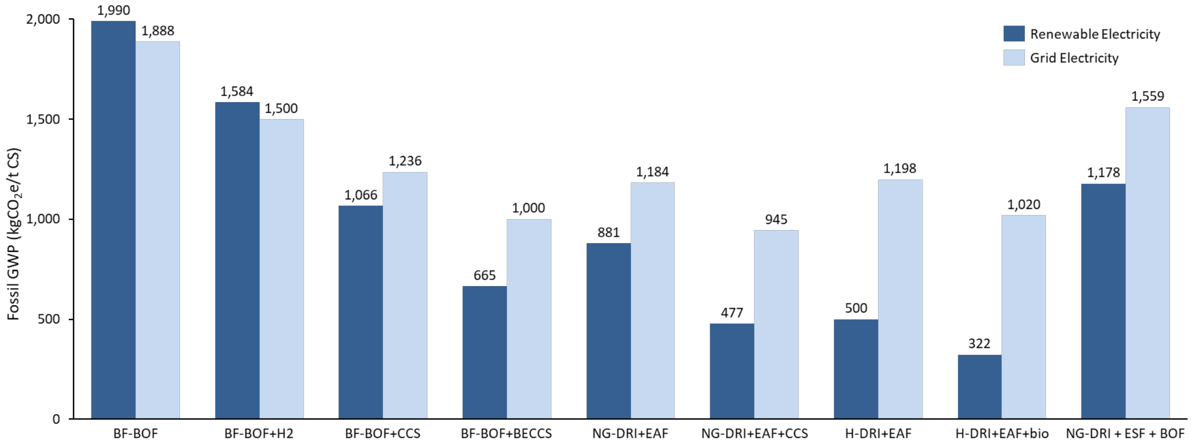
Lifecycle fossil GWP impacts of crude steel can be significantly lower if using onsite renewable electricity, which could be secured through Power Purchase Agreements

To 2050, the DRI pathways, which are more reliant on electricity, benefit from grid decarbonisation to a greater extent than those which do not. **A dramatic reduction in fossil GWP for the DRI routes is projected between now and 2050**. On the contrary, the life-cycle emissions of the BF-BOF routes do not significantly decrease over time with grid decarbonisation. **Overall, renewable electricity procured via PPAs can help reduce fossil GWP associated with all steelmaking pathways, with higher reduction for the DRI routes.**



Emissions intensity of production pathways over lifetime based on grid decarbonisation

When considering use of renewable electricity within the steel mill and at the pellet plant, as well as for the production of hydrogen, **H-DRI with bioenergy could deliver significant reductions in fossil GWP compared to basic oxygen steelmaking, over 80% reduction.** NG-DRI with CCS also shows strong potential for high levels of reduction. The complexity in procuring and securing sufficient renewable electricity that is deemed to be “additional” in the EU is likely to be a challenge the steel sector face. Renewable electricity could be secured through onsite generation or through PPAs; the latter would reduce geographical constraints and could therefore be critical to the decarbonisation of Europe’s steel industry.



Impact of using renewable electricity compared to grid electricity onsite (for steel mill and pellet plant)

Decarbonisation of the steel sector cannot be achieved without the role of significant supporting infrastructure: today it proves a critical bottleneck

The development of supporting infrastructure is critical to enable the transition to alternative low-carbon steelmaking pathways. Transitioning to alternative low-carbon steelmaking pathways can present significant infrastructure and supply chain challenges because infrastructure and supply chains have evolved around mass and energy flows resulting from integrated steel mills. Infrastructure support and new supply chains will need to play a vital role for the successful roll out of alternative steel technologies:

- **Access to CO_2 transport and storage infrastructure can greatly challenge the role that CCS can play for most of the EU-27 integrated steel mills**, as 19 out of 29 integrated steel mills in EU-27 countries are more than 300 km away from an announced CCS project. Moreover, the capacity of existing CO_2 storage projects developing in Europe today would be sufficient to account for 24 years of CO_2 storage capacity, if all steel mills in the EU transitioned to CCS-based pathways – assuming storage is dedicated to the iron and steel sector.
- **Hydrogen demand for steelmaking in the EU could claim up to 50% of the growth in hydrogen supply under the REPowerEU plan**, facing competition from other sectors including transport and chemicals. Proximity to transmission pipelines could reduce the hydrogen distribution cost component and improve the feasibility for using hydrogen.
- **Additional primary electricity demand for steel production could represent an increase of 37% of European industrial electricity use**. Moreover, 30% of the planned increase in renewable generation in the EU by 2030 could be claimed by primary steel production, if all steel mills were to transition to H-DRI based pathways. Additional renewable generation capacity and grid reinforcements will be needed to support the transition.
- **While there is potentially surplus sustainable biomass available for charcoal, the commercial use of biomass will require the establishment of supply chains**. True sustainable biomass availability may be significantly less due to accessibility, immature supply chains and competing uses. Supply chains for biomass, especially residues, are fairly immature, therefore significant biomass supply infrastructure is needed to tap into the full sustainable potential.
- **A shortfall in DR-grade pellet supply could become a bottleneck in the transition towards DRI-based pathways**. Demand for DR-grade pellets in Europe could grow to a volume three times as large as the global DR-grade seaborne market. As announced DR projects enter

production in the late 2020s and early 2030s there could be a significant shortfall in pellet supply.

The emergence of a green premium for clean steel can allow producers to pass on part of their increase in production costs – but this is likely to be insufficient to fully cover the cost differential

The emergence of a green premium on clean steel means that additional costs incurred producing clean steel could be passed on to customers, but the extent to which this may happen, whether green premia can fully cover the additional production cost, and the time span over which green premia will materialise are questions that do not have well defined answers. A green premium is the additional price above that paid for the equivalent conventional substitute that a consumer will pay because of the lower GHG footprint associated with clean steel. A potential green premium on steel will depend on the additional value customers attach to the reduced GHG footprint of clean steel and on the balance between supply and demand. Hence, green premia will have a temporary effect: as the supply of clean steel increases the premium over conventional steel will level off, and this represents a first mover advantage. Not all demand sectors are equally positioned to drive the offtake of clean steel. Sectors that purchase high volumes of steel, that face higher pressure to decarbonise, and that operate in concentrated markets purchasing directly from steel producers, such as the automotive sector, are better positioned to lead the way.

It is possible to estimate an upper boundary for green premia based on the abatement cost customers are willing to pay. Shadow carbon pricing acts as an indicator of the additional value customers attach to the reduced GHG footprint of clean steel. Thus, the shadow carbon price a steel consumer has adopted corresponds to the upper bound of the marginal abatement cost it will be willing to face to decarbonise its value chain. Our analysis shows that **steel consumers with a shadow carbon price of €100/tCO_2 would be willing to pay a maximum of 30% premium for clean steel compared to conventional steel**; this would increase to 45% for a shadow carbon price of €150/tCO_2. By itself, a green premium of 30% is not enough to achieve cost parity between conventional basic oxygen steelmaking and clean steel. Before the cost gap closes, additional support for either producers or consumers will be necessary to support uptake of clean steel. Alternatively, consumers may be able to pass costs on to end users and thus accept a higher green premium, in excess of what their internal carbon price dictates.

Based on the conclusions of the study, further work is required to explore additional areas

We recommend that future work focuses on four areas:

- **Extending the analysis**: further assessment that includes additional production pathways, such as electrolytic steelmaking, the application of learning rates to emerging technologies, coverage of additional environmental and social impact categories, or upstream and downstream decarbonisation options, can offer a more complete picture of future costs and associated impacts.
- **Steel and iron decoupling and its societal impacts**: this study has identified that high energy costs in Europe may adversely affect the cost structure for steel producers transitioning towards H-DRI pathways. Steel producers could potentially lower production costs by importing hot briquetted iron (HBI) to charge it into an electric arc furnace. Extending the analysis to other regions, bringing in wider geopolitical factors which may influence the roll out of technologies across the globe, is required to identify regions where transitioning to H-DRI presents a competitive advantage.

- **Exploring commercial arrangements and business models**: securing access to low-price and low-carbon electricity and hydrogen and being able to claim a green premium are vital for steel producers transitioning towards clean steel pathways. Future studies should explore the commercial arrangements and business models that could underpin the different pathways. A more complete understanding of the bargaining power of steel producers and customers in determining the green premium is also needed.
- **Assessing barriers and enablers in the transition**: a fuller understanding of barriers and enablers for different technology pathways is required, as this study has mainly focused on economic and environmental metrics that offer a partial picture only. Exploring the advantages and disadvantages of different policy mechanisms to drive the deployment of decarbonisation technologies is also needed.

Contents

Acronyms

ASU	Air Separation Unit
BAT	Best Available Technique
BECCS	Bioenergy with Carbon Capture and Storage
BF	Blast Furnace
BFG	Blast Furnace Gas
BOF	Basic Oxygen Furnace
BOFG	Basic Oxygen Furnace Gas
BOS	Basic Oxygen Steelmaking
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
COG	Coke Oven Gas
CS	Crude Steel
DR	Direct Reduction
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
ESF	Electric Smelting Furnace
EU ETS	European Union Emissions Trading Scheme
GHG	Greenhouse Gas
GWP	Global Warming Potential
HBI	Hot Briquetted Iron
HM	Hot Metal
HRC	Hot Rolled Coil
IEA	International Energy Agency
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCOA	Levelised Cost Of Abatement
LS	Liquid Steel
OEM	Original Equipment Manufacturer
OPEX	Operation Expenditure
PCI	Pulverized Coal Injection
PEM	Polymer Electrolyte Membrane
PM	Particulate Matter
TEA	Techno-Economic Assessment
TGR	Top Gas Recycle
TRL	Technology Readiness Level

1 Introduction

1.1 Study context

Steel is one of the essential components of our modern global economy, being one of the most widely used industrial products across the planet. Steel forms visible and invisible critical components of today's world, from infrastructure and transport to industrial equipment and packaging. Steel production has more than doubled in the 21st century and nearly 2 billion tonnes of crude steel were produced in 2020. Production of crude steel is set to keep rising by 2050 due to continued economic expansion and urbanisation, despite a saturation of the stock of steel in advanced economies.

While steel production is global (see Figure 1), over 50% of steel is currently produced in China and nine of the top ten producers are based in Asia. Nonetheless, Europe is the second largest steel producing region and is driving innovation and decarbonisation of the industry: in 2021 the European steel sector had a turnover of around €125 billon and directly employed 308,00 high-skilled people, with many more high-value jobs created indirectly (EUROFER, 2022).

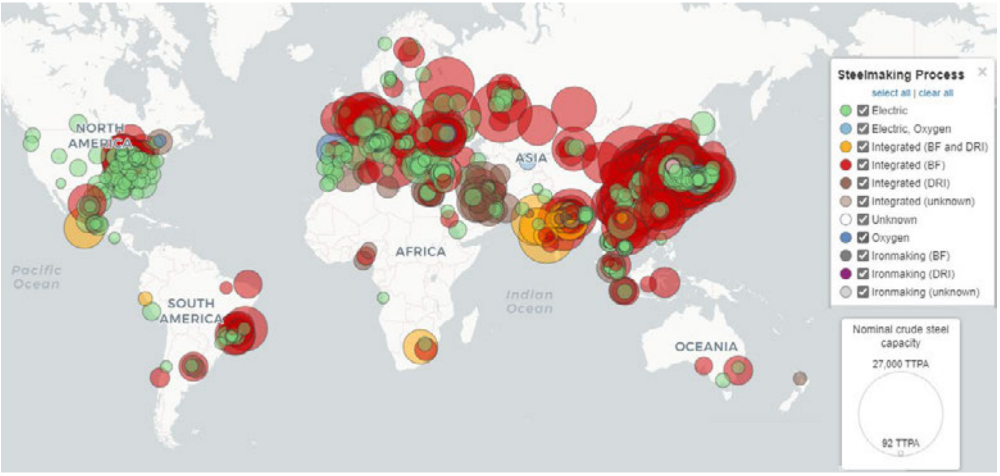


Figure 1: Global iron and steel plants from the Global Energy Monitor dataset (Global Energy Monitor, 2023)

Although a vital material in modern society, steel manufacturing is one of the largest sources of carbon emissions globally, responsible for 2.6 $GtCO_2$ of direct CO_2 emissions in 2019, or about 7**% of total energy-related CO_2 emissions** (IEA, 2020)**.** The high carbon-intensity of iron and steel production is partly explained by its large dependence on coal and coke as fuels, reducing agents, structural support for blast furnace burdenand as a source of carbon. Steel manufacturing is also highly energy intensive, accounting for 20% of industrial final energy consumption and around 8% of total final energy consumption (IEA, 2020).

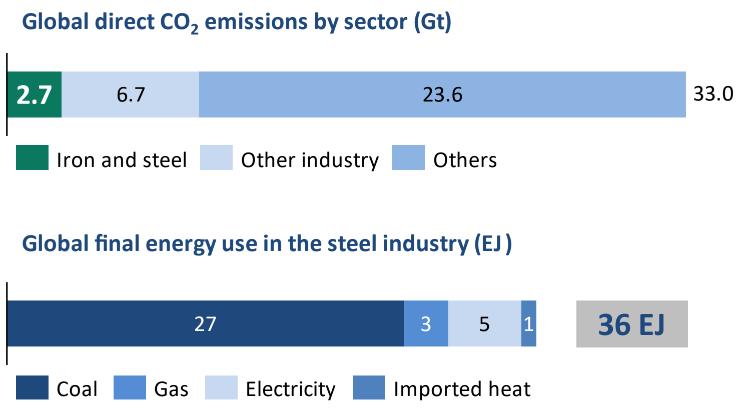


Figure 2: Global direct CO_2 emissions by sector (IEA, 2022b) and global final energy use in the steel industry (IEA, 2020)

In integrated steelmaking facilities, there are a number of highly complex and highly energy intensive industrial processes which are the source of direct emission (Scope 1), such as:

- Iron ore preparation plant (e.g., sintering)
- Blast furnace operation
- Coke oven operation
- Primary steelmaking process (i.e., basic oxygen furnace)
- Reheating furnaces
- CHP or power plants (which often combust steelmaking off-gases) or dependence on grid electricity and natural gas for power (Scope 2 or Scope 1 respectively)

These process steps are explained in detail in Section 2.1.1.

What is more, additional embedded emissions (i.e., Scope 3 emissions) arise in other parts of the iron and steel supply chains and product life cycle, including mining, transporting raw materials and finished products, and providing energy and electricity used in the different manufacturing steps.

1.2 Project scope and methodology

In light of the growing importance and urgency to decarbonise the steel industry, IEAGHG commissioned this study to investigate the environmental and technoeconomic outlook of a broad range of potentially disruptive technologies for decarbonising steelmaking. The study builds on the findings of previous IEAGHG studies in this sector, notably the 2013 Iron and steel CCS study (IEAGHG, 2013) and the 2018 Cost of CO_2 capture in the industrial sector report (IEAGHG, 2018), and explores retrofit opportunities as well as emerging decarbonisation technologies.

The **primary objective of this study is to deliver a combined techno-economic and lifecycle assessment of a range of decarbonisation pathways for steelmaking**. Multiple technology options for steelmaking decarbonisation are emerging (including multiple CCS configurations, smelting reduction, and hydrogen-based direct reduction of iron). All require different supply chains and feature unique infrastructure needs, including access to renewable electricity, low-carbon hydrogen, and CCS. The applicability of different technologies is likely to depend on multiple factors such as:

- Geography: certain locations will have access to resources which synergise with specific decarbonisation routes, such as proximity to CCS storage or an abundance of renewable electricity at a low cost, as was explored by Bataille *et al.* (2021).
- Cost pressures: the highly competitive market and the low profit margins that exist within the mature steel industry will influence which decarbonisation pathway is most suitable for steel producers.

- Commercial drivers: the development of lower cost decarbonisation options will provide a strong driver for decarbonising the steel industry whilst still remaining competitive.
- Policy support: government policy for low-carbon resources, decarbonisation technologies and the production of commodities will play a key role in shaping how low carbon steel will evolve.

It is thus essential to identify pathways for decarbonising steelmaking that are both cost-effective and able to tackle all the main sources of emissions from a life-cycle perspective. The study provides a **comparative analysis** of different steelmaking pathways, focusing on the applicability and suitability of the routes in Northwestern Europe.

The roll-out of clean steel technologies is envisioned to have significant implications on support infrastructure. Therefore, a **secondary objective of the study includes understanding the primary energy and infrastructure implications** associated with large-scale deployment of the different decarbonisation pathways. Clean steel production will likely be more expensive than steel produced today, thus posing additional economic strains on steel producers and consumers. As a result, another objective is to **estimate what price premium could be claimed** by clean steel on existing and future markets. A corresponding aim of this study is to develop recommendations for key stakeholders to support the sector as well as recommendations for further work.

The report is structured as follows:

- **Chapter 2** provides an overview of the current status of steelmaking before introducing the low carbon steelmaking pathways analysed in this study.
- **Chapter 3** presents the techno-economic assessment, including its methodology, and the results.
- In **Chapter 4** the life cycle assessment is explored, including its methodology, and the results.
- Decarbonisation of the steel sector will require significant deployment and investment in support infrastructure, this is discussed in **Chapter 5**.
- Production costs of clean steel are higher than that of the steel produced today. **Chapter 6** explores the potential price premia these lower carbon products could obtain.
- Finally, **Chapter 7** draws conclusions and recommendations for further works.

Box 1 – Key definitions

- Green Steel, Clean Steel and low-CO_2 steel are all terms used synonymously for steel that has been formed via production methods that have acted to minimise their GHG footprint as much as possible.[5] In this study we have adopted the term **Clean Steel.**
- In this study, **direct emissions** refer to the CO_2 emissions which are produced on the site as a result of the steelmaking processes, including emissions from any captive power generation. GHG direct emissions are mainly CO_2 – other GHG direct emissions such as methane or nitrous oxide are non-material. These are Scope 1 emissions under the Greenhouse Gas Protocol (GHGP).
- **Indirect emissions** in this study encapsulate emissions associated with the production of any electricity and hydrogen imported to the steelmaking site (Scope 2 and 3 under the GHGP, respectively). This terminology is used in the TEA.
- **Embedded emissions** covers all emissions associated with the supply of raw materials and waste treatment and is evaluated in the LCA (GHGP Scope 3 - Category 1,3,4,5)
- The term 'emissions' in the LCA refers to CO_2e. GHG emissions from the value chain can include gases other than CO_2. When considering indirect and embedded emissions the term 'emissions' uses CO_2 equivalents (CO_2e) which covers both CO_2 and non-CO_2 greenhouse gases such as

[5] Some definitions of green steel or clean steel do not address GHG emissions alone. For instance, ResponsibleSteel incorporates a wider range of social, safety and environmental issues.

methane and nitrous oxide. CO_2e uses the global warming potential (GWP) of a gas to convert it to an equivalent amount of warming that would have been caused by CO_2 – enabling an emissions value to be provided when a mix of pollutants are released.

- Greenhouse Gas (GHG) footprint, GHG emissions (collectively), carbon footprint, carbon intensity are all terms used interchangeably to describe direct, indirect and embedded emissions of a product. We refer to the **carbon intensity** of electricity and the **GHG footprint** of crude steel. In some cases, **GHG emissions** have been referred to when discussing a pathway.
- In the LCA, the GHG footprint is referred to as the **Global Warming Potential (GWP) Impact**.

2 Steelmaking pathways today and in the future

2.1 Current status of steelmaking

Steel is one of the essential components of our modern global economy, being one of the most widely used industrial products across the planet. In the 21st century, steel production has more than doubled with nearly 2 billion tonnes of steel produced in 2020, and production is set to rise by 2050 even under scenarios that include deployment of material efficiency measures (IEA, 2021a).[6] As Figure 3 shows, steel is used across a range of industries, with infrastructure, mechanical equipment and the automotive sector representing more than 75% of global demand.

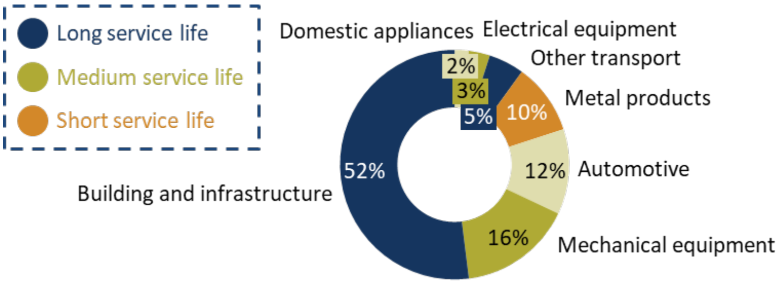


Figure 3: Industries using steel, by weight (World Steel Association, 2023a)

Steel is an alloy composed primarily of iron and carbon but may also include varying quantities of other elements, such as manganese, chromium and nickel. The relative composition of these constituents determines the specific physical characteristics of the end product; thousands of grades of steel are available, making it an extremely versatile material.

The key material input to ironmaking is iron ore, the majority of which is mined from the vast ore deposits of Australia and Brazil. This contrasts with iron production, where China dominates the market, with over half the global production capacity and around 70% of global iron ore imports. The accelerated infrastructure development in China over the last two decades has largely contributed to a doubling in global steel production. Out of the top ten steel production companies by volume, only ArcelorMittal (Luxembourg) is based outside of China (World Steel Association, 2023b).

The majority of modern steelmakers have followed a well optimised, competitive production route relying on established commodity supply chains from a limited selection of countries. Future steel production will have to balance an urgent need to decarbonise or transition away from incumbent technologies, while maintaining competitive pricing and limiting supply chain disruption.

There are two major steelmaking routes: the **primary** and **secondary routes**, distinguished by their main iron inputs.

- **Primary route:** uses **iron ore** as its main iron input, which is complemented with some scrap-based input.
- **Secondary route:** uses predominantly **scrap** as the iron input but some virgin iron ore is typically added to complement scrap.

Both the primary and the secondary route require large energy inputs. Energy provides heat to melt the iron input and to reduce the iron ore – i.e., to remove the oxygen atoms chemically attached to naturally occurring iron ores.

[6] The IEZ Net Zero Emissions by 2050 Scenario (IEA NZE) sees a 5% increase in production of steel by 2050.

2.1.1 Primary Steelmaking Routes

The primary production route is the dominating route, with over 77% of global steel production following this process (World Steel Association, 2022). The process comprises three phases. Namely, raw material preparation, ironmaking, and steelmaking. Once mined, and after undergoing a beneficiation process, iron ore inputs extracted from the earth's crust need further processing before being used for ironmaking. Concentrated forms of lump ore can be used directly, but fines need to be agglomerated. The main energy sources and reducing agents also require an intermediate preparation step to produce the coke or reducing gas required for ironmaking. In the ironmaking step, a combination of lump ore, sinter and pellets are chemically reduced to obtain iron, removing oxygen from the iron oxides. The two major methods for exacting this procedure are:

- **Blast Furnace** (BF), which predominantly uses **coke** as the reducing agent for iron ore to produce **pig iron.** Subsequently, this iron can then be converted to steel in **a Basic Oxygen Furnace** (BOF).
- **Shaft furnace**, which primarily uses **natural gas** as the reductant to **produce Direct Reduced Iron** (DRI). The DRI is then converted into steel using an **Electric Arc Furnace** (EAF).

Figure 4 shows the role of the main equipment in the steelmaking process.

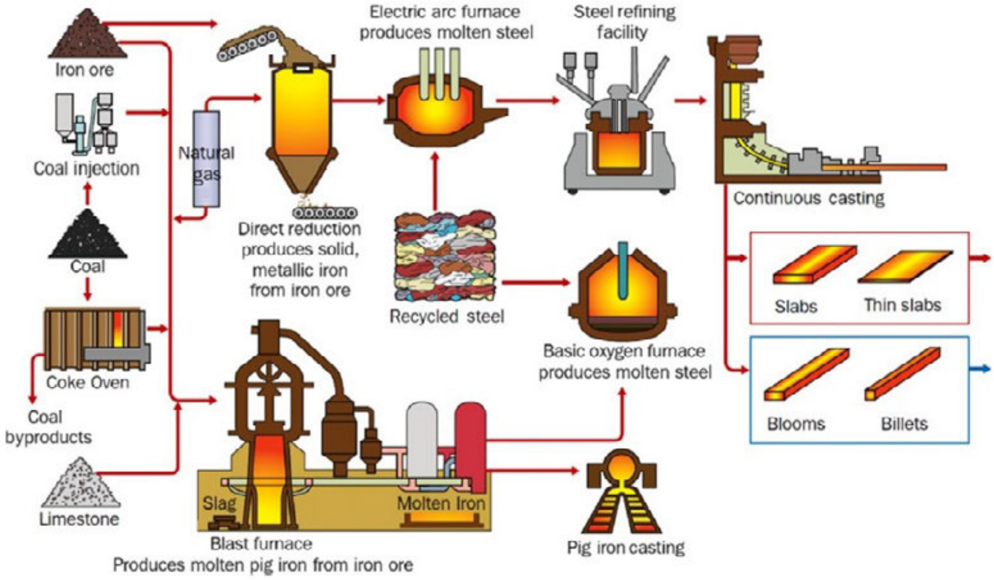


Figure 4: Ironmaking and steelmaking flowsheet for different production routes (Yang, Raipala and Holappa, 2014)

The combination of producing iron in a blast furnace and feeding this to a basic oxygen furnace is a coal-based process. It is often denoted BF-BOF and may be collectively referred to as Basic Oxygen Steelmaking (BOS). This is the most common and carbon-intensive steelmaking pathway, representing the status-quo in global production for the last 50 years.

The other primary production route, which combines iron production in a shaft furnace and steel production in an electric arc furnace, is a natural gas-based process and is denoted DRI–EAF. This is far less common than the BF-BOF route and currently represents less than 10% of global production from iron ore with only one operating plant in Europe (World Steel Association, 2023b). However, its use is more widespread in some other global regions as shown in Figure 5.

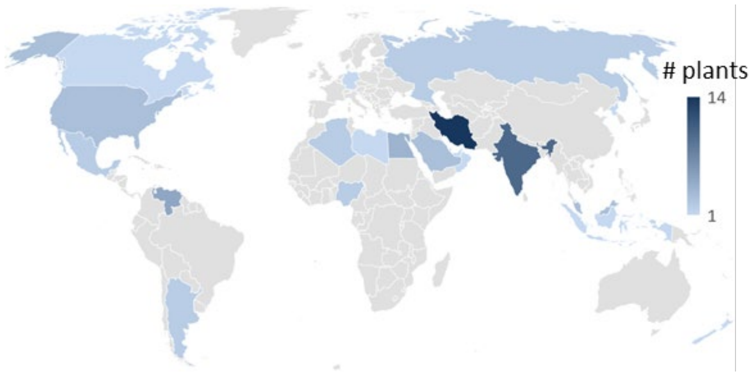


Figure 5: Integrated and merchant DRI sites global distribution (adapted from Global Energy Monitor (2023))

2.1.1.1 Basic Oxygen Steelmaking (BOS)

BOS steel plants are usually 'integrated' meaning that all steps of steelmaking, from smelting iron ore to rolled product, coexist on the same site, as shown in Figure 6. The main raw materials are iron ore and coal. Lump ore can be directly charged into blast furnaces, but fine iron ore concentrates require agglomeration before charging. Using heat and pressure, agglomeration processes form either pellets (spherical agglomerates) or sinter (irregular nodules) that can be charged in a furnace and allow the flow of gases. While integrated sites usually include sinter plants, pellet plants are typically located near the mining site. Pellets used in blast furnaces typically contain 58 to 65% iron (Fe) content. Iron ore is thus often imported to the site in the form of pellets, lumps and fines. A sinter production plant facilitates on-site agglomeration of fines. In sintering, ore fines, lime fluxes and coke breeze are mixed and fed on to an oven where they reach temperatures of over 1,500 °C. The ore reaches a half molten state where it sticks together forming irregular nodules that can be charged to the blast furnace.

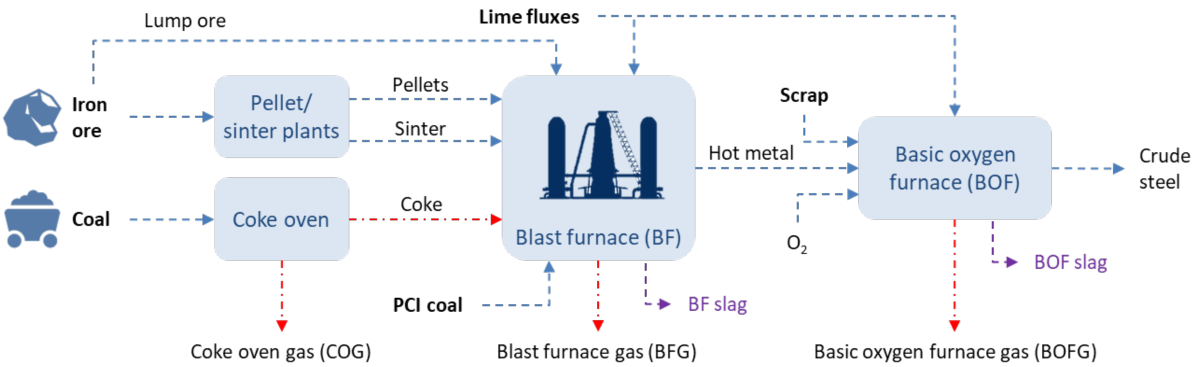


Figure 6: Basic oxygen steelmaking (BOS) pathway

Integrated sites import multiple forms of coal including different categories of coking coal and non-coking metallurgical coal. Coking coal has a higher purity and carbon content than thermal coal. It is processed in a coking oven into coke, a porous solid material with very high carbon content and few impurities. A typical blast furnace consumes thousands of tonnes of coke a day and consequently a dedicated coke production unit is usually required at the ironworks. The coking oven reaches high temperatures to decompose the coal into a coke residue in the absence of air in a pyrolysis process. The main by-product from coke production is a calorific gas known as coke oven gas (COG), emitted in the pyrolysis process and used as an internal fuel across the steel site. Part of the COG is recycled to the coke oven to provide heat, and the remainder is used as a fuel in other units. Other by-products include tar, benzole, and sulphur components. The red-hot coke needs to be cooled before being charged to the blast furnace. While it is typically quenched with water, it can alternatively be cooled with inert gas and sensible heat can be recovered using coke dry quenching. Coke dry quenching is a heat recovery system that uses sensible heat from hot coke to produce steam and generate electricity. After quenching, coke is screened and the smaller particles are separated as coke breeze, used in the sintering plant. Coke is charged to the blast furnace in alternating layers with the iron ore, providing an energy supply, a source of carbon monoxide, and porous structural support to bear the burden of iron ore and to allow the flow of gases. The coke production step is an energy intensive and costly step in integrated steelmaking, and hence steel producers try to increase the use of auxiliary reducing agents in the blast furnace. An auxiliary reducing agent widely used in ironmaking is pulverised coal injection (PCI), which allows to reduce the coke rate in the blast furnace. Coal used for PCI is typically high-quality thermal coal or non-coking metallurgical coal, which are cheaper than coke.

Ironmaking takes place in the blast furnace, where iron ore is reduced (oxygen is removed) to produce hot metal (or liquid pig iron) with a carbon content of around 4% that can be charged to the basic oxygen furnace for the steelmaking process. In the blast furnace, iron ore is used as the iron-bearing raw materials, and coke and pulverised coal act as reducing agents and heat source. Additionally, lime and limestone act as fluxing agents to remove impurities. Sinter, pellets and lump ore are charged into the upper region of a blast furnace together with coke and the lime fluxes. The blast furnace is a tall vessel with a significant temperature distribution across its height, and it operates continuously based on a counter-current flow principle. Temperatures at the top of the furnace, where coke, sinter, pellets lump ore and the flux are charged, can be as low as 200 °C while the bottom of the furnace, where most oxidation of coke takes place, can exceed 1,600 °C. Air enriched with oxygen (known as blast) is heated and blown into the bottom of the furnace through tuyeres providing a major heat input to the furnace. The hot blast reacts with the layered coke and with PCI coal (injected through a lance to the tuyeres) forming carbon monoxide which rises through the furnace reducing the layers of iron ore to liquid metal and producing carbon dioxide as a by-product. Limestone additives react with sulphur in the melt forming a calcium sulphide slag layer with lower density than the liquid iron. This lower density makes the slag more buoyant than the liquid metal causing it to separate out into a layer on top where it is skimmed off separately. Blast furnace slag can be sold to other industries such as cement and asphalt. The top gas leaves the furnace top at approximately 200 °C. This top gas, known as blast furnace gas, is a valuable fuel, as it has calorific value because of its carbon monoxide content. Blast furnace gas has a pressure of around 2 bar at the furnace top, and hence the pressure can be employed to drive a turbine generator and generate electricity before using blast furnace gas as a fuel in the hot blast, co-generation plant or other units within the site. This energy efficiency measure is known as top-gas pressure recovery turbine and is a popular energy-saving technology in ironmaking.

Hot metal is tapped from the bottom of the blast furnace and is transferred to torpedo carts that move the metal to steelmaking units at the site. At this stage of the production process the metal has a high carbon content making it very brittle. The basic oxygen furnace converts carbon-rich liquid hot metal to low-carbon steel. Hot metal is charged into a basic oxygen furnace in batches with a proportion of scrap. Scrap metal is used to control the process temperature of a basic oxygen furnace by absorbing excess thermal energy produced from carbon oxidation, with scrap representing 10% to 30% of the total charge weight (Jalkanen and Holappa, 2014). Lime additives are also rapidly added for fast slag formation, removing impurities from the metal such as silicon, sulphur and phosphorus. High purity oxygen is then blown through a lance onto the metal with the intention of oxidising iron carbide in the molten metal, reducing the carbon content of the melt until it becomes steel. This process produces a high temperature mix of carbon monoxide and carbon dioxide known as Basic Oxygen Furnace Gas (BOFG) which is calorific and often forms part of a fuel-mix (with Coke Oven Gas and Blast Furnace Gas) fired in the co-generation plant. The oxidation reactions that occur in the basic oxygen furnace are exothermic and consequently no thermal input is required for the unit.

Liquid steel is tapped from the BOF in batches at regular intervals at which point it is transported to treatment ladles where additives may be introduced to achieve specific characteristics in the final product. Following this, the metal is poured from the ladle into a holding bath that feeds a continuous casting unit and is solidified into billets, blooms or slabs as crude steel.

2.1.1.2 Direct Reduced Iron to Electric Arc Furnace (DRI-EAF)

The direct reduction of iron is the conversion of iron ore to metallic iron in a solid state. The ironmaking step takes place in a shaft furnace, where pellets and lump ore are reduced by a reducing gas typically produced from natural gas. The resulting direct reduced iron (DRI) is charged to an electric arc furnace, typically together with scrap, for the steelmaking process. The main process flows are shown in Figure 7. Unlike iron ore reduction in a blast furnace, iron ore is not melted in the shaft furnace. Consequently, any impurities in the iron ore (known as gangue) are retained unlike in the BF where a liquid slag layer forms. Hence, gangue minerals such as silica are carried on to the steelmaking step. If the steelmaking furnace cannot handle large amounts of slag resulting from the use of low-grade iron ores, as is the case for electric arc furnaces, higher grade pellets are required. These higher grade pellets are known as DR-grade pellets, which typically have more than 66% Fe content (Nicholas and Basirat, 2022).[7] DR-grade pellets have a higher cost per unit of iron compared to BF-grade pellets, which reflects their higher value in use. Also, not all iron ores can be beneficiated to reach a DR-grade.

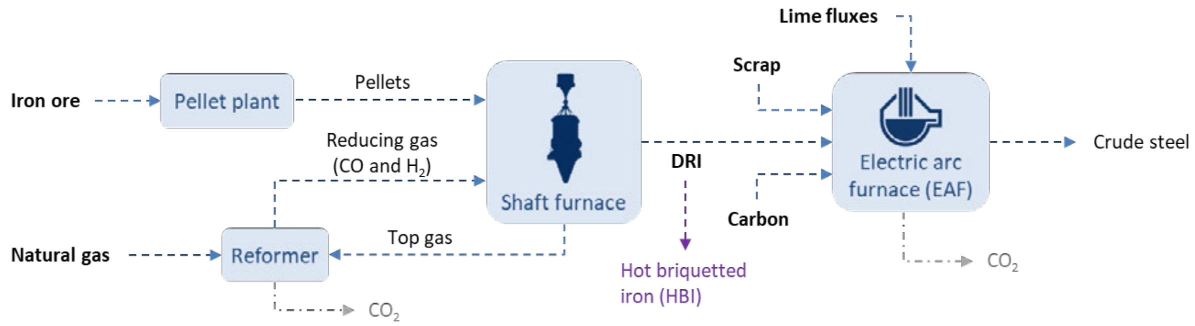


Figure 7: Natural gas-based direct reduced iron (DRI) to electric arc furnace (EAF) pathway

Direct reduction (DR) plants typically have a much smaller capacity than blast furnaces with an average plant size of 1.6 Mt/year compared to 3.2 Mt/year for blast furnaces. However, capacities of 2 million tonnes per year and higher have been achieved in several locations worldwide (Global Energy Monitor, 2023). Shaft furnaces are used to obtain metallic iron that can be fed to an electric arc furnace. When reducing gas is fed into a shaft furnace, it travels up the shaft against the counter current flow of pellet charge, which moves down through the shaft under gravity. The reducing gas is usually produced from the most abundant and cost competitive energy source available to DRI producers. The two leading shaft furnace DRI processes are the MIDREX process and the Energiron/HYL ZR (Zero Reformer) process. For most sites employing gas-based DR furnaces, natural gas is the primary feedstock and is converted to reducing gas (carbon monoxide and hydrogen) either in an external reformer (as in the MIDREX process) or by *in situ* reforming (as in the Energiron/HYL ZR process). Alternative energy sources include coal or coke oven gas. Under the MIDREX process, top gas from the shaft furnace is scrubbed and recycled through the reformer to utilise unspent carbon monoxide and hydrogen, as well as providing H_2O and CO_2 for the reformation process. With *in situ* reforming, CO_2 is removed from the top gas before recirculating it back with the feed gas and injecting oxygen. Iron ore is brought to its reduction temperature (>900 °C) through heating from the reduction gases, that also act as an energy source. The lower portion of the shaft furnace, known as the 'reduction zone' experiences the most intense heating and is where final reduction of the iron ore occurs before it is extracted from the bottom of the furnace as hot DRI. As the reducing gases rise to the top of the furnace they cool to 400°C, at which point pellets are only partially reduced.

DR plants can have a high flexibility in the product output, being able to produce cold DRI, hot DRI, or hot briquetted iron (HBI). The DRI product reaches a metallisation rate ranging between 90% and 96%, as not all iron ore particles are fully reduced. Also, DRI picks up carbon from the reducing gas and has

[7] Lower grade pellets (≤65% Fe) can be used but require an additional step such as processing in an electric smelting furnace (ESF) before being further processed in an existing BOF.

carbon content ranging from 0.5% to 4%. As DRI is highly porous, it can re-oxidise in the presence of oxygen in the atmosphere. Lowering the reactivity of DRI is desirable to avoid its oxidation and the potential overheating.[8] Until the late 1990s, virtually all DR plants cooled the DRI for later charging in the adjacent EAF to reduce its reactivity. More recently, the development of hot charging technologies using hot transport systems have allowed to utilise the sensible heat in hot DRI to lower the electricity consumption in the electric arc furnace and increase its productivity. DRI discharged at 700 °C from the shaft furnace can thus be charged at 500 to 600 °C to the electric arc furnace.

DRI can be batch-charged or fed continuously into an electric arc furnace, together with scrap and lime fluxes, to produce liquid steel with the required physical and chemical properties for casting. In the electric arc furnace, electric arcs formed between its three electrodes heat and melt the metallic charge. Unlike in the BOS route, the scrap input percentage is highly flexible. The amount of scrap can vary from very small levels, limited to home scrap only, to nearly 100% typical of the secondary route. Since electricity represents the major cost in EAF steelmaking, measures that can help reduce the burden of electricity in steel melting are often pursued to increase furnace productivity by reducing the melt time. A major source of heat in the furnace comes from blowing oxygen into the molten steel through oxygen lances, promoting the exothermic oxidation of carbon, silicon and iron in the melt. Additionally, natural gas burners are employed to provide thermal energy input, further decreasing specific electrical energy. Coal is charged amongst the scrap and DRI input to provide chemical energy for heating, to carburize the melt and to promote slag foaming in the furnace. Carbon can also be injected into the furnace with oxygen to form carbon monoxide which further propagates slag foaming. A foamy slag is desirable to optimise energy consumption and protect the refractory linings of a furnace. In total, the energy input from natural gas and coal often represents over 40% of the total energy input to an electric arc furnace. Direct CO_2 emissions from the EAF arise from the use of natural gas and coal, from the oxidation of carbon in the metallic inputs, and from the graphite electrodes consumption. As with a BOF, liquid steel is tapped from the EAF in batches at regular intervals, after which it is transported to treatment ladles and finally to a continuous casting plant in the form of crude steel.

2.1.2 Secondary Steelmaking Route

In the secondary steel production route, a charge consisting predominantly of scrap metal is fed to an electric arc furnace producing liquid steel which is recast into useful products. Scrap-based EAF represents ~23% of global steel production (World Steel Association, 2022), although some major manufacturing economies produce the majority of their steel via scrap-based routes. Notably, in the United States 69% of steelmaking is scrap-based (Koch Blank, 2019). EAFs cannot produce steel from iron ore, as they are not suitable for ore reduction. Alternative metallic inputs including pig iron and DRI/HBI may be blended with the scrap charge to meet deficits in scrap supply and to dilute tramp elements, such as copper, that are introduced during recycling (for instance, from copper wiring attached to steel parts) and cannot be removed to slag like other elements. Figure 8 presents the main process flows for secondary steel production. Secondary steel is often used in products that accept lower steel grades with a higher inclusion of undesirable and hard to remove elements. This is the case for many long steel products used by the construction industry, such as reinforcing bar or structural steel sections. However, electric arc furnaces can also produce higher grade steel with careful scrap sorting and higher shares of ore-based metallic inputs.

[8] Converting DRI to HBI, by applying pressure to the DRI pellets at 700°C, is the most successful method to reduce the reactivity of DRI. HBI is the most common form of merchant DRI – i.e., DRI exported to external sites instead of used in an adjacent steelmaking furnace.

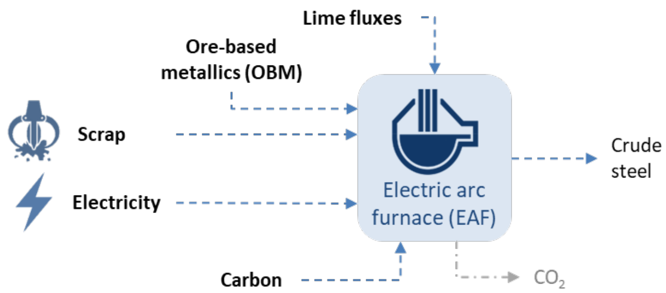


Figure 8: Scrap-based EAF or secondary steel pathway

The secondary steelmaking route is significantly less capital and energy intensive than the primary route, using 10 to 15% of the energy from integrated production. This is due to the fewer processing steps required when using scrap steel, which has already undergone the intensive reduction process. Consequently, it can achieve a lower GHG emissions intensity compared to the primary production routes even for electricity grids largely running on fossil thermal generation, and this route is set to decarbonise even further as the emissions intensity of electricity continues to decrease. Despite this, scrap availability limits the growth of the secondary route. As the steel market has grown markedly in the past decade, recycling does not provide enough feedstock even when the recycling rate is very high. Thus, the continuation of primary routes is still crucial to ensure that global steel demand can be met.

Steel is currently the most recycled material in the world with collection rates of around 85%, meaning that increased demand (and increased scrap prices) can only unlock low levels of additional scrap supply. Although over half of today's scrap supply is pre-consumer scrap form offcuts, a general move towards more efficient cutting processes is expected to reduce the volumes of scrap generated in this form.[9] The availability of other sources of scrap depends on current infrastructure where steel is embedded, such as buildings and equipment, reaching their end of life. This means that scrap supply lags steel production demand by the lifespan of its intended use case and consequently, despite a significant increase in the volume of steel production in recent decades, new volumes of scrap supply will not be accessible until the distant future. It is anticipated that even by 2050, primary production routes will retain the majority share of global production while the secondary steelmaking route may increase its share of production up to 46% (IEA, 2021a). Hence, despite a falling share of iron ore in metallic inputs, the hard-to-decarbonise primary route will continue to be fundamental for steelmaking.

A gradual increase in the share of scrap-based production will contribute in the reduction of the global steel sector's emissions; however, primary steel production is still needed and decarbonising this route remains the focus of innovation in the sector. Given the limited scrap availability, an over-reliance on emissions reduction via a faster transition to the secondary route will result in scrap steel being diverted from use as a feedstock in primary routes. Scrap steel plays an important role in increasing yield and reducing emissions from primary steel production, as it replaces a proportion of the virgin iron ore input. Hence, a focus on increasing production from the secondary route would redistribute total emissions from the steel industry by increasing the emissions intensity from the primary route. For these reasons, the secondary steelmaking route is not considered in further detail in this report.

2.2 The future of the primary route (the pathways in this study)

Steel production is a very large source of GHG emissions. To meet global climate objectives, society's steel needs must be met while reducing emissions to a small fraction of current processes. Energy efficiency improvement and higher scrap use can lead to a reduction in emissions. For instance, measures such as coke dry quenching, installing a top-gas pressure recovery turbine, scrap preheating,

[9] At the same time, it should be acknowledged that demand for steel products with more complex shapes could increase fabrication scrap.

heat recovery and reuse within a facility, improved data management techniques or endless strip production are already being adopted by steel producers. However, this alone will not lead to the deep reduction in emissions needed to meet climate goals. More disruptive measures will be required for deep decarbonisation. Carbon capture and storage (CCS), the alternative reduction of iron ore, and the use of sustainably sourced biomass-based feedstocks where possible are the distinct categories of technologies that can deeply reduce emissions from primary steel. Transition towards hydrogen-based direct reduction is quickly gathering pace in Europe, with multiple announcements of new plants. Other steel producers, particularly outside Europe, are considering retrofitting their integrated steel mills with CCS technologies to enable the continued use of existing equipment. Different alternatives for clean primary steel are shown in Table 1, grouped by the main technology group. The alternatives are presented in the sections below.

Table 1: Technology pathways for the future of primary steel

Pathway group	Technology pathway	TRL[10]
BOS	BF-BOF	-
	BF-BOF + CCS (on power plant)	8
	BF with TGR-BOF + CCS	6
	BF w/TGR-BOF + BECCS	6
	BF-BOF with hydrogen injection in blast furnace	7
DRI	NG-DRI + EAF	-
	NG-DRI + EAF + CCS	8-9
	H-DRI + EAF	6-7
	H-DRI + EAF with bioenergy	6
	H-DRI with fluidised bed reactor + EAF	5-6
	NG-DRI + Electric smelting + BOF	8
Others	Coal-based smelting reduction + BOF	7
	Coal-based smelting reduction + BOF + CCS	7
	Molten oxide electrolysis	5
	Electrowinning	4

2.2.1 BOS Pathways

Decarbonisation of basic oxygen steelmaking would require increased use of auxiliary reducing agents to reduce the use of coke or the use of CCS technologies.

BF-BOF with Carbon Capture and Storage

One option for decarbonising a BOS site is to capture carbon dioxide from the various flue streams on the site's integrated units. In some respects, this is appealing as it facilitates the continued use of existing assets. The difficulty of applying CCS to a BOS site stems from the fact that many flue streams are routed through other units, utilising the calorific content of the off gases as internal fuels. This means that a BOS site has many small emissions streams of varying CO_2 concentrations which makes capture more technically challenging. For example, the blast furnace is the single largest source of emissions; however, despite some BF gas being flared, the majority is either recirculated or utilised in the coke oven and co-generation plant meaning that the CO_2 primarily originating from the blast furnace is dispersed over multiple emissions points across the site. Many studies to date have concluded that as much as half of the emissions would remain even with CCS (Material Economics, 2019).

[10] TRL stands for Technology Readiness Level, a scale from 1 to 9 to measure technology maturity (IEA, 2023b). The TRL from each technology is defined based on ERM's own judgement and IEA's ETP Clean Energy Technology Guide (IEA, 2023a).

There are multiple possible approaches to carbon capture from steel mills. CO_2 can be captured from the blast furnace gas, before it is used as a fuel by other units, or it can be captured from the co-generation plant. Blast furnace gas is a mixture of CO_2, carbon monoxide, nitrogen, and low amounts of hydrogen. Capturing CO_2 from BF gas may involve separating all carbon containing molecules or separating CO_2 only. Under the first approach, a water-gas shift step is needed to convert CO to CO_2, and hydrogen-rich syngas is obtained. The hydrogen-rich syngas can be used internally and results in low CO_2 emissions. Alternatively, CO_2 can be separated from the top gas, and the carbon monoxide-rich process gas is be recycled back to the blast furnace. This process, called top gas recycling (TGR), involves important modifications to the blast furnace. The recycled process gas containing carbon monoxide and hydrogen needs to be preheated and injected into the blast furnace tuyeres and pure oxygen is used instead of the hot air blast. As a result, the top gas has an increased CO_2 concentration (as no nitrogen is incorporated), which reduces the burden on a capture system, and the blast furnace operates with a lower carbon input. The blast furnace under this configuration is often referred as oxy-blast furnace given the higher oxygen use. Recycling of the syngas allows to reduce coke rates and hence leads to emissions reduction even if CO_2 is released after separation. This process was initially developed under the ULCOS program and iterations of the concept are being developed by steel producers and steel equipment designers and suppliers (European Commission, 2014).

Integrated sites usually combine off-gases from the coke oven, the blast furnace and the basic oxygen furnace in a collection system. One of the largest point source emitting units in an integrated steel mill is the co-generation plant. Capturing CO_2 from the co-generation plant flue gas is a more typical case of post-combustion capture. As such, the most likely approach would be chemical solvent-based absorption. As an advantage, this approach offers an end-of-pipe solution with little modifications to the blast furnace required, and it can build on experience from post-combustion capture developed for thermal power generation. It can also capture CO_2 from more than one emission source as off-gases are combined. As a disadvantage, emissions from sources such as the blast furnace hot stoves, coke oven under-firing or the sinter plant are not addressed. This option is being explored, for instance, by British Steel in their Scunthorpe site.

BF-BOF and Bioenergy with Carbon Capture and Storage

The use of sustainably-sourced biomass can help to decarbonise primary steel. While biomass can be incorporated to the BF-BOF route in different processes, it is the injection of charcoal as an auxiliary reducing agent that holds the largest potential for biomass use in BOS.[11] As biomass generally has a high moisture and volatile contents, thermal treatment is required before utilisation. The injection of charcoal through the blast furnace tuyeres can potentially fully replace the use of PCI coal (Mousa *et al.*, 2016). This approach is exemplified by the Torero project developed by ArcelorMittal at the Ghent site, where up to 80,000 tonnes of torrefied biomass per year will partially replace PCI coal (ArcelorMittal, 2021).

When the use of charcoal injection as a replacement of PCI coal is combined with carbon capture, the CCS configuration is an example of a bioenergy with CCS (BECCS) application, which allows a further reduction in emissions.

BF-BOF with hydrogen injection

Auxiliary reducing agents, such as PCI and charcoal, used to decrease specific coke consumption in blast furnaces are not limited to just solids. Hydrogen can be used as an auxiliary reducing agent to reduce the reliance on coal. While hydrogen can reduce iron ore in the blast furnace, its use can negatively impact process operation and hence there are limits to its use. Iron ore reduction by hydrogen is endothermic (as opposed to reduction by carbon monoxide) and as coke layers in the blast furnace are thinned the flow of reducing gases can deteriorate. Yilmaz, Wendelstorf and Turek (2017) found

[11] Other ways are adding biomass to coal during coking, substituting coke breeze with biochar for sintering, or top charging of charcoal to the blast furnace.

that for a reference case of PCI injection rate of 120 kg/t hot metal, an optimal hydrogen injection rate of 27.5 kg/t hot metal can reduce CO_2 emissions from the blast furnace by up to 21%, assuming zero-carbon hydrogen and hydrogen pre-heating with the top gas. Hydrogen injection may be a transitional technology while other technologies develop. Several steel producers are trialling hydrogen injection in blast furnaces; in some cases, this includes injection of hydrogen-rich coke oven gas.

2.2.2 DRI Pathways

Decarbonisation of natural gas-based DRI (NG-DRI) can be achieved by capturing CO_2 from the reforming unit or from the shaft furnace top gas, or by transitioning towards alternative reducing gases – namely towards hydrogen-based direct reductions. Emissions can be further reduced by replacing fossil carbon inputs to the electric arc furnace by sustainably sourced biomass.

NG-DRI – EAF with Carbon Capture and Storage

The natural gas reformer represents the major source of emissions associated with the production of DRI. The ease with which CO_2 can be separated from the reformer's flue stream depends on the reforming technology. The two leading shaft furnace DRI processes are the MIDREX process and the Energiron/HYL ZR process, with MIDREX accounting for 79% of global DRI production in shaft furnaces (MIDREX, 2022). The MIDREX reformer uses steam and CO_2 reforming, and the flue gas stream has a relatively low CO_2 concentration. The Energiron/HYL ZR process, on the other hand, uses *in situ* reforming and the CO_2 separation step from the shaft furnace top gas is inherent to the process, emitting a concentrated stream of CO_2. Even for the MIDREX process, where there is no concentrated stream of CO_2, DR plants have a less complex design than BF-BOF sites and carbon capture can be retrofitted to DRI facilities with less modifications. The Emirates Steel Abu Dhabi DR plant, which has Energiron/HYL ZR technology, has the only operational CCS plant in the iron and steel sector, capturing 0.8 million tonnes of CO_2 per year for use in enhanced oil recovery (EOR).

Hydrogen-based DRI – EAF

While utilising carbon monoxide as a reducing agent for iron ore, production of CO_2 in significant quantities is chemically unavoidable. Reducing gas from natural gas reforming is a mixture of carbon monoxide and hydrogen. If a higher share of hydrogen is used, and thus carbon monoxide is displaced, emissions can be greatly reduced. Hydrogen-based DRI (H-DRI) describes DRI produced using hydrogen in significant proportions as a reducing agent which can lead to a significant reduction in total emissions when low carbon hydrogen is utilised. While this pathway implies a replacement of existing steel assets it has transitional benefits, as HBI or DRI can be fed into blast furnaces and basic oxygen furnaces as EAF capacity ramps up, and hydrogen can be increasingly blended with natural gas in existing DR plants.

The use of hydrogen in high proportions modifies the mass and energy balance in the shaft furnace. As hydrogen reduction is an endothermic reaction, hydrogen needs to be pre-heated before injection into the furnace. Hydrogen can be pre-heated with electrical heater or by the combustion of fuels. Moreover, if no carbon-bearing gases are used the iron ore does not get carburised in the shaft furnace. The carbon content in DRI (also known as in-situ carbon) plays an important role in the EAF by providing chemical energy, reducing the non-metallic Fe in DRI, carburising the melt and promoting slag foaming. Owing to the lack of carbon in this pathway's reducing gas, the H-DRI – EAF route requires additional carbon to be charged or injected into the EAF to compensate. Moreover, injected or charged to the EAF has a lower efficiency than in-situ carbon, and hence higher amounts of total carbon are required. Carbon charged or injected to the EAF is typically high-quality thermal coal, which increases the EAF's direct CO_2 emissions.

Hydrogen-based DRI – EAF with bio carbon source

Coal used in the EAF can be replaced with sustainably-sourced biomass to further reduce direct fossil CO_2 emissions. While more research is needed to understand the impact on slag foaming given the higher reactivity of biomass compared to anthracite, biomass can fully replace the role of coal in providing a chemical energy input.

Hydrogen-based DRI with fluidised bed reactor and EAF

Reduction of iron ore in a fluidised bed reactor, instead of in a shaft furnace, allows for the use of iron ore fines. In a fluidized bed reduction reactor, a perforated grid at the bottom of the reactor distributes high-temperature reducing gas, i.e. hydrogen. The iron ore fines are reduced while the flow of the reducing gas suspends them and causes the particles to behave as though they were a fluid. Thus, no pellets are required. This leads to reduced costs for iron ore and to lower energy demand for raw material preparation. Additionally, limonite, a type of iron ore that is difficult to use for pellets, can be used. The product obtained from the fluidised bed reactor is DRI, which can then be charged to an EAF for steelmaking. A steel producer, POSCO is developing this concept as part of the HyREX technology. POSCO is planning to build a test facility with annual production of a million tonnes by 2028 (POSCO, 2022).

2.2.3 Electric Smelting Pathways

The Electric Smelting Furnace (ESF) is a well-established piece of equipment with many applications across the metal refining industries, particularly in non-ferrous applications where mitigating yield losses from large slag volumes is customary practice. Two ESF designs are the Open Slag Bath Furnace and the Submerged Arc Furnace. The difference is than in an Open Slag Bath Furnace the electrodes are positioned at the top of the furnace (instead of submerged in the bath) and produce an open arc. The ESF has recently received renewed interest in steelmaking as a potential answer to the restricted supply of DR-grade pellets required in typical DRI – EAF steelmaking. The ESF can process high-gangue ore and provides an intermediate step between DRI ironmaking and the steelmaking unit. This use case for an ESF has not yet been deployed at commercial scale. Because the ESF can melt DRI with a wide range of gangue contents and separate off large volumes of slag maintaining high yields in the hot metal produced, the DR plant can be fed with BF-grade pellets.

Natural gas-based DRI with Electric Smelting Furnace + BOF

One option for integrating an ESF on site is to place it in between a DR plant and a basic oxygen furnace, as depicted in Figure 9. The continued use of steelmaking units and lack of disruption to iron ore supply chains makes this choice particularly useful for integrated BOS sites transitioning a portion of their production over to the direct reduction route. As well as facilitating continued usage of BF-grade iron ore pellets, the integration of an ESF before a BOF enables the production of a wider range of steel grades, including those that are more challenging to produce via the DRI – EAF pathways. Tata Steel Netherlands and Germany's ThyssenKrupp have committed to this pathway (including a transition towards hydrogen-based DRI) (Hatch, 2023).

The slag produced from the ESF has a similar composition to blast furnace slag and can be utilised for similar purposes by, for instance, the cement industry. The off gas produced in the ESF has valuable calorific content and can be used as an internal fuel at other parts of the steel site.

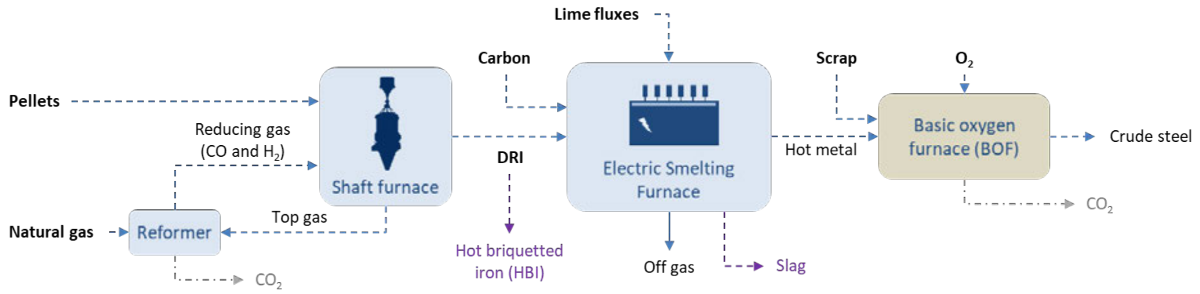


Figure 9: Natural gas-based DRI with electric smelting furnace (ESF) and BOF pathway

Future application of the Electric Smelting Furnace

The positioning of an electric furnace between a shaft furnace and a BOF can help a BOS site displace its largest source of emissions, the blast furnace. Although not covered in this study, further decarbonisation can be achieved by increasing the hydrogen content of the shaft furnace reducing gas and by switching the steelmaking unit to an EAF powered by renewable electricity and using high amounts of scrap. This provides an access route to H-DRI – EAF steelmaking for regions without a stable supply of high-grade iron ore.

2.2.4 Smelting Reduction

Smelting reduction is an established steel production method that has been in commercial operation in low volumes for multiple decades. The process typically works by firing non-coking coal in a melter-gasifier unit, producing a stream of hydrogen and CO_2. This gas is fed to a secondary chamber where iron ore is charged and partially reduced to a quasi-DRI state. The partially reduced ore then passes through to a metal bath where it is fully reduced to pig iron from direct contact with carbon particulates at the slag-metal interface This reduction process generates smelter off gas which acts as a source of chemical energy and rises prompting partial reduction in freshly charged ore.

There are various designs that follow this general procedure with some using a shaft furnace for the partial reduction of newly charged iron ore (Corex) and others using a system of fluidised bed reactors (Finex). Figure 10 illustrates these pathways. The HIsarna process aims to simplify the process further by bringing the furnace and smelting-reduction vessels together into a single unit.

Historically, smelting reduction technologies have proven to be unpopular, particularly in Western economies. The continued reliance on coal means that even with CCS capturing emissions from the concentrated off-gas stream, an underlying level of emissions remains and significant emissions reduction from the BOS reference case is difficult to attain. It is becoming increasingly clear that even in geographies with abundant, cheap supplies of coal, steel producers are more economical feeding hot DRI to an electric smelting furnace than to a melter-gasifier.

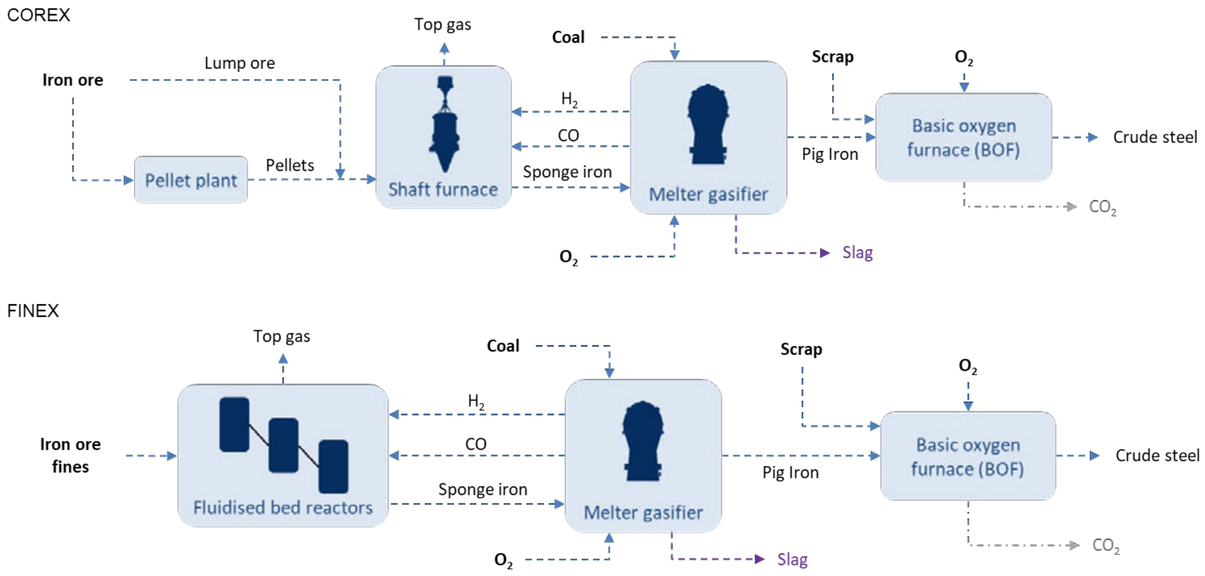


Figure 10: Smelting reduction pathways for Corex and Finex

2.2.5 Electrolytic Steelmaking

Primary steelmaking routes rely on chemical reducing agents in the process of reducing iron ore to pure iron; however, electrolytic reduction is an area of ongoing research and development. This route uses electrodes to separate iron and oxygen ions and has the potential to produce steel with a very low emissions intensity when supplied with renewable electricity. Additionally, it does not require DR-grade iron ore and can use lower qualities. Electrolytic steelmaking is a very compact solution that removes the requirements for coke, lime, a blast furnace or a basic oxygen furnace. Electrolytic steelmaking is currently at a very small production scale and still has significant development challenges before it can produce steel in commercial quantities. Developers are accelerating efforts to reach commercial scale by the end of this decade. It is not anticipated to be deployed at scale in the next decade, but it may play a significant role in the long-term future of low emission iron production. Two main electrolytic technologies, molten oxide electrolysis and electrowinning, are being developed. These are shown in Figure 11.

Molten Oxide Electrolysis (MOE)

Molten Oxide Electrolysis is a proprietary technology developed by Boston Metal. The basic principle involves raising mixed oxide material to high temperatures (1,600 °C) then passing an electrical current through the chamber. High purity molten iron separates out of the liquid metal electrolyte and accumulates at the bottom of the chamber by a cathode while oxygen bubbles out of the mix and exits the chamber as a gas. The high purity liquid iron can subsequently be tapped and proceed to a steelmaking unit. The MOE process occurs in small chambers called cells and these can be modularised to form a high-capacity production facility.

Electrowinning

Electrowinning is the name given to a process where fine iron oxide particles are suspended in an alkaline electrolyte. When a current is applied across the electrolyte, iron deposits on the cathode forming solid iron plates at 110 °C. ΣIDERWIN is a specific low temperature electrowinning process developed by ArcelorMittal that uses long flat electrodes to produce iron metal plates in a batch process.

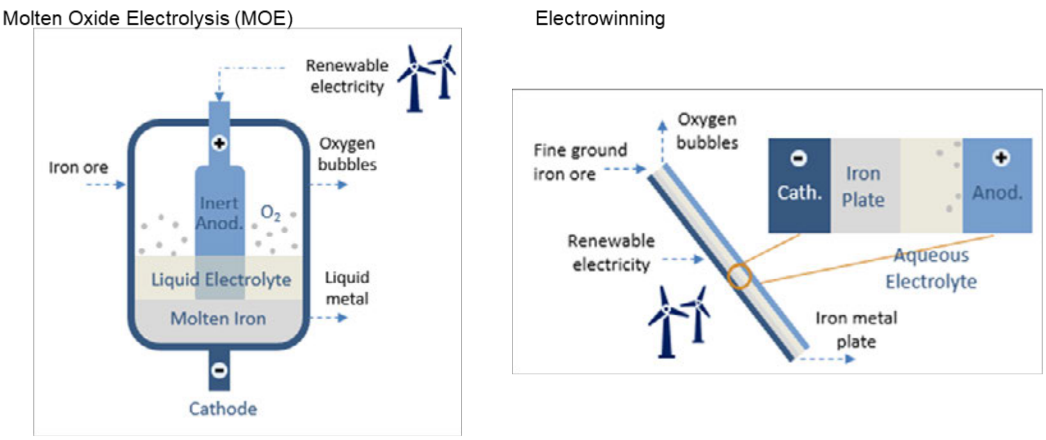


Figure 11: Electrolytic steelmaking pathways - MOE and Electrowinning

3 Techno-economic assessment

The techno-economic assessment (TEA) aims to investigate the economics of different steelmaking pathways in Northwestern Europe. The TEA focuses on the future production cost of a tonne of crude steel for an integrated steel mill nearing the end of a blast furnace campaign, and hence facing an investment decision: relining the blast furnace and continuing operations, potentially including some modifications, or switching to an alternative pathway. The decarbonisation pathways include modifications to the blast furnace, such as fitting CCS technologies or injecting hydrogen, and the transition towards direct reduction technologies, including natural gas- and hydrogen-based direct reduction. The TEA builds on a set of key inputs:

- **Steady-state mass and energy balances** for the main production processes;
- **CAPEX data**, scaled from available data for different furnaces and other equipment;
- **OPEX data**, derived from in-depth literature research;
- **Economic and financial assumptions**;
- **Energy cost**, obtained from short- and long-term price projections.

Performance data and costs are combined in a cash flow to derive quantitative key performance indicators (KPIs). The main outputs are:

- **Levelised production cost of crude steel** ($€_{2022}$/t CS)
- **Costs of CO_2 abatement** ($€_{2022}$/t CO_2)
- **Energy and feedstock consumption**.

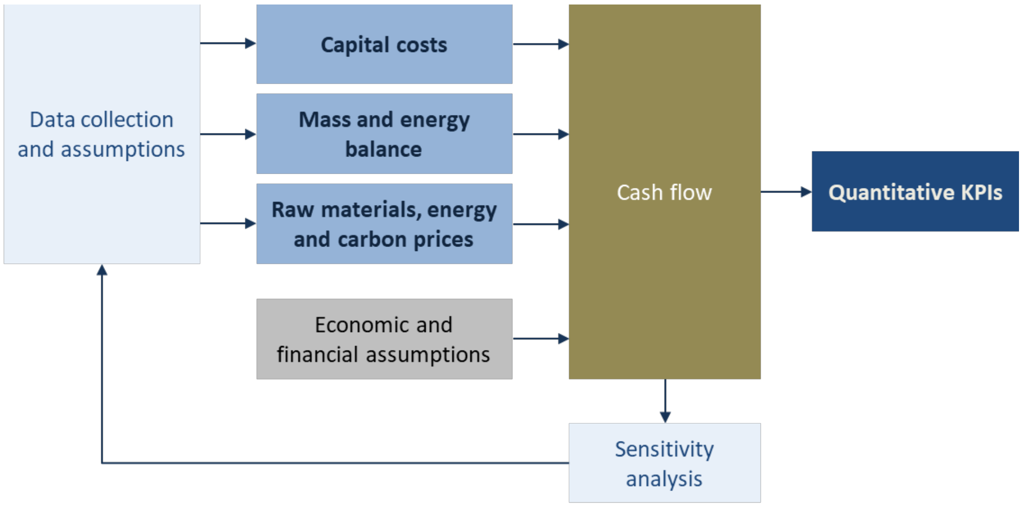


Figure 12: Techno-economic assessment methodology

As introduced in the previous chapter, there are multiple decarbonisation pathways for the iron and steel sector. This chapter provides an overview of the shortlisting process for identifying the steelmaking pathways considered in the TEA and LCA. We also present the methodology and a detailed description of each pathway, accompanied by modelling outputs. These include the energy and economic performance for each shortlisted pathway, accompanied by a sensitivity analysis on the most relevant input parameters.

3.1 Short list of steelmaking pathways for detailed assessment

To assess emerging technologies for primary steel decarbonisation, this study compares the cost and performance of steel decarbonisation pathways against a reference integrated steel mill in a coastal location in Northwestern Europe.

As covered in Section 2.2, some decarbonisation technologies rely on modifications to integrated sites keeping most existing equipment operational, while others require a more complete reconfiguration of steelmaking. A long list of steelmaking pathways was grouped under base cases for unabated steel production. These base cases are the integrated BF-BOF steel mill and natural gas-based DRI plus an EAF steelmaking step. Additional pathways, such as coal-based smelting reduction or electrolytic steelmaking, do not fit under these two base cases.

Table 2 presents the long list of steelmaking pathways that were initially considered and those that were progressed on to the TEA and the LCA. It also includes the reference name for each pathway used throughout the report. **Pathways were shortlisted based on their technological maturity and the potential to achieve commercial deployment by 2030**, their applicability for integrated sites, and their uniqueness. The latter point applies particularly to CCS options on integrated steel mills. While multiple CCS configurations are possible and have been explored, including the choice of capture technology and the process flow configuration, only one configuration was selected for detailed analysis. The decision to model an oxy-blast furnace with top gas recycling (TGR) aligns with the previous IEAGHG 2013-04 iron and steel CCS study. Also, it presents better data availability than other promising CCUS options being developed. Other pathways were excluded due to their lower technology maturity. Hydrogen-based direct reduction with a fluidised bed, such as the HyREX technology, is at an early stage of development. The same is true for electrolytic steelmaking, including molten oxide electrolysis and electrowinning technologies. While coal-based smelting reduction with gasification and carbon capture may be an option in some geographies, it is considered an unlikely pathway for the European steelmaking transition based on feedback from multiple stakeholders.

Table 2: Long list of technology pathways and those progressed for detailed assessment

Base case	Technology pathway	Progressed	Reference name
BF-BOF	BF-BOF	✓	BF-BOF
	BF-BOF + CCS (on power plant)		
	BF with TGR-BOF + CCS	✓	BF-BOF+CCS
	BF w/TGR-BOF + BECCS	✓	BF-BOF+BECCS
	BF-BOF with hydrogen injection in blast furnace	✓	BF-BOF+H_2
NG-DRI + EAF	NG-DRI + EAF	✓	NG-DRI+EAF
	NG-DRI + EAF + CCS	✓	NG-DRI+EAF+CCS
	H-DRI + EAF	✓	H-DRI+EAF
	H-DRI + EAF with bioenergy	✓	H-DRI+EAF+bio
	H-DRI with fluidised bed reactor + EAF		
	NG-DRI + Electric smelting + BOF	✓	NG-DRI+Smelt+BOF
Others	Coal-based smelting reduction + BOF		
	Coal-based smelting reduction + BOF + CCS		
	Molten oxide electrolysis		
	Electrowinning		

3.1.1 Pathway definition

This study assesses a hypothetical reference integrated steel mill producing crude steel in a coastal region of Northwestern Europe facing the decision of extending its blast furnace lifetime or transitioning to an alternative iron and steel production technology.

The definition and main characteristics for each pathway studied under the TEA (and the LCA) are described in Table 3. As discussed in Section 3.2.2, DRI pathways assume a lower crude steel capacity given the smaller size of shaft furnaces compared to blast furnaces.

Table 3: Pathway definition and key assumptions for TEA and LCA

	Pathway	Description
BF-BOF	**BF-BOF**	Integrated BF-BOF site with 4 Mt crude steel/year capacity. The plant operates coke ovens and a sinter plant to meet its needs. Pellets are imported. The plant includes best available technique (BAT) technologies such as coke dry quenching and a top pressure recovery turbine. Off-gases are used internally and in the on-site cogeneration plant, with surplus COG used downstream in the reheating furnaces. *This basic configuration applies to all BF routes.*
	BF-BOF + CCS	The blast furnace is retrofitted to an oxy-blast furnace with top gas recycling and CO_2 capture with amine absorption with a 94% capture rate. Steam for the carbon capture unit is provided by the co-generation plant and an electric boiler.
	BF-BOF + BECCS	Charcoal is injected to the blast furnace as an auxiliary reducing agent, fully replacing PCI coal. The blast furnace is retrofitted to an oxy-blast furnace with top gas recycling and CO_2 capture with amine absorption with a 94% capture rate. Steam is provided by the co-generation plant and an electric boiler.
	BF-BOF + H_2 injection	Hydrogen is injected to the blast furnace as an auxiliary reducing agent, replacing up to 120 kg PCI/t hot metal.
DRI	**NG-DRI + EAF**	Natural-gas based direct reduction under the MIDREX process with 2 Mt crude steel/year capacity. Hot DRI is charged to an EAF together with scrap. DR-grade pellets are imported. *This basic configuration applies to all DRI routes.*
	NG-DRI + EAF + CCS	CO_2 is captured from the flue gas stream from the gas reformer. Waste heat recovery from EAF off-gas plus an electrified auxiliary boiler provide steam to the capture plant, using amine absorption technology with a 95% capture rate.
	H-DRI + EAF	100% hydrogen-based direct reduction with electric preheating of the reducing gas.
	H-DRI + EAF w/bioenergy	100% hydrogen-based direct reduction with electric preheating of the reducing gas. Charcoal is used to replace solid fossil carbon inputs to the EAF.
	NG-DRI + Electric Smelting Furnace + BOF	DRI is produced by a MIDREX shaft furnace using natural gas and BF-grade pellets, which are imported. Hot DRI is charged to an electric smelting furnace which melts and carburises the DRI. The hot metal produced from the electric smelting furnace is fed to a BOF where it is converted to crude steel, with a 2 Mt crude steel/year capacity.

3.2 Methodology

3.2.1 Boundary limit

The definition of the boundary limit of the integrated steel mill and other steelmaking pathways are key to calculate the energy requirements, the direct CO_2 emissions, and the cost per unit of steel produced. **The functional unit for this study is a tonne of crude steel** with a carbon content of 0.1%. Processes up to and including continuous casting were included within the boundaries. Equipment for downstream processes such as reheating furnaces and hot rolling mills were not included.

Upstream processes were not included within the boundary limit when accounting for energy use and direct greenhouse gas (GHG) emissions. Hence, energy and material flows from the manufacture of purchased pellets and burnt dolomite were not included. While some integrated steel mills include a captive pellet plant, this is not representative of most steel mills that import pellets. Energy and material flows from these upstream processes are included as part of the LCA.

Figure 13 to Figure 15 show a schematic representation of the boundary limits, including material and energy flows, for the different steelmaking pathways.

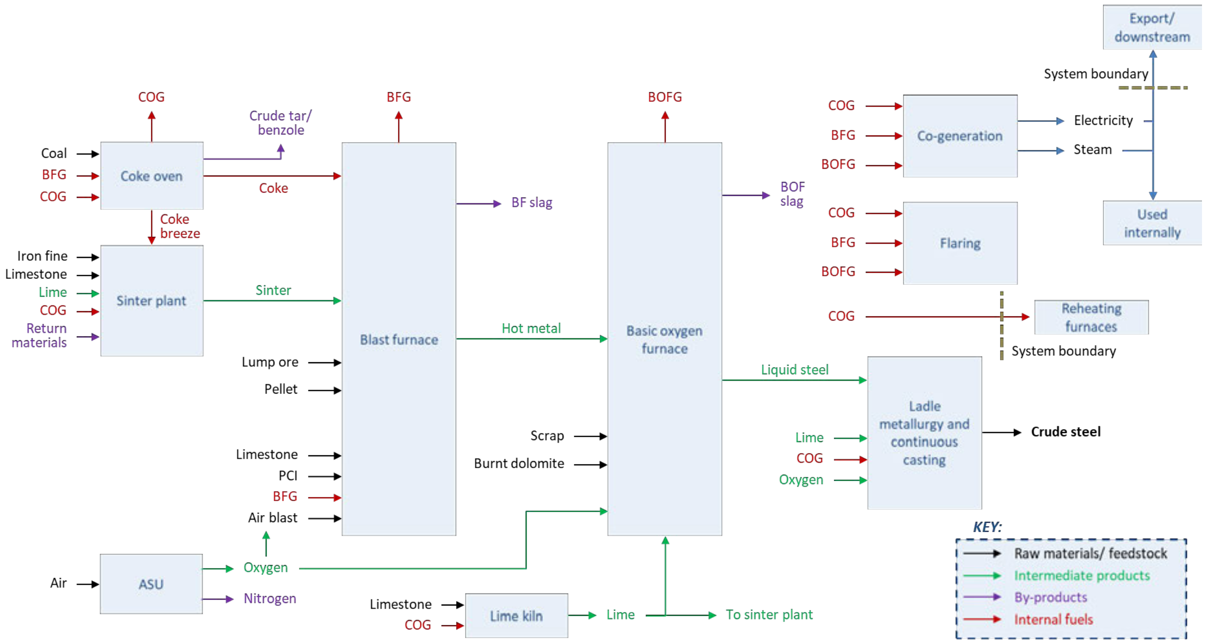


Figure 13: Integrated steel mill material process flow[12]

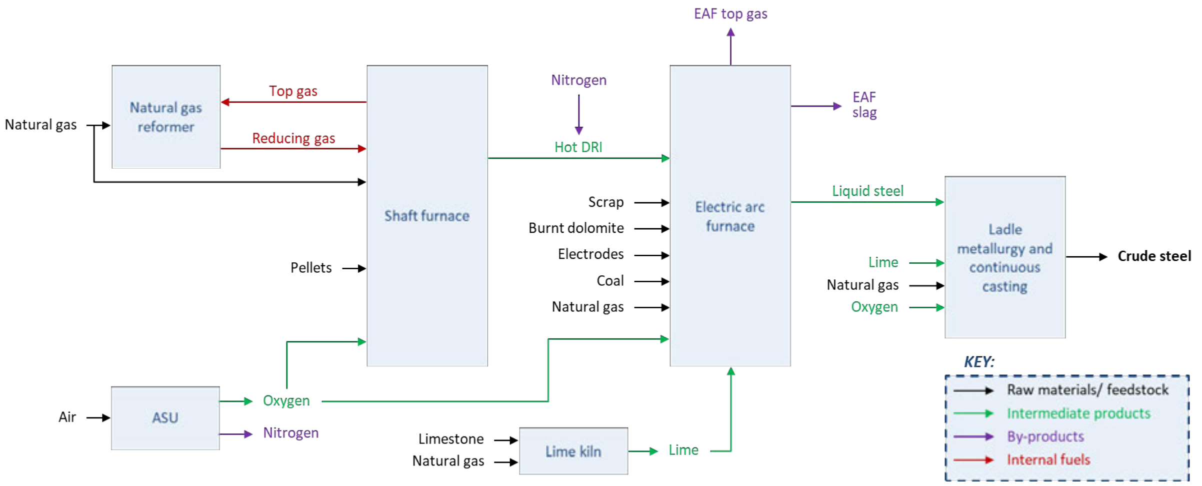


Figure 14: Natural gas-based direct reduction steel plant material process flow

[12] The blast furnace represented in the flowsheet includes the hot stoves.

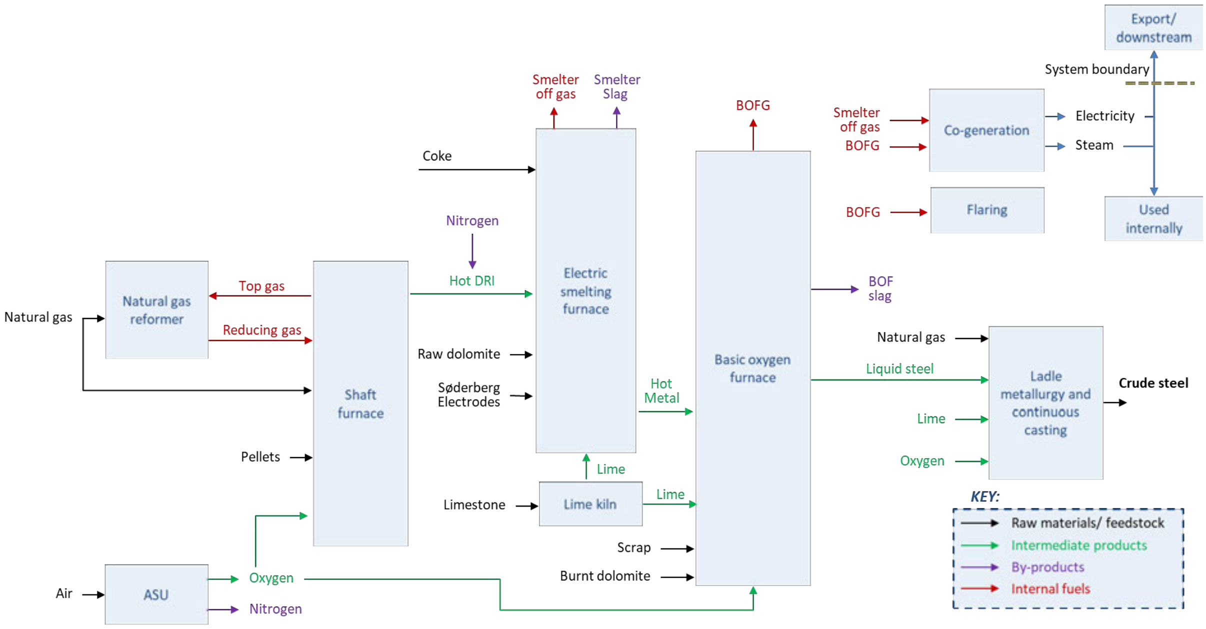


Figure 15: Material process flow for a steel mill with a direct reduction plant and electric smelting furnace

The diagrams shown above are a simplified representation of the material process flows included in the study and do not show all of the mass flows that were calculated. The major raw materials, energy flows, and utilities considered for the study were:

- Iron ore fines
- BF-grade pellets
- DR-grade pellets
- Lump ore
- Purchased scrap
- Fluxes (limestone and burnt dolomite)
- Coking coal
- PCI coal
- Charcoal
- Natural gas
- Hydrogen
- Electricity
- Water
- Other consumables (such as electrodes, amine solvent, EAF refractory lining)

The outputs sold outside the boundary limit include crude steel, the main product, and several by-products. The outputs were:

- Crude steel
- Crude tar and benzole
- Granulated BF slag and smelter slag
- Steel slag (EAF slag and BOF slag)
- Electricity

The different steel sites modelled handle several intermediate products and industrial gases and off-gases. This study included:

- Coke
- Sinter
- Lime
- Hot metal
- Sponge iron (or DRI)
- Liquid steel
- Blast furnace gas (BFG)
- Basic oxygen furnace gas (BOFG)
- Coke oven gas (COG)
- Oxygen

Finally, some materials were accounted as waste going to landfill or to other form of disposal. For some, the amount going to landfill is reduced by internal reuse or by selling them as by-products. Materials going to disposal are:

- Sinter sludge
- BF sludge
- Mill scales
- Steel and ladle metallurgy (LM) slag
- EAF dust
- Spent refractory lining
- Waste solvent
- Wastewater
- CO_2 for transport and storage

This study does not include the impact from other raw materials and by-products such as ferroalloys, quartzite, olivine, desulphurisation slag, or argon.

3.2.2 General assumptions

The steel mill is located in a coastal region of Northwestern Europe. The site is assumed to have access to natural gas and hydrogen via a pipeline, access to a port that handles imported raw materials, connection to electric infrastructure with spare capacity for increased power demand, and access to CO_2 transport and storage infrastructure.

The reference steel mill includes multiple best available technique (BAT) technologies and is considered to perform better than average. The site is equipped with coke dry quenching and a top pressure recovery turbine, has minimal flaring of off-gases, and has minimised waste to landfill through internal reuse of mill scales and sludge and selling a high share of the steel slag that is produced.

The reference plant has an annual production capacity of 4 million tonnes of crude steel per year and operates at 85% capacity utilisation factor. The production capacity is typical of European integrated steel mills (IEAGHG, 2013). Pathways that involve a transition to DRI have a smaller annual production capacity of 2 million tonnes, consistent with the smaller capacity of shaft furnaces compared to blast furnaces.

All pathways assume a 20% scrap share of the metallics input for crude steel production. Subject to scrap availability, the use of scrap can be a key driver to reduce emissions intensity; as the share of scrap use increases, the energy requirements for steelmaking decrease. However, while the BF-BOF route can only use between 10% and 30% scrap as total metallic input (Jalkanen and Holappa, 2014), the DRI route is much more flexible as EAFs can theoretically operate between 100% DRI input and 100% scrap input. Adopting a unified scrap use allows for a fair comparison between different primary production routes in a context of limited scrap availability.

The study further assumed the coke plant operates with a balanced coke production (i.e., no coke imports or exports). In addition, the captive power plant is owned by the steel site and has a balanced steam production. While there are no steam exports, electricity imports and exports from and to the grid were included in the relevant pathways. Natural gas is only used as fuel for the power plant when the use of off-gases is not sufficient to meet the steam demand.

3.2.3 Capital costs

The study takes the perspective of a brownfield site located in Northwestern Europe facing the end of campaign of their blast furnace. Hence, the capital cost structure differs significantly from a greenfield steel site.

Only the commissioning of new units and the relining of the blast furnace (for pathways that retain its use) were considered as capital costs. The potential refurbishment cost of other existing units, such as coke ovens or basic oxygen furnace, was not included. The basis for estimating the capital cost included the total installed cost for equipment, project engineering, site construction, civil works, and commissioning. Neither additional recurring capital expenditures nor contingencies were included.

Reference costs for individual units derived from literature were scaled to their required size using scaling factors and a power law relationship. Table 4 shows the reference costs used for this study.

Capital costs were derived from a steel industry CAPEX database, public reports, and academic papers (Smith, 2005; IEAGHG, 2013, 2020; Element Energy, 2018; IRENA, 2020; Metals Consulting International, 2023). There is significant uncertainty around the capital cost of some units, particularly those that have not yet been deployed at scale.

Connection costs to utilities were not included. This is a simplification, as connection costs could be significant for pathways relying on new energy flows, or pathways where energy flows increase significantly, such as those including electric arc furnaces.

Table 4: Installed CAPEX costs for different units

Expenditure	Reference cost (M€)	Reference size	Size units[13]	Main reference
Blast furnace relining	259	4,000	kt HM/y	(Metals Consulting International, 2023)
DRI shaft furnace	682	2,000	kt DRI/y	(Metals Consulting International, 2023)
Electric arc furnace	290	2,000	kt LS/y	(Metals Consulting International, 2023)
Oxy-blast furnace retrofitting	152	3,900	kt HM/y	(IEAGHG, 2013)
Capture plant	655	3,500	ktCO_2/y	(IEAGHG, 2013)
Capture plant DRI	734	5,500	ktCO_2/y	(IEAGHG, 2020)
Electric boiler	6	50	MW_e	(Element Energy, 2018)
Natural gas boiler	0.5	17	MW_{th}	(Smith, 2005)
Air separation unit	169	55,400	Nm^3/h	(IEAGHG, 2013)
Electric smelting furnace*	350	1,500	kt HM/y	Expert input

* There is a higher uncertainty linked to the cost of electric smelting furnace given that it is a nascent technology for processing DRI into hot metal.

Financial assumptions

The study assumed an economic lifetime of 25 years and a discount rate of 7% to represent the cost of capital in the cash flow. This discount rate is in line with the cost of capital for iron and steel companies in advanced economies (IEA, 2021b). Interest during the construction period was included. For each unit, a construction period of between 1 and 3 years was adopted. A capital expenditure curve was assigned to each unit depending on the construction duration according to Table 5. Decommissioning, recurring capital expenditures, working capital and depreciation of the steel mill were not included. The currency used throughout the study is €$_{2022}$, adjusting in terms of real 2022 prices. The cash flow was built in real terms, so no inflationary effect was included.

Table 5: Capital expenditure cost as percentage of total investment

Year	Build rate (years)		
	1	**2**	**3**
-3	-	-	10%
-2	-	40%	35%
-1	70%	35%	30%
1	30%	20%	20%
2	0%	5%	5%

[13] HM: hot metal; DRI: direct reduced iron; LS: liquid steel

3.2.4 Energy and raw material costs

Raw materials and energy sources reported in this study do not include the full array of inputs required by a steel mill. Instead, the materials modelled herein intend to provide an approximation of a steel mill operation. Generally, steel producers use various types of widely differing coals and additives for coke oven operation and pulverised coal injection. This study assumed only two types of coal are used: coking coal and PCI coal, both imported from Australia. A sensitivity on the coal origin is tested in Section 4.3.5 to analyse how it affects the LCA impacts. Steel mills also typically import a combination of various ore fines for the sinter plant. This study specifies that generic sinter fines are imported from Brazil. Iron ore pellets (either BF-grade or DR-grade pellets depending on the pathway) are also imported from Brazil, while lump ore is imported from Australia.

The IEAGHG 2013-04 report provides unit costs for a large set of materials, feedstock and energy sources used in an integrated steel mill. However, some commodities have seen strong price variations since then and an update is necessary. An integrated steel site and the combination of multiple production routes result in a large set of cost components. Following the Pareto principle, a small share of the cost components represents a large share of total costs. Using unit costs from the IEAGHG 2013-04 report, cost components were sorted by their impact on steel production costs. For elements that represent less than 10% of the production cost for any pathway, values from IEAGHG 2013-04 were used, adjusted by inflation and currency.

Twelve raw materials and energy sources represent more than 90% of production costs for all routes. These elements, in no particular order, are:

- Iron ore fines
- BF-grade and DR-grade pellets
- Coking coal and PCI coal
- Charcoal
- Natural gas
- Electricity
- Hydrogen
- CO_2 transport and storage
- Carbon price
- Purchased scrap

For these cost components current costs, short-term projections and long-term projections were researched. A fixed unit cost was adopted for elements where we expect a small variation over time in real terms, such as the CO_2 transport & storage tariff. For short-term projections of commodities, we used either trends from market-intelligence companies or the trading of futures as a proxy for their expected prices. Logistics costs are added to the reference FOB (Free On Board) price. Long-term projections of energy prices follow the IEA World Energy Outlook projections under the Announced Pledges Scenarios (APS) (IEA, 2022c). 2021 and 2022 have seen very high volatility in commodity prices as a consequence of supply chain disruptions and the invasion of Ukraine. When using fixed values, we have avoided taking the 2020-2022 period as a reference.

Hydrogen supply

The delivered hydrogen cost and the environmental impacts for steelmaking pathways that use hydrogen, such as H-DRI or the injection of hydrogen in blast furnaces, is highly dependent on the hydrogen supply strategy. Hence, **five different archetypes for hydrogen sourcing were modelled based on published literature. Literature includes IRENA** (2020)**, BEIS** (2021, 2022)**, Gigastack** (2021)**, Hydrogen Import Coalition** (2021)**, and IEAGHG** (2022). Table 6 presents the five archetypes and their definition, together with their GHG emissions intensity. All hydrogen supply archetypes assume over the fence supply. Hydrogen is considered renewable when it meets the criteria set under the Renewable Energy Directive (RED III) to be considered as a renewable fuel of non-biological origin (RFNBO). Thus, the renewable hydrogen archetypes assume electrolysers are connected to new renewable electricity production, meeting the requirements for the principle of additionality.

Table 6: Hydrogen supply archetypes definition

Archetype	Archetype definition	GHG emissions intensity (kg CO_2 /GJ)[14]
CCS-enabled hydrogen	Steam methane reformer equipped with CCS; pipeline transport distance <100 km; carbon cost is not included	23
Electrolytic grid hydrogen	Hydrogen produced with PEM electrolyser connected to the grid; pipeline transport distance <100 km	132
Local renewable hydrogen	Hydrogen produced with PEM electrolyser powered by renewable electricity meeting additionality criteria; long-term contract with supplier (hence paying current CAPEX and efficiency); pipeline transport distance <100 km	0
Market renewable hydrogen	Hydrogen produced with PEM electrolyser powered by renewable electricity meeting additionality criteria; market price for renewable hydrogen when market is established; pipeline transport distance <100 km	0
Renewable hydrogen imports	Renewable hydrogen imported from Middle East, shipped as liquefied hydrogen.	30

Current and future costs of hydrogen supply are hotly researched topics at the moment. Availability of renewable electricity and hydrogen infrastructure, the carbon intensity of the grid, or the origin of natural gas are all relevant variables that influence the cost and GHG emissions impact of hydrogen. By including five hydrogen supply archetypes a wide range of potential costs and GHG emissions impact is covered. Figure 16 illustrates the cost projections for the different archetypes and the wide range of costs. The market renewable hydrogen archetype is taken as the central archetype and is used when reporting results, except where noted otherwise.

Costs do not include policy support. With policy support for the hydrogen producer or for the off-taker, the delivered hydrogen cost could be lower than what is represented here. Potential hydrogen storage requirements for supply reliability were not included, neither in the costs nor in the GHG emissions intensity. The infrastructure requirements for large-scale hydrogen production are covered in Section 5.3.

[14] Operational GHG emissions, not including infrastructure emissions.

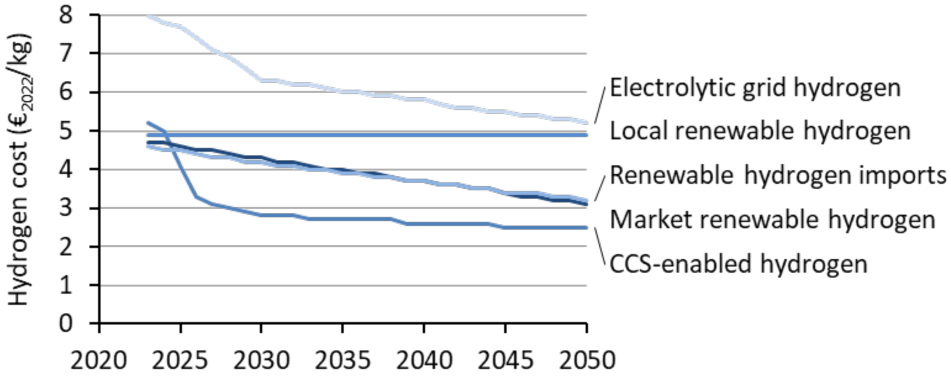


Figure 16: Hydrogen cost projection (without carbon cost) up to 2050 by supply archetype

Carbon pricing

For the carbon price we modelled both the EU ETS price and the phasing out of free allowances under the introduction of the Carbon Border Adjustment Mechanism (CBAM).

The carbon cost faced by steel producers in the EU is a combination of the price of emissions allowances traded on the European Union Emissions Trading Scheme (EU ETS) and the free allocation of allowances. Under the EU ETS, steel producers are allocated free allowances and must pay for allowances above the allocation at the EU ETS market price for their direct emissions. The 10% best performers set the benchmarks and the level of free allocation for the entire sector (European Commission, 2021). As the Carbon Border Adjustment Mechanism (CBAM) is introduced, the free allocation of allowances will be gradually reduced between 2026 and 2034 as depicted in Figure 17 (European Parliament, 2022).[15] Because the reference integrated steel mill being considered is high-performing and includes various best available technologies, this study assumed it is among the best performing 10% of the installations and hence it receives free allocation of 100% of emissions until 2025. Most steel mills, even high-performing ones, will be unable to benchmark at every process step, so this assumption represents an upside for the base case. Revenues from selling excess free allowances were not included in the model.

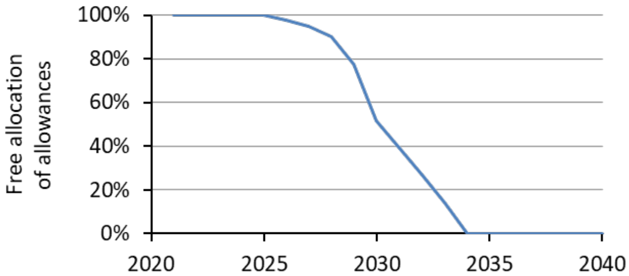


Figure 17: Phasing out of free allowances as part of CBAM introduction (European Parliament, 2022)

The EU ETS carbon price is not normative and hence projections are inherently uncertain. We have used EU ETS allowances (EUA) futures from the EEX exchange for short term projections. For long term projections we have used scenarios from the IEA World Energy Outlook 2022 under the Announced Pledges Scenario (APS).

CO_2 transport and storage cost

The boundary limit of the capture plant includes compression for pipeline delivery. All other downstream costs are included as the CO_2 transport and storage cost. A cost representative of a coastal region in

[15] The agreement reached in December 2022 has not yet received formal adoption.

Northwestern Europe was assumed. The Porthos CCS project transport and storage tariff review study and an estimate of the Aramis project transport and storage tariff were taken as a reference (Xodus Advisory, 2020, 2022). A transport and storage cost of €53.6/t CO_2 was assumed, after adjusting the currency. This cost could be significantly lower for locations with access to pipeline transport and onshore storage in depleted oil and gas fields with existing infrastructure, and could be higher for projects requiring long distance shipping of CO_2. These cases are explored in the sensitivity analysis.

3.2.5 Annual operating and maintenance costs

Maintenance costs were estimated as 5% of the installed CAPEX of new units. This is aligned with the average maintenance cost from the IEAGHG 2013-04 report. Items requiring frequent replacement, such as refractories in the electric arc furnace, were categorised as consumables rather than maintenance costs.

Maintenance costs cover both new units being installed, such as the capture plant or the direct reduction shaft furnace, and existing units from the brownfield site. The maintenance for units that already exist, such as the coke ovens or the air separation units, was included for the routes where these units keep operating. For instance, the maintenance cost of coke ovens was not included for the DRI pathways.

Labour costs of €71 per tonne of crude steel and €50 per tonne of crude steel were adopted for BF-based pathways and EAF-based pathways, respectively. For the DRI with electric smelting pathway a labour cost of €71 per tonne of crude steel was also assumed.

Overheads, depreciation and interest have not been included in the model. We do not expect this to be a significant driver of cost differences between different routes.

3.2.6 Pathway modelling

Mass and energy balance

Mass and energy balances were established for each unit process in the different steelmaking pathways. Mass and energy balances were first evaluated for individual unit processes and then linked together for the whole steel mill. **The mass and energy balances were determined by using iron and steel production data from industry**. The balances assumed steady state conditions. For some steelmaking pathways, parametrised equations were used to reflect the effect of some variables on the mass and energy balance. For instance, the electrical consumption in the electric arc furnace was adjusted depending on the scrap feed, the temperature of the DRI, and the carbon input. The balances for each material and energy flow were calculated based on mass and energy flow rates per tonne of product of the unit process and mass and energy flow rates per tonne of crude steel.

BF-BOF process modelling

The model for the integrated steel mill and its modifications (the oxy-blast furnace with CCS, the incorporation of charcoal, and hydrogen injection) was largely based on results from the IEAGHG 2013-04 study. We have deviated from the IEAGHG 2013-04 study in certain areas to align with a high-performance BF-BOF.

There are three main variables that vary from mill to mill and affect CO_2 emissions and energy use:

- **Coke rate:** the coke rate can be reduced with auxiliary reducing agents, such as pulverised coal injection (PCI). Alternatively, charcoal or H_2 can be used as auxiliary reducing agents.
- **Sinter/pellet ratio:** higher use of pellets contributes to an increased performance in blast furnaces, which reduces slag rates and coke rates.
- **Use of scrap in the BOF:** increasing the scrap rate by up to 30% can reduce emissions intensity by decreasing the hot metal-to-liquid steel ratio.

Accordingly, the model developed admits the variation of three input variables:

- **Pulverised coal injection (PCI) rate** in the blast furnace
- **Pellet share** in the blast furnace metallic burden
- **Scrap use** in the BOF

Other feedstocks and energy inputs have a lower impact on total emissions. The mass and energy balances are mostly dependent on fixed values and yields derived from literature.

The coke plant includes a coke dry quenching system to generate electricity at 180 kWh per tonne of coke. The BF is equipped with a top pressure recovery turbine to generate electricity, generating 40 kWh per tonne of hot metal. Additionally, no BOF slag is sent to landfill; all BOF slag is sold.

Off-gas utilisation can vary largely between different steel mills. In this study, it is assumed coke oven gas (COG) is sent to the coke oven, sinter plant, lime kiln, continuous casting, and reheating furnace (the latter being outside the boundary limit). Blast furnace gas is utilised in the coke ovens, the hot stoves and the co-generation plant. BOF gas is used in the co-generation plant.

A high PCI rate of 200 kg/t HM was assumed. A coke replacement ratio of 0.90 was assumed, consistent with results from Liu *et al*. (2022) and assumptions from a study by Hatch (Mourao *et al.*, 2013).

The composition of the furnace charge is a key differentiator in the operation between different integrated steel mills. Northwestern European steel producers typically use a high sinter rate. A metallic charge consisting of 65% sinter, 30% pellets, and 5% lump ore was assumed. This is aligned with typical furnace charges in Northwestern Europe (Harvey, 2020). The share of pellets in the blast furnace charge impacts the fuel rate, the ore-to-hot metal ratio, and blast furnace slag production. For each of these three parameters, data points for various integrated steel mills with different sinter and pellet usage were adjusted as a function of the pellet share.

A scrap share of the metallics input of 20% was assumed in the BOF, consistent with other pathways as detailed in Section 3.2.2. The amount of hot metal charged to the BOF was adjusted accordingly. The scrap use represents total scrap. The amount of purchased scrap was determined by subtracting home scrap availability.

Table 7 presents the main performance parameters for the integrated steel mill. Modifications to the reference pathway result in deviations from the performance. The use of hydrogen injection as an auxiliary reducing agent allows to decrease the PCI rate compared to the reference, but an increase in the coke rate is required. A maximum hydrogen injection rate of 27.5 kg per tonne of hot metal was assumed. Effects on PCI and coke rate, and adjustments to the BF gas composition and flows, were modelled following Yilmaz *et al*. (2017).

Table 7: Main performance parameters for the reference integrated steel mill[16]

Pathway	Parameter	Value	Unit
BF-BOF	Iron ore fines in sinter plant	792.3	kg/t sinter
	Specific energy demand for coke underfiring	3,876	MJ/t coke
	Specific energy demand in lime kiln	3,370	MJ/t lime
	Sinter feed to BF	65%	
	PCI rate	200	kg/t HM
	Fuel rate in BF	493	kg coke$_{eq}$/t HM
	Ore-to-HM ratio	1.58	
	%C in hot metal	4.5%	

[16] PCI: pulverised coal injection; HM: hot metal; LS: liquid steel

	BF slag rate	272	kg/t HM
	Scrap use in BOF	20%	
	Home scrap availability	73.1	kg/t LS
	Purchased scrap	144.2	kg/t LS
	Co-generation plant electric efficiency	37%	
	Electricity generation from coke dry quenching	180	kWh/t coke
	Electricity generation from top pressure recovery turbine	40	kWh/t HM
BF-BOF+H2	Hydrogen injection rate	27.5	kg/t HM
	Decrease in PCI rate	120	kg/t HM
	Coke rate increase	15.9	kg/t HM
	BF top gas	5,307	MJ/t HM
	BF top gas used for hot blast + H_2 heating	2,102	MJ/t HM
BF-BOF+CCS	Adjusted fuel rate	395	kg coke$_{eq}$/t HM
	CO_2 concentration in BF top gas	34%	vol%
	Reboiler heat duty	2.35	GJ/tCO_2
	Capture rate	94%	
	Specific power demand (capture plant + compression train)	170	kWh/tCO_2
BF-BOF+BECCS	Charcoal-PCI replacement ratio	0.899	kg PCI/kg charcoal

For the two CCS pathways, an oxy-blast furnace with top gas recycling and chemical absorption capture was modelled. This study assumed the use of an amine solvent with a 40% MDEA + 10% Pz formulation. The lower N_2 and higher CO concentration of oxy-blast furnace process gas compared to BF gas is reflected in the mass and energy flows when the process gas is exported to other units. Additionally, it was assumed that steam for the capture plant is supplied by steam recovered from the BOF and by the co-generation plant. As this is not sufficient to meet the steam demand for the capture plant, an electric boiler was modelled to provide steam to the capture plant.

In the BECCS pathway, charcoal injection is used to replace PCI coal, and coke is still produced from fossil coking coal. A full replacement of 200 kg per tonne of hot metal of PCI coal was assumed. The replacement ratio was calculated as the ratio between the gravimetric energy density of charcoal and PCI coal. No modification to the oxy-blast furnace process gas composition was reflected in the study.

DRI-EAF process modelling

The model for the natural gas-based DRI process and electric arc furnace (EAF) and its modifications (the addition of a capture unit for the shaft furnace, hydrogen-based direct reduction, and hydrogen-based direct reduction with use of biomass in the EAF) build on a set of common assumptions.

It was assumed the DRI process follows a MIDREX process. The MIDREX process accounts for 79% of global DRI production in shaft furnaces (MIDREX, 2022). It should be noted that the alternative ENERGIRON technology may be fitted with CO_2 capture and storage with lower energy requirements as the off-gas has a high CO_2 concentration. MIDREX direct reduction plants can be configured flexibly around three main parameters:

- **Feed materials**: feed materials can be either DR-grade pellets or lump ore. It was assumed DR-grade pellets constitute 100% of the feed to the shaft furnace. As covered in Section 3.2.2, imports of pellets from Brazil were assumed.
- **Energy sources and reducing gas**: energy sources can be natural gas, coal, pet coke, or coke oven gas. This study assumed use of natural gas, reformed in a MIDREX reformer. The

MIDREX reformer uses both steam reforming and CO_2 reforming, recycling the shaft furnace top gas.

- **Product output**: the product from the shaft furnace can be cold DRI, hot DRI, hot briquetted iron (HBI), or a combination of the previous ones. This study assumed the product is hot DRI, charged directly to the EAF. This implies that the site is equipped with a system to transfer hot DRI, thus reducing power consumption.

A scrap share of the metallics input of 20% in the EAF was assumed, consistent with other pathways as detailed in Section 3.2.2. The amount of purchased scrap was determined assuming 73.1 kg per tonne of liquid steel of home scrap availability. Coal and natural gas are used in the EAF as injection carbon and complement the electric energy input.

The specific electricity use in the EAF was obtained from Köhle's equation (Pfeifer and Kirschen, 2002), adapted to include the sensible heat provided by the hot DRI and adjusting the DRI coefficient based on Kirschen *et al*. (2011) and Battle *et al*. (2014).

Table 8 presents the main performance parameters for the DRI and EAF pathways. Modifications to the natural gas based DRI pathway result in deviations from the performance. For the hydrogen-based direct reduction process, it was assumed that the reducing gas consists of 100% hydrogen and no residual use of natural gas is retained. Hydrogen was assumed to be preheated by an electric heater. It was further assumed that the DRI metallization is identical to that from the natural gas-based process and that the hot DRI has the same temperature. As the DRI has no carbon content, additional carbon needs to be added to the EAF. Given the lower efficiency of injection carbon compared to in-situ carbon (Hornby Anderson, Metius and Kobayashi, 2002), a higher total carbon input is required. Additional carbon injection was assumed to be solely from coal in the H-DRI+EAF pathway. In the H-DRI+EAF+bio pathway, it was assumed that charcoal fully replaces coal for carbon injection with a replacement ratio of 0.899 kg coal/kg charcoal. This is subject to significant uncertainty, given the higher reactivity of biomass and its impact on foaming the slag.

Table 8: Main performance parameters for the DRI and EAF pathways

Pathway	Parameter	Value	Unit
NG-DRI+EAF	Ore-to-DRI ratio	1.42	
	Natural gas used in the shaft furnace	266 9.5	Nm^3/t DRI GJ/t DRI
	Electricity use in the shaft furnace	110	kWh/t DRI
	DRI metallization	93%	
	%C in DRI	2%	
	Hot DRI temperature	600	°C
	Hot DRI share of DRI input	100%	
	Scrap use in EAF	20%	
	Home scrap availability	73.1	kg/t LS
	Purchased scrap	151	kg/t LS
	Slag formers added to the EAF	60	kg/t LS
	Total C input to the EAF[17]	23	kg/t LS
	Natural gas use in the EAF	0.75	Nm3/t LS
	Electricity use in the EAF	334	kWh/t LS
	Slag rate in the EAF	100	kg/t LS
H-DRI+EAF	Hydrogen use in the shaft furnace	650	Nm^3/t DRI

[17] Total carbon includes in-situ carbon (C content in DRI) and carbon from additional sources as coal or natural gas.

	Electricity use in the shaft furnace[18]	860	kWh/t DRI
	%C in DRI	0%	
	Total C input to the EAF	48	kg/t LS
	Coal input to the EAF	54	kg/t LS
H-DRI+EAF+bio	Charcoal input to the EAF	60	kg/t LS
NG-DRI+EAF+CCS	CO_2 concentration in reformer flue gas	20%	vol%
	Reboiler heat duty	2.6	GJ/t CO_2
	Capture rate	95%	
	Specific power demand (capture plant + compression train)	124	kWh/t CO_2

For the CCS pathway, a post-combustion capture plant with amine-based chemical absorption, processing off gas from the MIDREX reformer, was modelled. This is a stream with a CO_2 concentration of 20 vol%, which contrasts with much higher concentrations from the Energiron/HYL process. Given the flue gas similarity, capture is conservatively modelled after a supercritical coal power plant although the CO_2 concentration is higher in the reformer flue gas. The IEAGHG 2020-07 study and the National Energy Technology Laboratories Cost and performance baseline for fossil energy plants are used as the main references (NETL, 2019; IEAGHG, 2020). Heat for the capture plant is provided by an electric boiler and waste heat recovery from the EAF top gas. Waste heat recovery provides around 20% of the heat input to the capture plant.

DRI-Electric smelter-BOF process modelling

To model the DRI with electric smelting pathway it was assumed the DRI production follows the MIDREX process in accordance with the other DRI pathways. The shaft furnace is fed with BF-grade pellets and a lower metallization is achieved. Other shaft furnace operating parameters remain unchanged: we have assumed use of natural gas reformed in a MIDREX reformer and the product is hot DRI charged to the electric smelting furnace. Given its lower technology maturity, the electric smelting furnace was modelled following engagement with stakeholders who provided technical input.

Heating inside the electric furnace was assumed to be purely electrical (radiative and resistive from the electrodes). Coke is added to the electric smelting furnace for carburization of the melt, further reduction processes and to adjust the carbon content. The total carbon input to the electric smelting furnace is 61 kg per tonne of hot metal (t HM), of which 24 kg/t HM is in-situ carbon from the DRI. Coke use in the electric smelting furnace is 48 kg/t HM. The pre-existing coke oven was assumed to close under such reduced levels of production and the remaining coke demand is imported.

Slag produced from the electric smelting furnace was modelled with a similar composition to BF slag, as specified by industry, and 100% of the slag produced is sold as granulated BF slag. Calorific off gas from the smelter, modelled with a calorific value of 10.8 MJ/Nm^3, is used entirely in the on-site power plant although in practice this gas could also be used in the shaft furnace. Scrap use in the BOF follows the same approach taken for the BF-BOF pathways.

3.2.7 Output metrics

Performance data and costs were combined in a cash flow to derive quantitative key performance indicators (KPIs). The main outputs are:

- **Levelised production cost of crude steel**
- **Costs of CO_2 abatement**

[18] Electricity use includes 750 kWh/t DRI for hydrogen preheating to 950 °C.

- **Energy and feedstock consumption**.

The levelised production cost of crude steel is the breakeven price for crude steel assuming all project cash flows are brought to present value. That is, it is the price at which steel producers can sell crude steel and achieve equal production costs and revenues in present-day euros.

Energy consumption is reported as final energy demand. It does not include energy transformations outside the boundary limit. The TEA also computes direct CO_2 emissions and indirect GHG emissions from purchased electricity and hydrogen. This GHG accounting is simplified and does not include GHG emissions associated with material imports or downstream processes. A more complete assessment of GHG emissions and other environmental impacts is presented in the LCA in Chapter 4

The levelised cost of CO_2 abatement (LCOA) represents the cost per tonne of CO_2 abated assuming all production cost differentials throughout the economic lifetime are brought to present value. It is calculated following Equation (1). This metric can be compared with carbon pricing and can be interpreted as the carbon price that would be needed to make a given steel production pathway achieve cost parity with the base case BF-BOF pathway. An alternative way of calculating the LCOA uses different discount rates for costs and emissions. This approach is not followed here, as the perspective of an industrial for whom CO_2 is an economic product is taken.

$$LCOA = \frac{\sum \frac{Additional\ costs_i}{(1+r)^i}}{\sum \frac{Abated\ emissions_i}{(1+r)^i}} \tag{1}$$

The LCOA was calculated by including abatement of direct CO_2 emissions and indirect GHG emissions from purchased electricity and hydrogen. The carbon price on emissions allowances under the EU ETS for steel producers, however, only applies to direct CO_2 emissions. As a result, electricity- or hydrogen-intensive pathways may achieve cost parity with the base case BF-BOF pathway at a lower carbon price than the LCOA. To account for this, **a breakeven effective carbon price was also calculated by including only direct CO_2 emissions in the denominator**.

3.2.8 Sensitivity analysis

A supplementary sensitivity analysis was carried out by varying input parameters. Parameters were deviated from the baseline scenario to reflect a low-cost and a high-cost scenario. The sensitivity analysis was used to identify the most important parameters affecting steel production costs for different routes and to spot out the major sources of uncertainty.

Parameters were changed one at a time keeping other parameters fixed to assess the sensitivity of results to each parameter. Rather than studying the sensitivity of the results to a uniform perturbation to all input parameters (for instance, by modifying all parameters one at a time by ±10%), low- and high-cost scenarios were introduced. This allows reflection of the fact that some parameters are subject to greater uncertainties on their future evolution. A global sensitivity analysis was also used. Under a global sensitivity analysis, all input parameters are varied at the same time to reflect the low-cost and high-cost scenarios. In this way, the expected range of production costs can be obtained.

As covered in Section 3.2.4, the techno-economic analysis uses cost projections from 2023 to 2050 for the key cost variables. For the sensitivity analysis, an equivalent fixed cost was used instead to allow for changes in a single parameter, rather than changing the entire time series. For a constant annual steel production, the equivalent fixed cost results in the same present cost as when cost projections are used.

The parameters considered for the sensitivity analysis are energy prices (including electricity, coal, natural gas, and hydrogen), iron ore (focusing on the DR premium – i.e., the price differential of DR-grade pellets over BF-grade pellets), effective carbon price, the heat duty of regeneration,[19] and CO_2 transport and storage costs. Table 9 shows the input parameters for the sensitivity analysis under the central scenario and the variations introduced for the low- and high-cost scenarios.

Table 9: Parameters for the sensitivity analysis under different scenarios

Sensitivity	Unit	Low	Central	High
Electricity	€/MWh	25	56	150
Coking coal	€/t	50	179	350
PCI coal	€/t	50	139	350
Natural gas	€/GJ	2	8.6	13
Hydrogen	€/kg	2	4.1*	8
DR premium	%	0%	9.3%	50%
Carbon price	€/t CO_2	40	78.2	160
Heat duty of regeneration	GJ/t CO_2	2.0	2.35**	3.2
CO_2 transport and storage	€/t CO_2	15	53.6	90

* The central cost range depends on the hydrogen supply scenario. Cost from table is for 'Market renewable hydrogen' supply archetype.
** Central values are 2.35 GJ/t CO_2 for capture from an oxy-blast furnace and 2.55 GJ/t CO_2 for capture from a shaft furnace.

The low and high energy prices include current high prices under the energy crisis and low prices informed by pre-crisis prices and optimistic projections. For electricity prices, the low range represents optimistic assumptions on renewable energy costs for industrial users, while the high range is representative of typical electricity prices for industrial users in Northwestern Europe in 2022, noting that steel mills often access lower electricity prices than other industrials. The same low and high prices were adopted for coking coal and PCI coal for simplicity. The upper bound is representative of 2022 and early 2023. The announcement by BHP (the largest shipper of coking coal) in November 2022 that they have no "growth capital" allocated to coking coal may raise concern about future prices (Fernyhough, 2022). As for natural gas, the range spans between a cost that could be representative of the Henry Hub price before the energy crisis and a high price expected in Europe in the short term. In the case of hydrogen, the high cost represents the upper end of the expected delivered cost for low-carbon hydrogen. For the low cost range, while costs as low as or even lower than $1/kg are often proposed for renewable hydrogen, this can be seen as an unrealistic and aspirational goal (Wan and Butterworth, 2023). A low cost of €2/kg was assumed, consistent with a low natural gas price in the case of CCS-enabled hydrogen or a strong reduction in renewable energy costs and electrolyser system CAPEX for renewable hydrogen.

The carbon price included in the sensitivity is the effective carbon price. It takes into account both the price of emissions allowances traded on the EU ETS and free allowances allocated to the steel mill. The effective carbon price is calculated as the EU ETS price * (1 – % of free allowances).

For CO_2 transport and storage, the low cost is representative of pipeline transport for storage in a depleted onshore oil and gas field. The high cost may be representative for offshore storage and CO_2 shipping. It should be noted that for long shipping distances this cost could be higher than €90/t CO_2.

3.2.9 Limitations of this study

Results from the analysis cannot be generalised for all steel mills as they are affected by certain limitations:

- The analysis does not include some mass flows as detailed above.

[19] The heat duty of regeneration is the required heat input per tonne of CO_2 captured.

- The analysis takes the perspective of an existing integrated steel mill and hence excludes capital costs that would be faced by a greenfield site.
- Even for a brownfield site, connection costs could be significant. These are not included in this study.
- The levelised cost of production metric provides a simplified representation of production costs throughout the economic lifetime of the investment. The evolution of production costs offers a more complete picture.
- Results are highly sensitive to energy and feedstock costs, and these are subject to deeply uncertain projections. Projections explore potential pricing scenarios but are not predictions of future prices.
- The mass and energy balances did not build on bottom-up modelling of the processes, nor did they account for enthalpy changes and chemical energy from the different reactions involved. Less mature pathways could see significant performance improvements in the future compared to what is modelled in this study.

3.3 Results

The techno-economic analysis of the nine steelmaking pathways is reported in the following section. Apart from reporting steel production costs, the techno-economic analysis includes an assessment of direct CO_2 emissions, indirect emissions from purchased electricity and hydrogen production, and final energy demand. These results, particularly those related to GHG emissions, should be read together with the LCA results from Chapter 4.

3.3.1 GHG emissions and final energy demand

Direct CO_2 emissions and final energy demand for all pathways are shown in Figure 18. It was assumed that charcoal is sustainably sourced, and hence biogenic emissions are not included – but they are discussed within the LCA chapter.

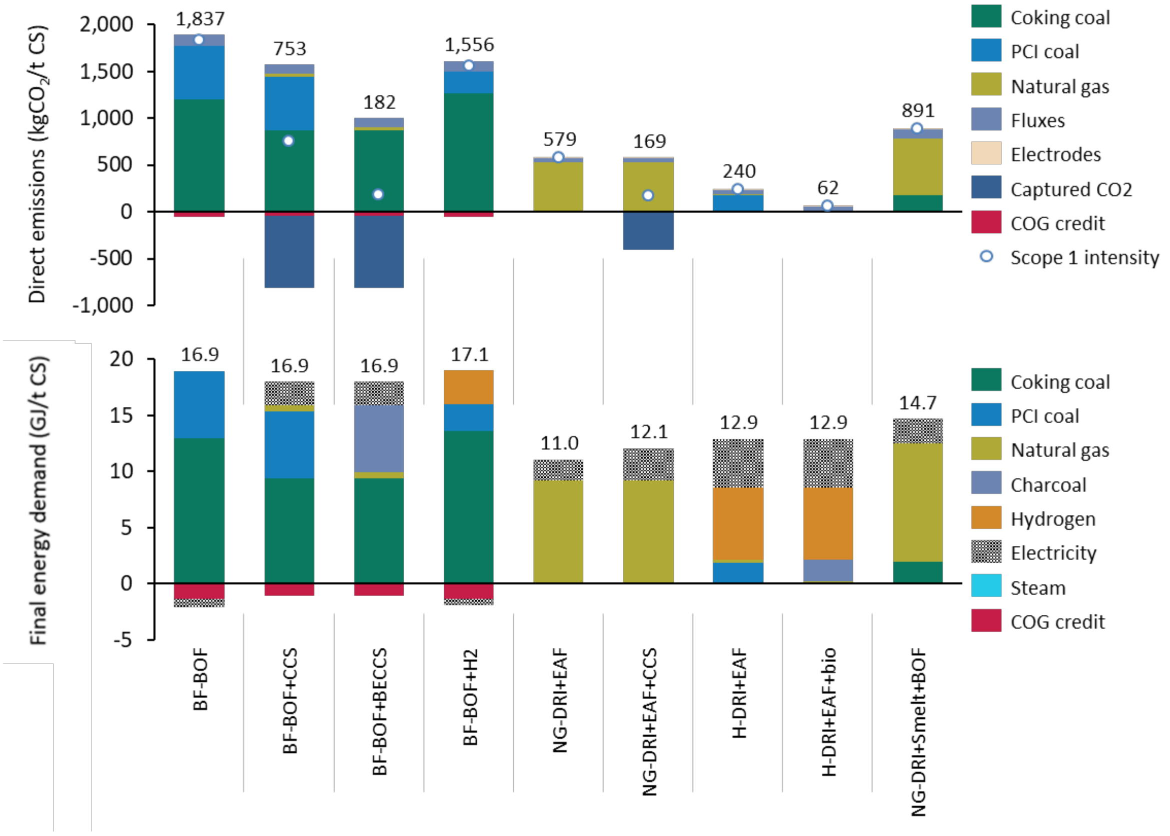


Figure 18: Direct emissions intensity and final energy demand for steel production pathways

Results show that **transitioning from BF-BOF steelmaking lowers a site's final energy demand and can significantly reduce the direct CO_2 emissions intensity of the crude steel product**:

- **Modification of the integrated steel mill retaining use of the blast furnace can reduce direct CO_2 emissions, but emissions reductions greater than 60% may only be possible with extensive use of biomass and CCS**. The final energy demand remains fairly similar across all pathways that include the blast furnace. Hydrogen injection into blast furnaces leads to only 15% abatement of direct CO_2 emissions and a slightly higher final energy demand.
- **Significant direct CO_2 emissions reduction can be achieved when using CCS technologies**. The BF-BOF+CCS pathways can lead to 60% direct CO_2 emissions reduction by capturing almost 780 kg CO_2/t CS and reduced use of coke in the oxy-blast furnace. While this pathway lowers energy demand from coking coal, this is balanced by the additional electricity demand for the capture plant. When incorporating charcoal injection as a full replacement of PCI coal in the BF-BOF+BECCS pathway, direct fossil CO_2 emissions are strongly reduced to about 10% of the BF-BOF base case. The feasibility of using such a high amount of charcoal in a blast furnace from a supply chain point of view is explored in Chapter 4.
- **The commercially mature natural gas-based DRI pathway provides significant immediate reductions in direct CO_2 emissions and minimises the final energy demand.** The additional inclusion of CCS increases the final energy demand but can bring the direct CO_2 emissions down to 169 kg CO_2/t CS, 9% of the BF-BOF case.
- **The use of hydrogen as the reducing agent provides a significant decrease in direct CO_2 emissions**, although direct emissions from the EAF increase compared to the NG-DRI+EAF pathway. The H-DRI+EAF+bio pathway results in further emissions abatement by substituting charcoal for coal in the EAF, bringing the direct CO_2 emissions intensity down to 62 kgCO_2/t CS, a 97% reduction on the base case.

- **Transitioning to DRI pathway with an electric smelting furnace and maintained BOF operation allows the continued use of BF-grade pellets**. Emissions reductions are significant but modest when compared to other DRI pathways. The direct CO_2 emissions intensity of this pathway is 48% of the emissions intensity from the base case, and the final energy demand is reduced by 13%.

While reductions in direct CO_2 emissions are valuable and inform the carbon cost the steel producer needs to face, indirect emissions from electricity generation and from hydrogen production can be significant for pathways making an intensive use of those energy sources. Figure 19 shows the direct CO_2 emissions and indirect emissions from purchased electricity for the different steel production pathways, plotted against the ResponsibleSteel standard Near Zero threshold (ResponsibleSteel, 2022).[20] The results are average emissions over the site's lifetime, taking into account improvements in steel emissions intensities over time from a decarbonising electricity supply. A location-based approach is followed to quantify the carbon intensity of the grid – i.e., external electricity imported to the steel mill has been assumed to take grid average carbon intensities. With indirect GHG emissions from purchased electricity accounted for, H-DRI+EAF+bio remains the lowest emissions pathway, reaching an 88% reduction in GHG emissions intensity compared to the base case.

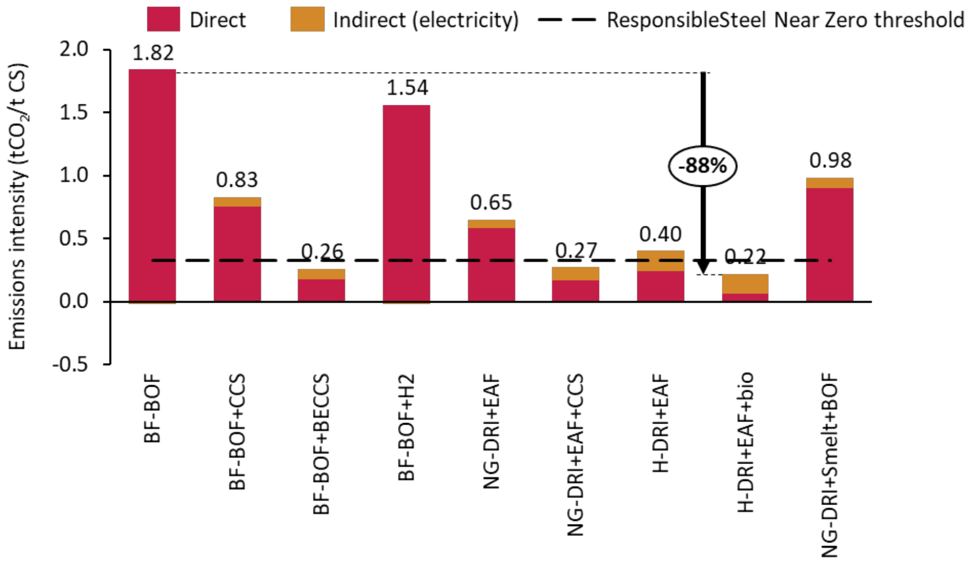


Figure 19: Average direct and indirect emissions from purchased electricity of production pathways over lifetime

Indirect emissions from purchased electricity represent a large share of total emissions for the lowest-carbon pathways. As Figure 19 shows, the H-DRI+EAF pathway is not able to meet the Near Zero threshold from the ResponsibleSteel standard when a grid average carbon intensity is considered. Additionally, Figure 19 does not reflect indirect emissions from hydrogen production because the market renewable hydrogen supply archetype, with a GHG emissions intensity of 0 kg CO_2/GJ, was adopted (see Section 3.2.4 for archetype definition). However, indirect GHG emissions from hydrogen production could have a significant impact on the total GHG emissions intensity of steel production.

Figure 20 shows how the GHG emissions intensity for the H-DRI pathways could change depending on the electricity and the hydrogen source:

[20] The ResponsibleSteel standard Near Zero emissions intensity threshold accounts for direct CO_2 emissions and GHG emissions associated with the generation of electricity imported to the site and with imported materials. The comparison in the charts is a simplification as GHG emissions associated with imported materials are not shown here – but they are covered in the LCA in Chapter 4. For a scrap share of metallics input of 20%, the Near Zero threshold is 0.330 t CO_2/t CS.

- **The H-DRI+EAF pathway can only meet the ResponsibleSteel standard Near Zero threshold when procuring low-carbon electricity and renewable hydrogen transported by pipeline**.
- Electrolytic hydrogen using grid electricity has the highest associated GHG emissions due to the GHG footprint of the electricity used to produce it. Similarly, importing renewable hydrogen requires batch liquefaction and transport with high associated emissions. The local renewable hydrogen or the market renewable hydrogen archetypes have the lowest associated GHG emissions.
- Indirect emissions from purchased electricity can represent a large share of total emissions for the H-DRI routes. By procuring renewable electricity, the GHG emissions intensity of the H-DRI+EAF pathway can be reduced by 39% to 240 kg CO_2/t CS. In the case of the H-DRI+EAF+bio pathway, renewable electricity delivers an even greater reduction in the GHG emissions intensity, and would allow for the use of CCS-enabled hydrogen while still meeting the Near Zero threshold.

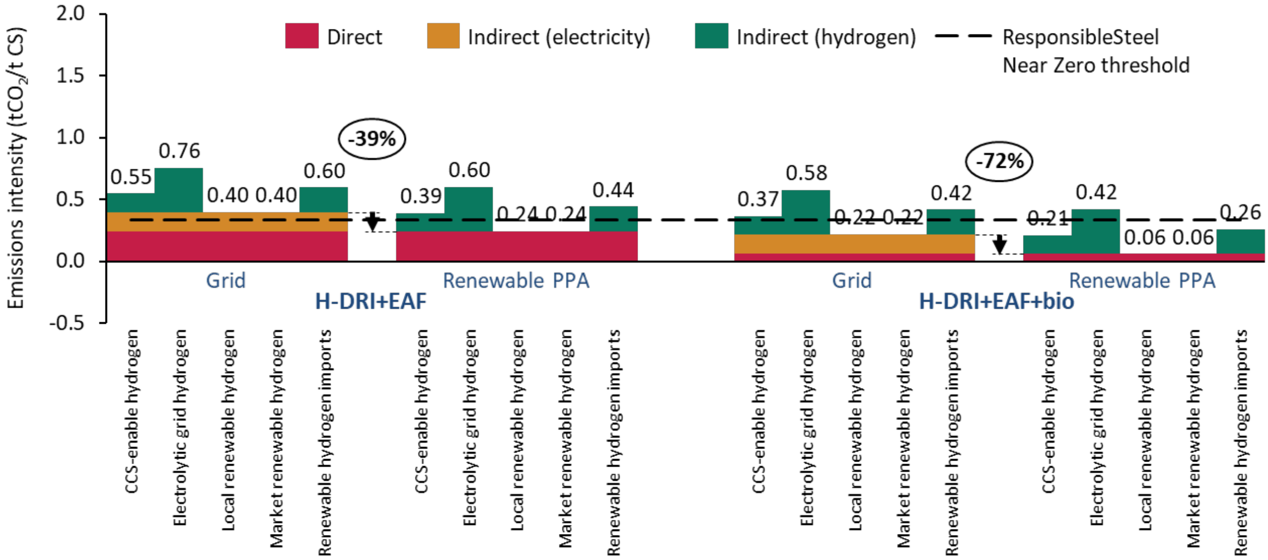


Figure 20: Average emissions intensity of production pathways over lifetime for different hydrogen supply archetypes for grid electricity and renewable electricity

3.3.2 Production costs and levelised cost of abatement

Steelmaking under the BF-BOF pathway results in the lowest levelised cost of production across all pathways, even after accounting for carbon pricing. Figure 21 presents the breakeven steel prices of the different steelmaking pathways. The base case BF-BOF pathway remains the cheapest production route and all BF-BOF pathways present lower costs than any DRI route. Pathways involving CCS imply a relatively modest production cost increase compared to the base case, ranging between 5% and 18%. The H-DRI pathways have the highest breakeven prices, 44% greater than the base case (including carbon price).

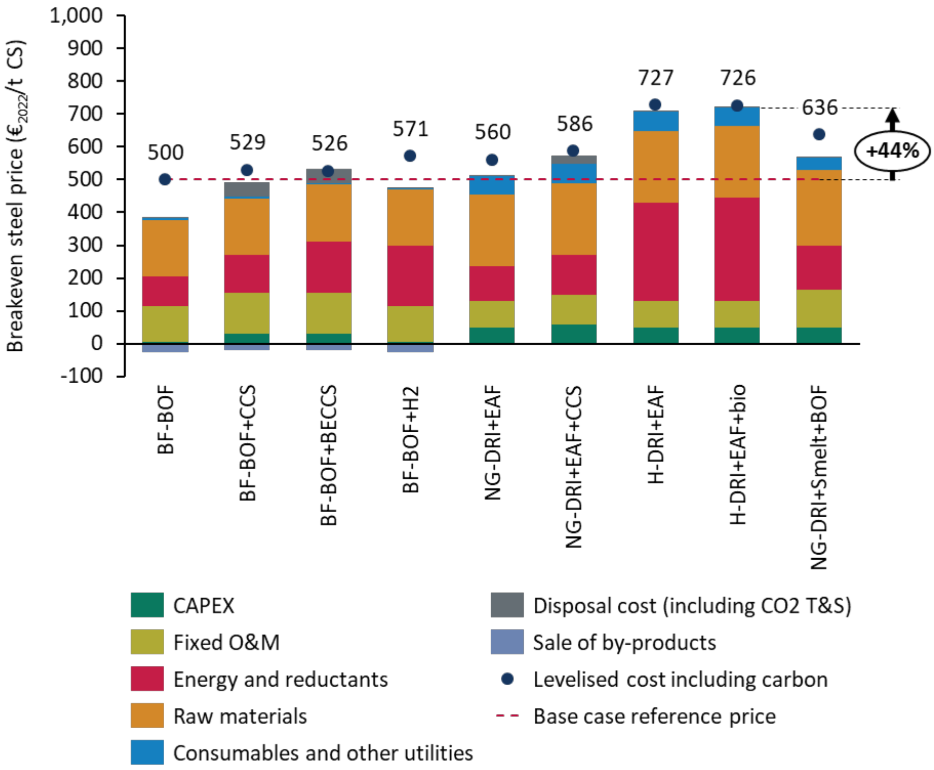


Figure 21: Breakeven steel price across production pathways

The results expose that current carbon pricing is not a sufficient incentive towards pathways with a lower GHG emissions intensity. While some pathways are close to reaching cost parity with conventional integrated steelmaking and would require little additional support, stronger policy support would be required for H-DRI pathways to reach cost parity. As can be seen in Figure 21, CAPEX represents a relatively small portion of the levelised costs. Government funding or capital grants could unlock access to capital for a sector that has typically struggled to raise private capital, but it does not address the much larger operating costs expected under the H-DRI pathways. These higher operating costs are dominated by increased costs for energy and reductants.

Transitioning away from conventional BF-BOF steelmaking modifies the cost structure of steel production. As it is evident from Figure 21, pathways with significant usage of hydrogen pay much more for energy than pathways using natural gas or coking coal. When compared to the BF-BOF base case, H-DRI pathways pay more than three times more for energy and reductants per tonne of crude steel. The difference in the cost structure as sites transition away from conventional integrated steelmaking is further explored in Figure 22.

Raw materials are the largest cost component for the BF-BOF pathway. **The relative importance of raw materials in the cost structure decreases for all other pathways**. For routes using hydrogen, costs are mostly driven by energy. Energy and reductants represent 40%, 42% and 43% of production costs excluding carbon for the BF-BOF+H2, H-DRI+EAF and H-DRI+EAF+bio pathways, respectively. The changing cost structure illustrates the shifting balance between the importance of raw materials and energy costs as sites transition away from the BF-BOF route. Sites that are well positioned to access cheap raw materials might lose cost competitiveness if they cannot also access cheap energy. At the same time, reliance on pathways where energy represents a larger share of total production increases the exposure of steel producers to the risk of price volatility. While price volatility is an inherent risk for all commodities, prices of energy are generally more volatile than prices of other commodities.

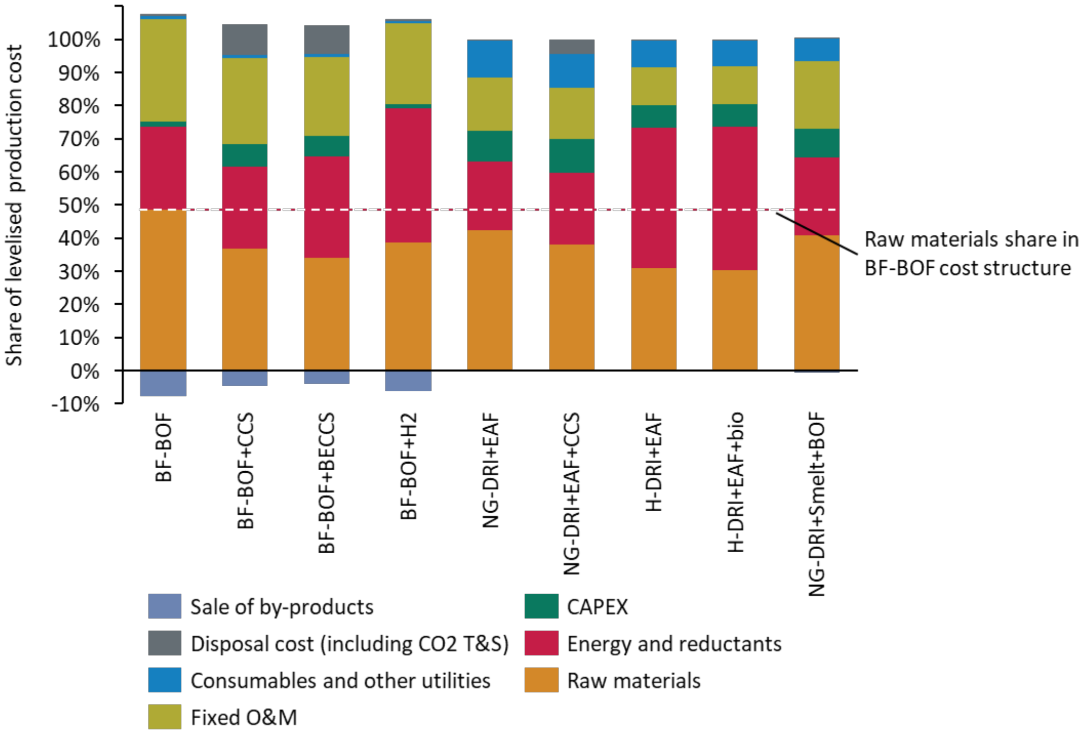


Figure 22: Cost structure for different steel production routes, not including carbon

Figure 21 and Figure 22 show levelised production costs by calculating the present value of a cash value. In reality, the breakeven steel price for steel producers will vary together with variations in raw materials, energy and carbon costs. As those costs change over time, the production cost of a tonne of crude steel will evolve differently for each pathway.

Figure 23 shows the breakeven price for steel over time for the different pathways. **The gap between the breakeven steel price for the BF-BOF pathway and other routes closes as carbon costs increase and energy prices decrease**. There is, however, significant uncertainty in future projections.

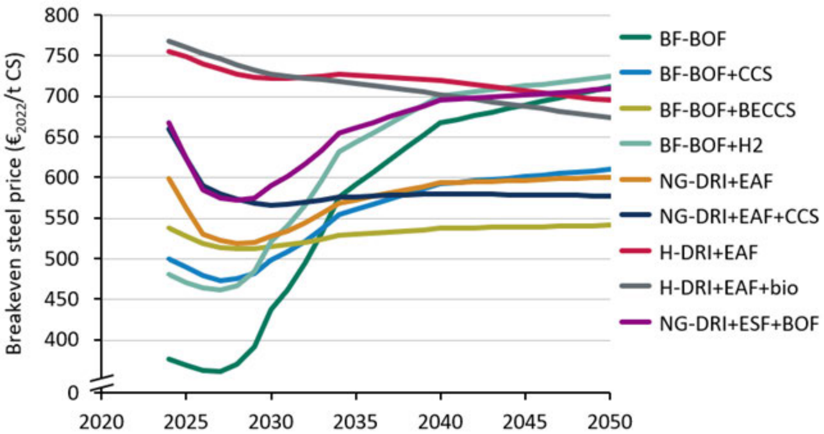


Figure 23: Breakeven price for steel for different steel production pathways over time

The trends in the evolution of prices for the different pathways change over time:

- In the short term, all routes see a decline in production costs as energy and commodity prices slowly recover from the current all-time highs.
- **In the medium term, the phasing out of free allowances increases the breakeven price as sites have to pay for an increasing share of their emissions**. This leads to a very sharp

price increase for carbon intensive pathways, with BF-BOF and BF-BOF+H2 routes seeing the steepest cost increase. Pathways with low direct CO_2 emissions, such as BF-BOF+BECCS, H-DRI+EAF, and H-DRI+EAF+bio, only see a very small cost increase.

- Over the long term and after the complete phasing out of free allowances in 2035, carbon intensive pathways continue to experience rising costs due to the increase in carbon costs. The H-DRI routes see a long-term decline as hydrogen price decreases over time. **By 2050, the BF-BOF+BECCS and the NG-DRI+EAF+CCS pathways present the lowest breakeven price**. By then, only the BF-BOF+H2 pathway results in a higher breakeven price for steel than the base case BF-BOF pathway.

Pathways relying on CCS seem to have a cost advantage over other production pathways, namely H-DRI. It should be noted, however, that the techno-economic modelling does not capture certain risks faced by different decarbonisation technologies. In the case of CCS, for instance, low public acceptance in some major steel producing countries (Dütschke *et al.*, 2015) and lack of political consensus to provide political and regulatory stability may shift steel producers' preference towards H-DRI pathways. In addition, CCS pathways will inherently result in a higher production cost than their unabated alternative, excluding carbon costs. Pathways that do not rely on CCS, on the other hand, could theoretically reach lower production costs even without carbon pricing as they depend on new energy flows. A wider range of potential future production costs for the H-DRI+EAF pathway are explored in Box 2. Other challenges on the supporting infrastructure are discussed in Chapter 4.

Box 2 – H-DRI in the spotlight

The cost gap between the BF-BOF pathway and H-DRI+EAF could close before 2040, depending on the hydrogen sourcing strategy and evolution of costs. Figure 24 shows that the breakeven price of steel for routes using hydrogen strongly depends on the hydrogen supply archetypes, as defined in Section 3.2.4.

Before the 2040s there remains a significant gap between BF-BOF and H-DRI. Considering that in Northwestern Europe there is momentum behind a transition towards H-DRI and given its higher breakeven steel price, this might only be economically justified if producers either receive operational support or if they can secure a substantial green premium on H-DRI steel over a long term. The possibility of securing a green premium on clean steel is discussed in Chapter 6.

H-DRI could be economically competitive in other regions with a higher potential for low-cost hydrogen and electricity. Transporting DRI (as HBI) to European EAFs might prove more economically efficient than transporting liquid hydrogen, as it can be transported in bulk carrier at lower costs than hydrogen liquefaction and regasification. A detailed assessment on H-DRI costs in different regions and associated trade flows is not addressed in this study, but is an area for further work.

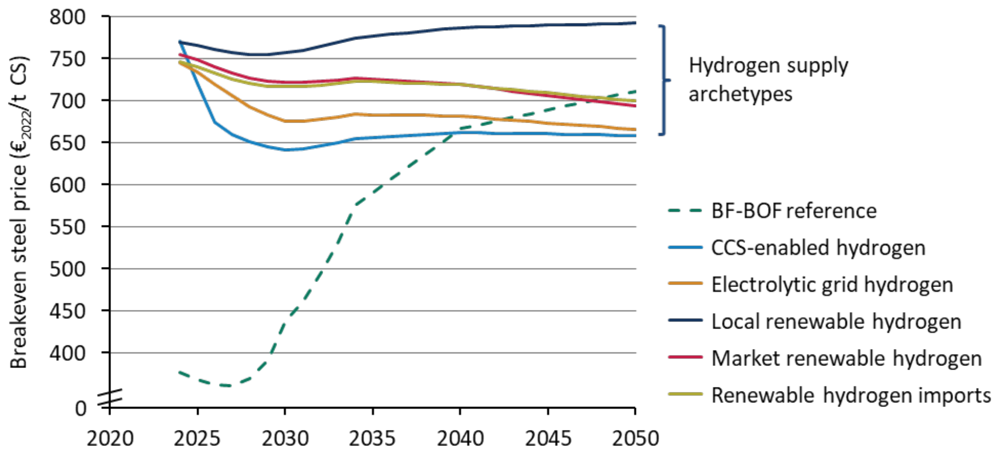


Figure 24: Breakeven steel price for H-DRI pathways depending on hydrogen supply archetype

Figure 25 shows the levelised cost of abatement (LCOA) for direct and indirect emissions for the different decarbonisation pathways. The three CCS pathways and the NG-DRI+EAF pathway present a relatively low LCOA. The two H-DRI pathways and the NG-DRI+Smelt+BOF pathway have an LCOA ranging between 229 and 251 €/t CO_2. **Injection of hydrogen in a blast furnace is the least cost-effective pathway for GHG emissions reduction**, with an LCOA of €334/t CO_2.

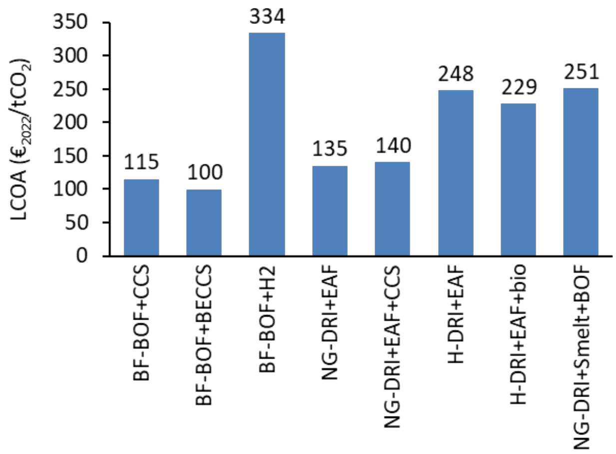


Figure 25: Levelised cost of abatement (LCOA) for different steelmaking pathways

For some routes, the breakeven effective carbon price - which only applies to direct CO_2 emissions - is within the range of future carbon price projections. Figure 26 illustrates the breakeven carbon price and the GHG emissions abatement for the different pathways. The three CCS pathways and the NG-DRI+EAF pathway have a breakeven carbon price lower than €200/t CO_2, the upper end of carbon price projections in Europe towards 2050. However, BF-BOF+CCS and NG-DRI+EAF do not deliver deep direct emissions reductions. In the case of the modelled BF-BOF+CCS route, this is explained due to the CO content in the upgraded blast furnace process gas, after CO_2 separation, and due to the additional emissions sources in the integrated site that are not routed to a capture plant. Alternative CCS configurations could potentially lead to higher emissions reductions. For hydrogen routes, the breakeven carbon price is higher than expected carbon prices up to 2050. H-DRI could still be the most cost-competitive pathway delivering deep decarbonisation when CCS routes are deemed not to be feasible.

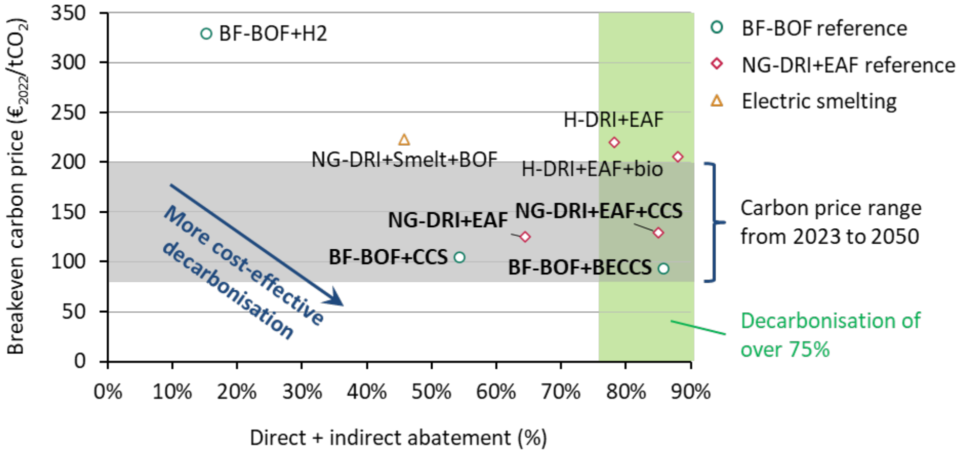


Figure 26: Breakeven carbon price and emissions intensity reduction for different steelmaking routes

While under this analysis **H-DRI provides less cost-effective decarbonisation** than NG-DRI+EAF+CCS or BF-BOF+BECCS, the **former might be the preferred option under strategic considerations**. Continued reliance on natural gas for NG-DRI+EAF+CCS threatens energy security, and biomass availability may limit the BF-BOF+BECCS pathway. This is further explored in Chapter 4. For H-DRI to be a cost-effective abatement option, it will require sustained policy support.

3.4 Sensitivity analysis

The sensitivity analysis shows that all routes exhibit a high sensitivity to energy prices, with the relevant energy carrier varying between pathways. Figure 27 presents sensitivities from the different pathways to variations in the price of electricity, coal, natural gas, and hydrogen.

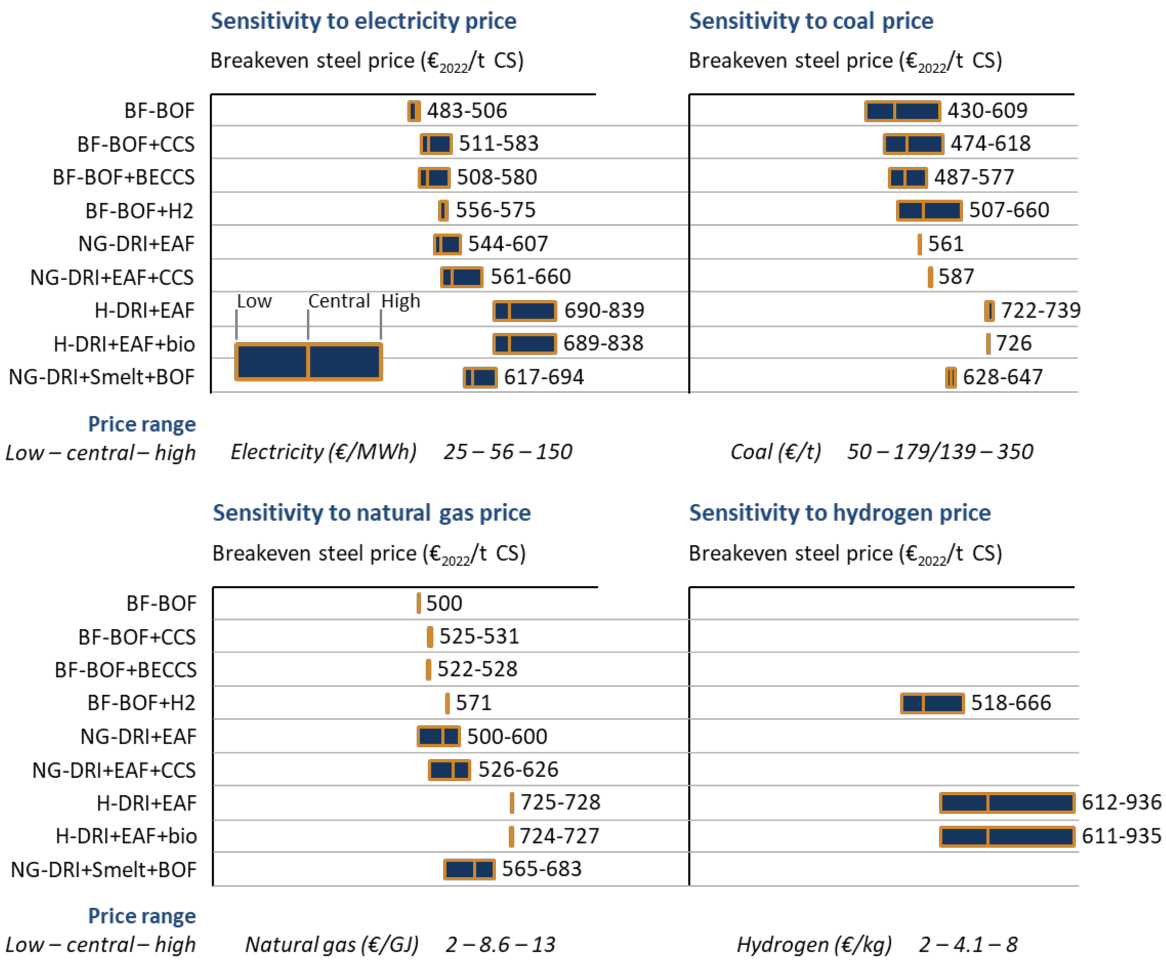


Figure 27: Sensitivity of breakeven steel price to energy prices for different pathways

Not all pathways are equally sensitive to prices of different energy carriers:

- The most electricity-intensive steel production pathways show a strong sensitivity to electricity prices. This is particularly the case for the H-DRI pathways, where production costs could vary by -5% to +15%. Access to low-cost electricity can significantly lower the breakeven steel price but it is not sufficient on its own to make H-DRI cost-competitive.
- The BF-BOF pathways show a strong sensitivity to coal prices. High coal prices can make DRI pathways competitive on a cost basis. Given recent announcements by coking coal miners that put future coking coal availability and cost in question (Fernyhough, 2022), this could be a major source of concern for producers opting to continue use of their blast furnaces.
- Access to cheap natural gas price could lower the production cost of natural gas-based DRI pathways significantly and move them closer to cost-parity with the BF-BOF routes. Levelised production costs could vary by -11% to +7% for the NG-DRI+EAF pathway.
- The H-DRI pathways have a higher use of hydrogen per tonne of crude steel than injecting hydrogen in a blast furnace. Thus, H-DRI pathways are more sensitive to variations in its price. Variation on the breakeven steel price when moving from a low-cost to a high-cost scenario can amount to over 50%, as further shown in Figure 28. Although low hydrogen prices can greatly reduce the levelised cost of production (by -16% compared to the central scenario), access to low-cost low-carbon hydrogen (€2/kg) is not sufficient on its own to make H-DRI competitive on a cost basis with BF-based routes.

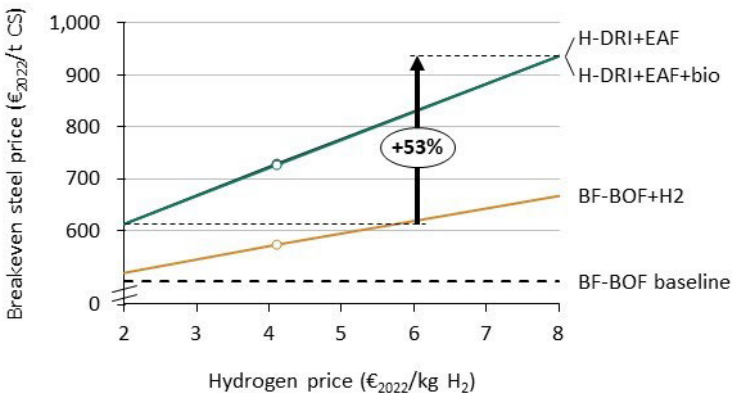


Figure 28: Breakeven steel prices against hydrogen cost

Carbon prices can level the playing field for cleaner alternatives but are not sufficient to allow hydrogen-based pathways to compete on a cost basis. Figure 29 and Figure 30 show the sensitivity of levelised production costs to the effective carbon price. Steelmaking pathways with a high GHG footprint, such as BF-BOF or BF-BOF with H_2 injection, are very sensitive to the effective carbon price. Thus, with an increase in EU ETS prices and/or a faster phasing out of free allowances, the cost gap between the BF-BOF pathway and alternatives with a lower carbon footprint closes. Under the high carbon price scenario multiple pathways (BF-BOF+CCS, BF-BOF+BECSS, NG-DRI+EAH, and NG-DRI+EAF+CCS) have a lower breakeven steel price than the conventional BF-BOF pathway.

With an effective carbon price of around €100/t CO_2 the BF-BOF+CCS route could be cost-competitive with the continued use of an unabated blast furnace. DRI routes achieve cost parity with effective carbon prices of €120/t CO_2 and greater. Within the modelled ranges, carbon pricing alone would not be sufficient for H-DRI to reach cost-parity with the BF-BOF route. Lower hydrogen or electricity prices, operating cost support, or the ability to secure green premia would be required to cover the gap.

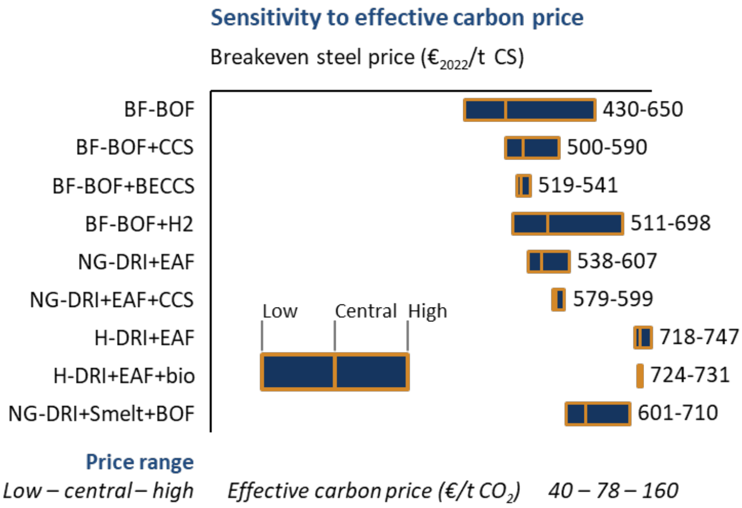


Figure 29: Sensitivity of breakeven steel price to effective carbon price for different pathways

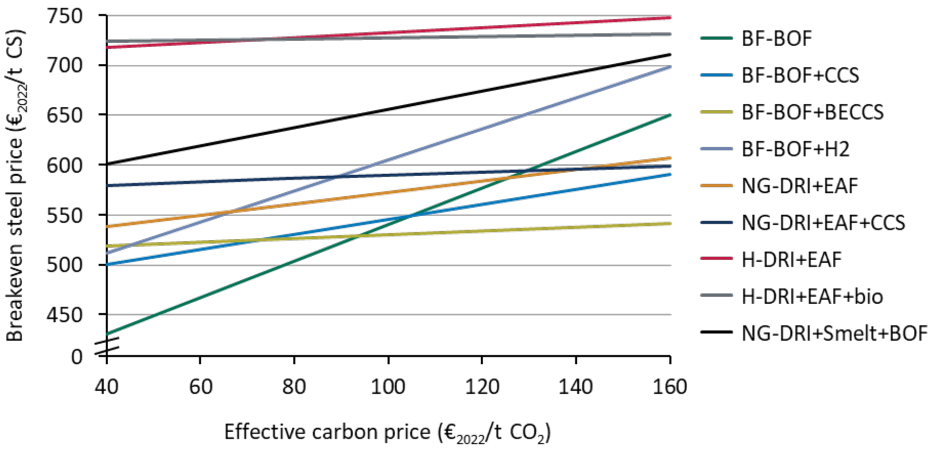


Figure 30: Breakeven steel prices against effective carbon prices

The sensitivity analysis shows **there is a low sensitivity to the heat duty of regeneration for all CCS pathways**. Despite some uncertainty on the heat duty of regeneration, total levelised production costs have a small sensitivity to variations within expected ranges. Continued development of carbon capture technologies can result in a decrease in the heat duty of regeneration. Conversely, real-life performance of capture systems could reveal a larger energy demand than expected. By varying the heat duty between 2.0 and 3.2 GJ/t CO_2 a wide range of possibilities is captured. Figure 31 shows how the breakeven steel price varies depending on the heat duty for this range. The results demonstrate that steel production costs show a low sensitivity to the heat duty for the BF pathways. The sensitivity is even smaller for the DRI pathway.

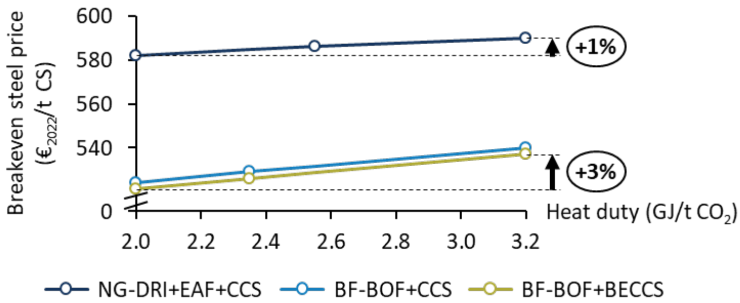


Figure 31: Breakeven steel price sensitivity to heat duty of regeneration

Figure 32 presents the sensitivity of CCS pathways to CO_2 transport and storage (T&S) costs. CO_2 T&S costs can vary largely depending on the transport distance, transport mode (pipeline or shipping), and whether infrastructure is shared with other emitters to achieve economies of scale. The production cost for an oxy-blast furnace could vary by -6% to +5% from the central case as transport costs move from a very optimistic €15/t CO2 to €90/t CO_2.

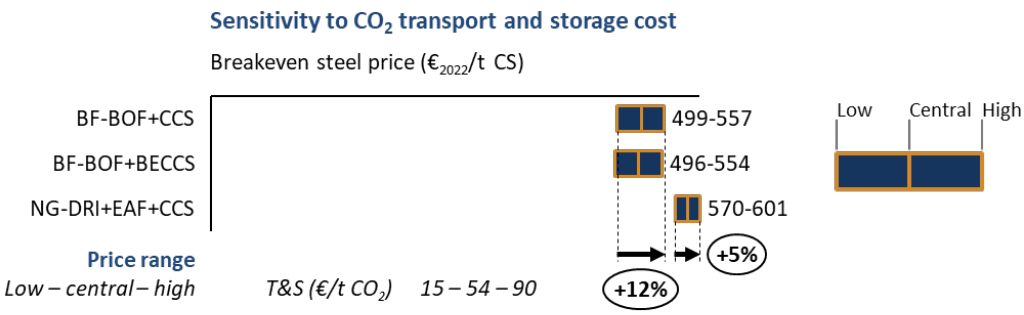


Figure 32: Sensitivity of breakeven steel price to CO_2 transport and storage cost for different pathways

The global sensitivity analysis (see Section 3.2.8) reflects the full range of levelised production costs that can be obtained as all input parameters are varied at the same time to reflect the low-cost and high-cost scenarios. The analysis, shown in Figure 33, reflects that under certain combinations low-carbon pathways could be cost-competitive with unabated steel production using blast furnaces. Except the H-DRI pathways, all pathways could potentially achieve lower levelised production costs compared to the BF-BOF baseline cost.

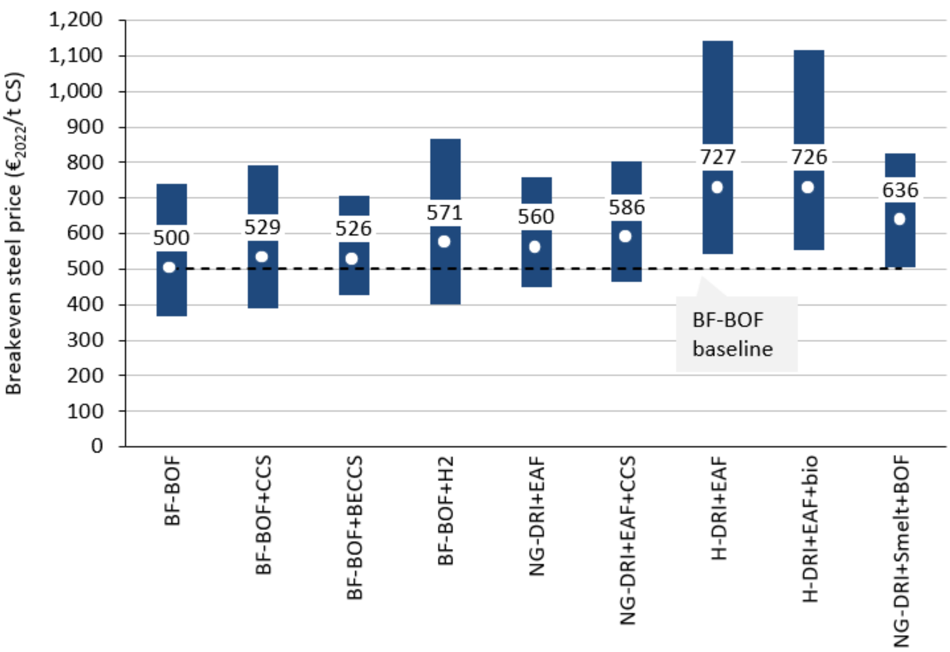
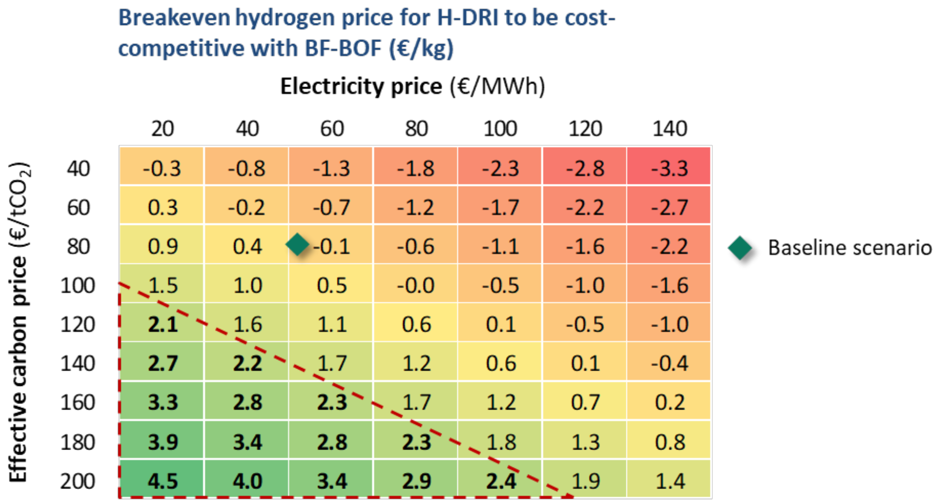


Figure 33: Ranges for production costs under the low and high scenarios

Further explorations to understand the conditions under which H-DRI could compete on a cost basis with conventional BF-BOF steel show that this may be possible under some combinations of electricity, hydrogen, and effective carbon prices. Three of the main variables affecting the cost-competitiveness of H-DRI steelmaking are the price of electricity, hydrogen, and the effective carbon price. A breakeven hydrogen price for the H-DRI pathway to be cost-competitive with BF-BOF can be calculated by changing electricity prices and effective carbon prices simultaneously. If steel producers can procure hydrogen at the breakeven hydrogen price, H-DRI steel can be produced at the same cost as conventional BF-BOF steel. The lower the electricity price, steel producers may be willing to pay more for hydrogen. Similarly, the higher the effective carbon price, steel producers will be ready to pay more from hydrogen.

Results are shown in Figure 34. Under average electricity and carbon pricing in the central scenario hydrogen would need to be free for H-DRI steel to be cost-competitive with BF-BOF steel. Unless there are major breakthroughs, it is unlikely that steel producers will be able to procure low-carbon hydrogen at less than €2/kg before 2050. With low-cost electricity and high effective carbon prices (beyond what was included in the sensitivity analysis) H-DRI steel can be cost-competitive with BF-BOF steel when paying €2/kg for hydrogen. There is a sweet spot triangle where steel producers can reach cost parity with integrated sites without the need for hydrogen prices to drop below €2/kg. For instance, if steel producers can access electricity at €40/MWh, and if effective carbon prices rise to €140/t CO_2, the H-DRI+EAF pathway may reach cost parity with the BF-BOF if it can secure hydrogen supply at a price of €2.2/kg.



Effective carbon price (€/tCO2) \ Electricity price (€/MWh)	20	40	60	80	100	120	140
40	-0.3	-0.8	-1.3	-1.8	-2.3	-2.8	-3.3
60	0.3	-0.2	-0.7	-1.2	-1.7	-2.2	-2.7
80	0.9	0.4	-0.1	-0.6	-1.1	-1.6	-2.2
100	1.5	1.0	0.5	-0.0	-0.5	-1.0	-1.6
120	**2.1**	1.6	1.1	0.6	0.1	-0.5	-1.0
140	**2.7**	**2.2**	1.7	1.2	0.6	0.1	-0.4
160	**3.3**	**2.8**	**2.3**	1.7	1.2	0.7	0.2
180	**3.9**	**3.4**	**2.8**	**2.3**	1.8	1.3	0.8
200	**4.5**	**4.0**	**3.4**	**2.9**	**2.4**	1.9	1.4

Figure 34: Required hydrogen price for H-DRI to be cost-competitive with BF-BOF depending on electricity and effective carbon prices

4 Life Cycle Assessment

The life cycle assessment (LCA) aims to assess and compare the life cycle environmental impacts of different steelmaking pathways in Northwestern Europe. The focus of the LCA is aligned with the TEA in terms of technological, geographical and temporal scope. This study is aligned with the ISO 14040 and 14044 frameworks, with the LCA comprising four key stages:

- Goal and Scope
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation of Results

4.1 Goal and Scope

The LCA Goal and Scope is the process for defining the aims of the study, which then informs the definition of the system boundaries, functional units, choice of methodology and data requirements. The Goal and Scope is the critical first step in an LCA.

4.1.1 Goal of the study

The **intended application** of this study is to **assess and compare the environmental impacts of different steelmaking pathways**, comparing different decarbonisation options against the conventional integrated steelmaking pathway. As discussed previously, multiple technology options for decarbonising steelmaking are emerging, and the most suitable pathway will depend on a myriad of factors including existing assets, geographical, or supply chains. In this study, the environmental impacts of 8 alternative steelmaking pathways, in addition to the basic oxygen steelmaking route (BOS or BF-BOF) are assessed (refer to Chapter 3). This LCA study explores which pathways could deliver the best performance in terms of environmental impacts and could therefore contribute most effectively to decarbonising the steel industry. Therefore, all 8 alternative steelmaking pathways are compared against the environmental performance of the BOS pathway The study also highlights environmental hotspots in the steelmaking lifecycle for the selected impact categories, identifying where potential improvements could be made to mitigate identified impacts and achieve maximum levels of decarbonisation.

IEAGHG commissioned this study to guide the steelmaking industry stakeholders towards sustainability initiatives led with environmental consciousness.

As such, the **intended audiences** of this study are primarily policy and decision makers and industry personnel, but also the general public. It is envisaged that the data and the impact assessment generated in this LCA study will improve the understanding of decarbonisation pathways and of development needs regarding research and policy making to mitigate environmental impacts associated with steel production.

The LCA results are intended for comparative assertions for public disclosure. However, the commissioners of this study have decided not to conduct a critical review. While a formal review in line with ISO 14071[21] will not be conducted, an in-depth review by an IEAGHG panel will be conducted to evaluate the robustness and integrity of this analysis.

[21] Environmental Management: Life cycle assessment – Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006 (ISO/TS 14071:2014)

4.1.2 Scope of the study

LCAs are guided by two key standards: ISO 14040 and ISO 14044. These standards provide the requirements and guidance on methodological choices as well as providing a framework for transparency and reporting:

- ISO 14040: Environmental management – Life cycle assessment – Principles and framework
- ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines

There remain methodological choices to be made by the LCA practitioner. In this LCA study, where these methodological choices remain, the World Steel Life Cycle Inventory (World Steel Association, 2017, 2018, 2021) serves as the most appropriate guidance, to ensure alignment with the industry. The World Steel LCI methodology was developed in accordance with both ISO 14040 and ISO 14044.

System boundary and declared unit

The **system boundary** selected is **cradle-to-gate** up to the point of crude steel production, this includes:

- All of the steelmaking processes and on-site ancillary services that are required
- All necessary inputs and outputs per process including materials, energy inputs, emissions, wastes and co-products
- All related upstream processes, i.e., raw material acquisition, and waste treatment

Downstream processing of crude steel is dependent on the final product/use and the process does not differ based on the upstream steelmaking pathway. Therefore, downstream processing of crude steel, product use and end-of-life lifecycle stages were excluded from the study. The cradle-to-gate system boundary is summarised in Figure 35.

The function of a system in LCA terminology is a quantitative description of what the system is expected to deliver, i.e., what its fundamental defining properties are, and what might define it in relation to the market. Where the product of interest is not a final product, it should be referred to as the **declared unit**. The declared unit of the system was defined to be **1 tonne of crude steel, with a carbon content of 0.1%.** Due to the assumption that all pathways are fed with 20% scrap at the BOF or EAF stage, it is assumed all pathways yield the same quality of crude steel.

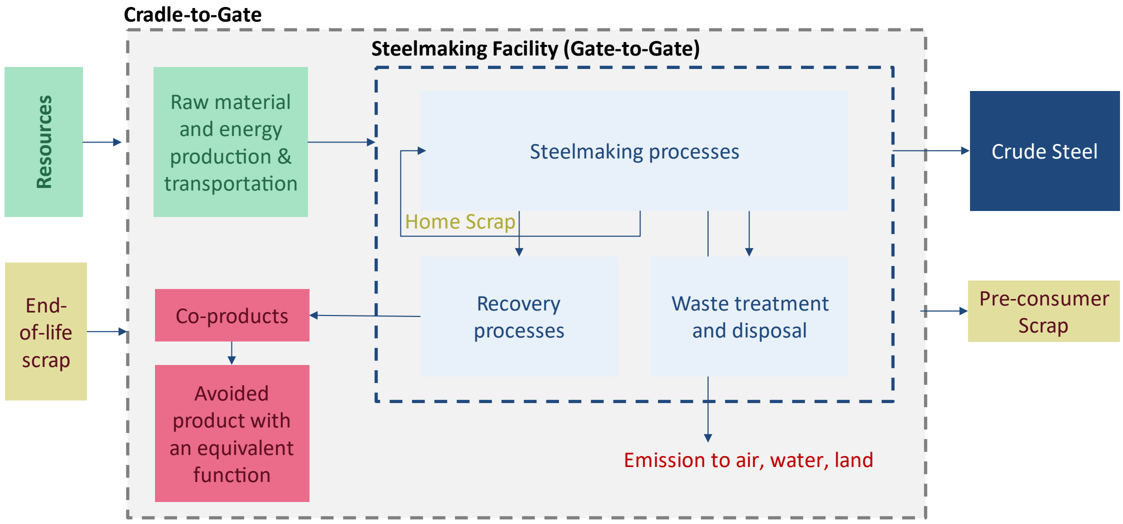


Figure 35: System Boundary for Cradle-to-Gate. Adapted from World Steel Inventory (2017)

In the Cradle-to-Gate system, a cut-off approach is used for all recycled products, including scrap. A Cradle-to-Gate with recycling system can also be adopted, under which the impacts of using steel scrap in the steelmaking process (e.g. associated with the municipal facilities) and the credits for end-of-life recycling, at a specified recycling rate, are included within the system boundary (see Figure 36). According to World Steel, Cradle-to-Gate with recycling should be reported separately for transparency: this forms a sub-section of the results in Section 4.3. The credit, which is a function of the global recycling rate (RR) and scrap input of the system (S), increases with increasing recycle rate assumed and decreases with increased scrap input as the credits are based on the recycling rate minus the scrap input. Refer to Appendix 9.1.1 for further details.

Chapter 3 provides an overview of the material process flow for the pathways assessed.

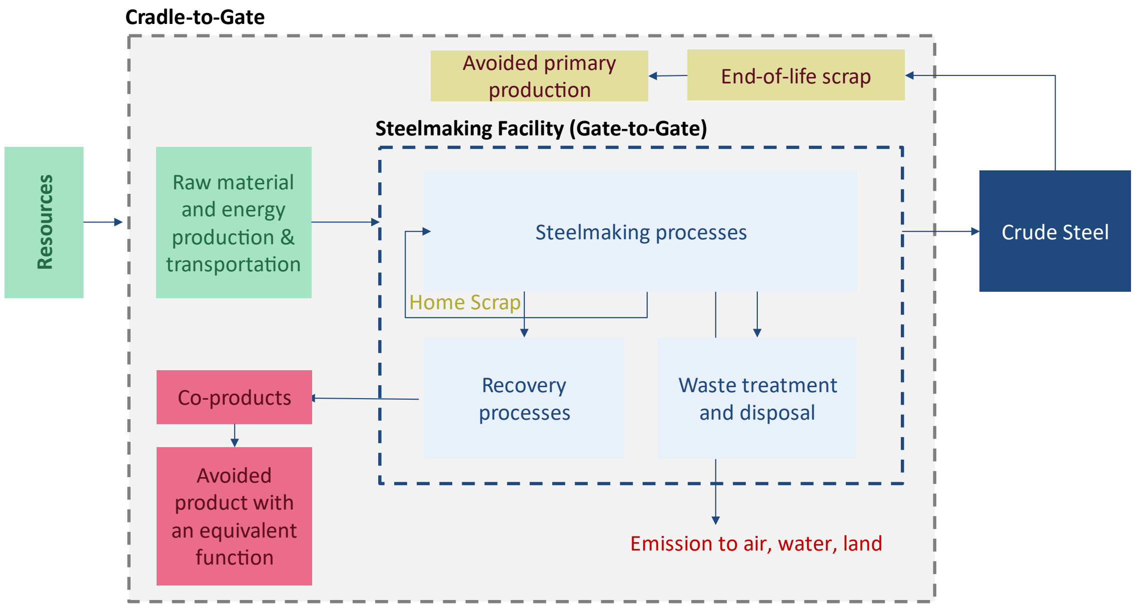


Figure 36: System Boundary for Cradle-to-Gate with Recycling

Limitations of this study

A number of **processes were excluded from the analysis**:

- Capital goods, R&D, business travel, commissioning and decommissioning, repair and maintenance, cleaning and legal services, marketing, operation of administration offices etc. is excluded in accordance with World Steel, due to limited materiality. This includes impacts of infrastructure. While impacts of infrastructure are not included, Box 3 in Section 4.3.1 estimates the effect of GHG emissions associated with energy infrastructure.
- Impacts from accidents, spills, or similar is excluded in accordance with World Steel LCI (2017).
- The environmental impacts associated with human labour, for example workers' food consumption and energy use for housing, are outside of the boundary of this LCA study. Some authors have suggested methods for the inclusion of human labour impacts in LCAs (e.g., (Rugani, Panasiuk and Benetto, 2012)), but in general these impacts are not included. It is often assumed that these environmental burdens would occur regardless of whether the worker is employed in the system under consideration or in another occupation (i Canals *et al.*, 2007).
- Long-term impacts caused by elementary flows that occur over time frames of substantially more than 100 years are not included in the analysis. These emissions largely relate to landfill, uranium mining, milling sites (radon emissions), and repositories of nuclear waste (Hischier *et al.*, 2010). Given the uncertainty in assessing impacts over such long timescales, and the fact that none of these processes are directly required for the steelmaking pathways, long-term impacts were excluded from the analysis.

ISO 14044, World Steel and ILCD (International Life Cycle Data system)[22] allow for the use of lower quality data or estimates for less relevant processes and elementary flows and even cut-off of the irrelevant ones. Cut-off criteria applied as followed: each excluded material flow must not exceed 1% of mass, energy or environmental relevance, for each unit process and the sum of excluded flows must not exceed 5%. Material flows in the steel site such as ferroalloys, quartzite, olivine, desulphurisation slag, or argon were excluded. Moreover, modelling of electrolysers for hydrogen is simplified and does not include catalysts. The study also assumes that off-gases are fully oxidised when combusted (flared or used in other units). After assessment of direct emissions levels of GHGs other than CO_2 (namely, CH_4 and N_2O) from stationary combustion following the GHG Protocol, these were excluded as they fall below the cut-off limit.

Life cycle inventory

The life cycle inventory (LCI) lists all material and energy flows associated with the declared units, as well as the corresponding background datasets.

The background data traces all material and energy inputs/outputs (including pollutants and greenhouse gases) required to build the elementary flows into and out of the biosphere and technosphere. Background data account for indirect material and energy flows resulting from the production, consumption and end-of-life of all materials and energy inputs used in steelmaking. In this study, Ecoinvent v3.8 was used to collect background data. Each dataset in Ecoinvent is usually available based on three different system models: cut-off system model, allocation at the point of substitution (APOS) and consequential system model (Ecoinvent, n.d.). Datasets for this study use the 'cut-off system model': the underlying principle of this method is that the producer is fully responsible for the adequate treatment of all wastes produced from a production system and no credit is received for the provision of recyclable material into or out of the product system. It should be noted that the exception to this is when the scrap recycling credit is evaluated, though this is defined separately for transparency purposes, as recommended by World Steel.

[22] The ILCD is an initiative developed by the European Commission's Joint Research Centre (JRC) and the Directorate-General for the Environment (DG Environment) since 2005, with the aim to provide guidance and standards for greater consistency and quality assurance in applying LCA. (European Commission, no date)

Foreground data relates to inputs and outputs directly associated with the steelmaking pathways or scenarios (see Section 3.1.1) including, for example, source of energy, transport mode, technology used, yields, etc. Foreground data are typically within the control of the steel plant operator. In this study, foreground data have been collected for both the LCA and TEA from a range of literature sources. That is, the data has been obtained from secondary sources as opposed to primary sources such as steel mill operators. Secondary data has been validated through stakeholder interviews.

The following assumptions were applied for data collection:

- **Transport:** World Steel assumes 0.03 MJ diesel is consumed per kg steel product within steelmaking sites. Compared to all other energy flows in BF-BOF case, this is equivalent to 0.02%, therefore no internal transport within the steelmaking site has been included.
- All external transport, e.g., pellet shipping from Brazil to Netherlands is included. In the majority of cases, this is done by using "market" flows, whereby transportation is already built into the data set.
- **Fuel and energy:** all energetic inputs to process stages are included. Country/region specific background datasets have been used for all energy inputs, e.g., Netherlands grid electricity.
- **Raw and process materials:** process modelling for upstream processes that could be performed on-site by some steel producers, such as pelletisation, has been used. Else, secondary data sets have been used and documented in the LCI.
- **Emissions to air:** flaring of process gases is included. It is assumed that during flaring the process gases are fully oxidised and the only GHG emitted to air is CO_2.
- **Waste for disposal:** all waste flows have been assigned with the appropriate treatment method within the analysis, e.g., waste-water treatment, landfilling.
- **Materials for recovery:** materials exported across the system boundaries for external applications are classified as co-products and a system expansion approach has been applied. If there is no external application, the appropriate waste treatment has been applied.
- **Scrap recycling:** for the Cradle-to-Gate analysis, a cut-off approach is adopted. When recycling of scrap is included in the assessment, the credit for scrap recycling is applied separately. This has been derived from World Steel's dataset in GaBi.

Further details on foreground and background data can be found in Section 9.2.

LCIA and impact categories

Life Cycle Impact Assessment (LCIA) uses the LCI results to model the environmental impacts of identified material/energy flows and expresses them in the form of a range of 'midpoint' impact categories. Midpoints may be further normalised into 'endpoints' to allow for comparison of impact categories. The analysis conducted in this study is limited to midpoints, whereby flows identified in the LCI are assigned to impact categories based on their ability to affect the environment on a per-declared-unit basis.

Categories of interest to the industry were selected:

- **Global Warming Potential**: Intergovernmental Panel on Climate Change, Sixth Assessment Report (IPCC AR6), 100-year time horizon. Specifically, the following impacts are reported:
    - **Fossil GWP:** covers fossil CO_2, CH_4 and N_2O emissions and fluorinated gases (e.g., HFCs)
    - **Biogenic GWP:** include IPCC values 'GWP 100 – Biogenic' and 'GWP 100 – CO_2 uptake', accounting for the characterisation factor for biogenic methane.

Impacts are reported in the following units: kg CO_2eq / tonne of Crude Steel or kg CO_2eq/ t CS

Resource use, fossil: Environmental Footprint (EF) 3.0 [23] indicator. Refers to abiotic resource depletion of fossil resources, e.g., oil, natural gas, coal. Impacts are reported in the following units: GJ/ t CS

Resource use, metals and minerals: EF 3.0 indicator. Refers to the use of non-renewable abiotic natural resources. Impacts are reported in the following units: kg Sb eq*/ t CS.

*In the same way that the GWP of different gases are converted to CO_2 equivalent figures, abiotic depletion of metals and minerals are calculated to an equivalent of Antimony (Sb eq).

Normalisation and weighting were not used in this study based on the decision not to use endpoints.

Beyond the impact categories selected, there are a number of other categories which could be evaluated. For the Environmental Footprint 3.0 series, those of relevance included photochemical ozone formation (kg NMVOC eq.) and particulate matter (disease inc.). Hence, mass flows that could be relevant for these categories – NO_x, SO_x and $PM_{2.5}$ emissions for example - were not included in the mass and energy balance.

Treatment of co-products

Steelmaking delivers more than one useful function. It delivers several other goods and products or services, such as process off gases or slag, in addition to the main product – i.e., crude steel. This system is therefore said to be a multifunctional system. This study seeks to quantify the life cycle impacts of the declared unit, 1 tonne crude steel. Therefore, there is a need to assign the impacts of the system among the different products.

The ISO framework provides a hierarchy for solving multifunctionality:

1. **System subdivision** divides the process into two or more sub-processes so that the main product is removed from the co-products.
2. **System expansion/substitution** expands the system to model the avoided impacts that the co-products bring about beyond the system boundaries by substituting equivalent products from primary production.
3. **Allocation** partitions the impacts of the inputs and outputs to the system between the different products based on a criterion – physical (e.g., mass, energy) or non-physical (e.g., economic value).

Following World Steel's Lifecycle Inventory which makes use of the ISO hierarchy, system expansion was used for this study. This involves attributing all the impacts of the system's inputs and outputs to crude steel, but giving credits for the avoided impacts of co-products, for instance slag, that are used outside the product system based on how these outputs are displacing an alternative production of similar products, such as clinker as in the case for blast furnace slag. This is represented visually in Figure 37.

[23] High-quality data, purchased and endorsed by the European Commission for environmental footprinting.

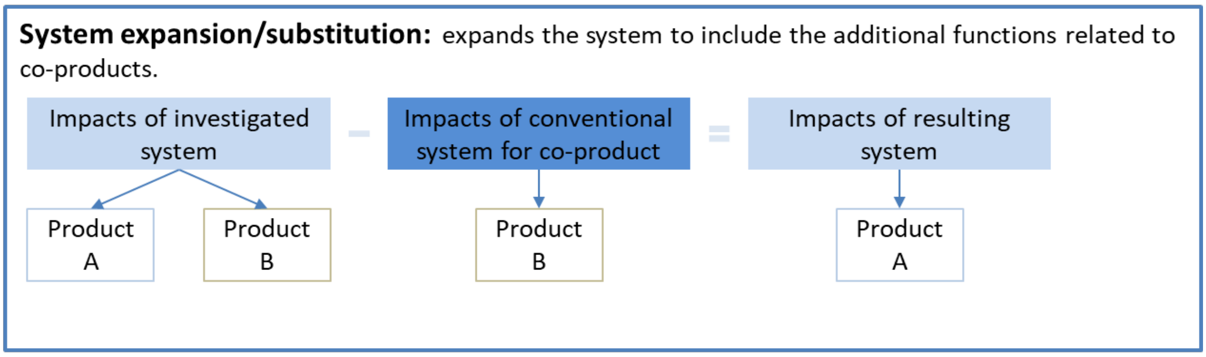


Figure 37: System expansion approach

Due to the decision to follow a system expansion approach, the co-products that leave the system boundary and are sold into another system need to be accounted for. Decisions on what the co-product "replaces" can materially impact the results, therefore it is important to ensure the most relevant alternative is used. Table 10 describes the assumptions applied to the co-products of the systems evaluated, defining their function and the avoided product used in the analysis.

Table 10: System expansion assumptions

System co-product	Co-product function	Avoided Product	Data Source
Excess Electricity	Electricity production	Electricity, high voltage {NL}| electricity, high voltage, production mix|Cut-off,U[24]	Ecoinvent V3.8 - allocation, cut-off by classification - unit
Crude Tar	Any tar application	Bitumen seal {RER}|production |Cut-off,U	
Benzole	Any benzene application	Benzene {RER}|production|Cut-off,U	
Coke oven gas (COG)	Heat production	Natural gas, high pressure {DE}|natural gas production| Cut-off, U	
Blast Furnace Slag	Cement or clinker production	Cement, Portland {Europe without Switzerland}| production| Cut-off,U	
BOF Slag	Aggregate or roadstone	Gravel, crushed{CH}|production|Cut-off,U	
Smelter Slag	Cement or clinker production	Cement, Portland {Europe without Switzerland}| production| Cut-off,U	
EAF Slag	Aggregate or roadstone	Gravel, crushed{CH}|production|Cut-off,U	

Data description

The foreground data used in this analysis are from the TEA assessment and include inputs and outputs associated with the different stages (e.g., sintering, BOF) of the crude steel production process, as described in Section 3.2. Main sources include IEAGHG technical report 2013-04 (IEAGHG, 2013), EU BAT (Best Available Techniques) Reference document for iron and steel production (Rainer *et al.*, 2013) and the MIDDEN[25] report on Decarbonisation options for the Dutch steel industry (Keys, van Hout and Daniels, 2021).

[24] In SimaPro, the Ecoinvent libraries are divided into unit (U) and system (S) processes. Unit processes describe a distinct part of a life cycle, not a whole life cycle in themselves. For example, as per the Ecoinvent database, *Gravel, crushed {CH}| gravel production, crushed | Cut-off,U unit process* represents the "production of 1 kg of crushed gravel. The typical technology for Swiss-based production was assumed. This activity ends with the crushed gravel produced and the recultivation process done. This dataset includes the whole manufacturing process, internal processes (transport, etc.) and infrastructure."
[25] The Manufacturing Industry Decarbonisation Data Exchange Network

Background data have been described by specific data whenever possible. However, some are collected from generic data sets, average data, or industry estimates. Main sources include LCA databases,[26] scientific and technical literature.

Data quality

Based on the guidance outlined in ISO 14067:2018 on product carbon footprinting, Table 11 outlines the relevant data quality requirements and the approach taken in this study to account for each one.

Table 11: Data quality requirements and approach taken in this study

Parameter	Description	Approach
Time-related coverage	Age of data and temporal applicability	Data are representative of BAT for existing steelmaking pathways. Other routes rely on process modelling data as they are not yet at commercial scale. Background data is from Ecoinvent v3.8 and year of publication varies depending on the parameter. The emission factors for electricity, a key flow in the steelmaking pathways, has been modified to reflect likely decarbonisation trends towards 2050 in the sensitivity analysis.
Geographical coverage	Geographical area for which data for unit processes should be collected	Background data used represents Northwestern Europe (Netherlands) to the extent possible. Foreground data is representative of operational experience in Northwestern Europe for blast furnaces and of global experience for DR shaft furnaces, given the lower penetration of the technology in Northwestern Europe.
Technology coverage	Specific technology or technology mix	Primary steel production is the focus of the study. As mentioned previously, BAT data as well as process modelling data have been used in the analysis. Each technology and the unit processes it includes are clearly defined in chapters 0 and 3 of the report.
Precision	Measure of the variability for each data value expressed	Data precision varies depending on the maturity level of the steelmaking pathway. The base cases use estimates based on modelling validated by operational plants. Innovative routes involving hydrogen reduction or CCS use estimates based on process modelling, not validated by full-scale operational plants.
Completeness	Percentage of total material and energy flow that is measured/estimated	Cut-off criteria was checked to see if the sum of the excluded material flows in the system do not exceed 5% of mass, energy or environmental relevance.
Representativeness	Qualitative assessment of the degree to which the data set reflects the true population of interest	The study is representative of key steelmaking pathways that may be established or are at R&D or demo-scale operation. For each pathway, the data represent normal process operation and process maintenance periods, but excludes abnormal operations, accidents, spills and similar events.
Consistency	Qualitative assessment of whether or not the study methodology is applied uniformly to the various components of the sensitivity analysis	The study method was applied to all components of the analysis, uniformly across the different technology pathways
Reproducibility	Assessment of whether an independent practitioner will be able to reproduce the study and obtain comparable results.	While the information about the method used has been included, foreground data values have not been disclosed due to data confidentiality.
Source of Data	Qualitative assessment of data sources used.	Secondary data used and validated through stakeholder interviews: peer-reviewed papers, process metallurgy treatise, IEAGHG reports and other reports from public bodies are used for foreground data. BAT data for existing steelmaking technologies was utilised. Ecoinvent V3.8 used for background data

[26] Primarily Ecoinvent V3.8

Uncertainty of the data	Qualitative assessment of data uncertainties	Foreground data based on modelling is subject to some uncertainty and can vary from site to site depending on the energy efficiency levels and operational considerations.

Contribution and sensitivity analysis

Contribution analysis of the LCIA results is carried out to assess which sub-processes carry most of the impacts, helping to identify environmental hotspots within each pathway.

Sensitivities explored in the study include:

- the impact of background datasets for grid electricity on iron ore pellet production in Brazil and on the steelmaking facility in Northwestern Europe,
- the impacts of grid decarbonisation on the steelmaking facility in Northwestern Europe,
- the impact of renewable electricity use at the pellet plant and steelmaking facility, and
- the impact of source of coal.

Comparisons

According to World Steel, comparisons and comparative asserts shall only be done based on a functional unit and not based on declared units (i.e., on a final product and not an intermediary product). This LCA uses declared units since it is focused on an intermediary product (crude steel). It is, however, acceptable to compare several crude steel production pathways to understand potential benefits or downsides of the different decarbonisation options for crude steel production, since those do not depend on how crude steel is further processed down the supply chain. Downstream of the declared unit of 1 tonne of crude steel, all processing would be agnostic of the upstream pathway. As it is assumed that all pathways incorporate the same share of scrap as metallics input, inclusion of tramp elements and nitrogen levels in crude steel does not differ significantly between steel production technologies. Thus, processing will depend on the desired characteristics of the steel products, such as steel grade and product type (e.g., coil or rod), and not on the crude steel production technology.

It should be noted that due to comparative assertions being made in this study, it should undergo an ISO 14071 compliant critical review by a panel to be viewed as ISO compliant.

Software

All life cycle assessment modelling is carried out in SimaPro Version 9.4.0.2 LCA software. SimaPro is used widely in industry and academia for conducting ISO-compliant LCAs. It allows use of LCA database values from a variety of databases such as Ecoinvent and operates transparently keeping all assumptions and supply-chains visible (Simapro, 2021). Note, data from Ecoinvent is not available for circulation in the absence of a license.

4.2 Lifecycle Inventory

As explained in section 4.1.2, the life cycle inventory analysis is the data collection step of an LCA. It consists of compiling all foreground and background data for the systems under consideration. As previously discussed, foreground data relates to inputs and outputs directly associated with the steelmaking pathways. The background data traces all material and energy inputs/outputs (including pollutants and greenhouse gases) required to build the elementary flows into and out of the biosphere and technosphere. Both foreground and background systems are set within the “technosphere”, which can be thought of as the “man-made environment”. The technosphere exists within the “biosphere”, or what is considered as the natural environment. All flows within and between the fore- and background system are modified by human activity, and as such do not necessarily enable analysis of their impacts on the biosphere. Therefore, in this LCA study all environmental impacts are traced back to the elementary flows resulting from all activities in the technosphere.

In this study the LCI includes all the material and energy inputs and outputs associated with the multiple steelmaking pathways.

As mentioned in Table 11, secondary sources, e.g. relevant literature, were used to obtain foreground data, as discussed in Section 3.2.6. Background data is from Ecoinvent v3.8. More detail can be found in the Appendix.

4.2.1 Inputs

This section provides an overview of the energy and non-energy inputs in the life cycle stages included in the system boundaries for different steelmaking pathways or scenarios. The flows of energy and non-energy outputs recirculated within the system vary between steel mills, with variations in the volume/quantity recirculated, and the sub-unit where it is recirculated in. A high degree of heat integration is assumed in accordance with BAT, minimising the volume of off-gases flared, sensible heat rejection, and waste to landfill.

The different steelmaking pathways consume and produce electricity at different stages. Some of the produced electricity is assumed to be re-circulated from one unit to another within the steelmaking plant, while the electricity demand deficit is met through supply of grid electricity. Excess electricity exits the system boundary and is treated as a co-product, as described in Section 4.1.2. In this study we have assumed that the iron ore pellet plant is sited in Brazil and therefore consumes Brazilian grid electricity. The pellets are then imported from Brazil. The other crude steel production stages included within the system boundaries are assumed to use electricity from the Dutch grid. Accordingly, appropriate Ecoinvent process flows have been used in the analysis (details in the Appendix). It was noted that the data associated with the Netherlands and Brazilian grid are outdated in Ecoinvent 3.8. That is, emissions are higher compared to the IEA's 2021 estimated emissions, as shown in Table 12. Nonetheless, in order to evaluate other impact categories, the Ecoinvent datasets were used in the analysis. The implications of the background data for grid electricity are explored in the sensitivity analysis in Section 4.3.5

Table 12: Comparison of grid electricity emission factors in Ecoinvent and IEA

Parameter	Ecoinvent v3.8 data ($kgCO_2e/kWh$)	IEA data ($kgCO_2e/kWh$)
Grid electricity (The Netherlands)	0.57 *(year 2014)*	0.43 *(year 2020)*
Grid electricity (Brazil)	0.17 *(year 2015)*	0.10 *(year 2020)*

Furthermore, in case of the BF-BOF + hydrogen injection and H-DRI routes, we have assumed that local renewable hydrogen or market renewable hydrogen is sourced (refer to Section 3.2.4 for archetype definitions). This is owing to the TEA results, which highlighted the high emissions associate when using electrolytic hydrogen with grid electricity, or imported renewable hydrogen.

As mentioned previously, steel plant process gases such as Coke Oven Gas (COG), Blast Furnace Gas (BFG) and Basic Oxygen Furnace Gas (BOFG) are recirculated on-site, including in the co-generation plant. Most of this recirculation occurs within the system boundary defined in this study. However, some process gases are used outside the system boundary but still within the steel plant. For example, COG can be used as a substitute for natural gas in reheating furnaces for hot rolling of steel, which is part of the integrated site. However, as this is outside the system boundary, COG is treated as a co-product (see 1.1.1).

Table 13: Process energy inputs

Unit	Applicable steelmaking pathway	Energy input to the unit	Origin
	All pathways	Natural gas	Technosphere

Iron ore pellet plant *(not onsite; assume pellets imported from Brazil)*		Grid electricity (NL/BR)	Technosphere
Sinter plant	All BF-BOF pathways	Electricity *(from on-site coke oven and/or co-generation plant)*	Internal flow
		BF-BOF pathway outputs used as energy input in the system: Basic Oxygen Furnace (BOF) slag, Blast Furnace (BF) return fines, BF dust, coke breeze, Coke Oven Gas (COG)	Internal flow
Coke oven	All BF-BOF pathways, and NG-DRI + Smelting + BOF pathway	Electricity *(from on-site coke oven)*	Internal flow
		Steam *(from on-site BOF)*	Internal flow
		BF-BOF pathway outputs used as energy input in the system: Blast Furnace Gas (BFG), COG	Internal flow
Lime kiln	BF-BOF, BF-BOF+H2 pathways	Electricity *(from on-site coke oven)*	Internal flow
		BF-BOF pathway outputs used as energy input in the system: COG	Internal flow
	All other pathways	Grid electricity	Technosphere
		Natural gas	Technosphere
Air separation unit (ASU)	BF-BOF, BF-BOF+H2 pathways	Electricity *(from on-site co-generation plant)*	Internal flow
	BF-BOF+CCS, BF-BOF+BECCS, all NG-DRI pathways, all H-DRI pathways	Grid electricity	Technosphere
	NG-DRI+Smelting+BOF pathway	Electricity from the grid and co-generation plant	Technosphere and internal flow
Blast furnace	All BF-BOF pathways except CCS and BECCS pathways	Electricity *(from blast furnace and co-generation plant)*	Internal flow
		Steam *(from BOF)*	Internal flow
		BF-BOF pathway outputs used as energy input in the system: Coke, BFG	Internal flow
		PCI coal and hydrogen *(for BF-BOF+H2)*	Technosphere
Oxy-blast furnace	BF-BOF + CCS and BF-BOF + BECCS pathways	Electricity *(from co-generation plant)*	Internal flow
		Natural gas	Technosphere
		BF-BOF pathway outputs used as energy input in the system: Coke, OBF-PG	Internal flow
		PCI coal or charcoal *(for BF-BOF+BECCS)*	Technosphere
Shaft furnace	All NG-DRI pathways	Grid electricity	Technosphere
		Natural gas	Technosphere
	All H-DRI pathways	Hydrogen	Technosphere
Basic oxygen furnace (BOF)	All BF-BOF pathways and NG-DRI + Smelting + BOF pathway	Electricity *(from co-generation plant)*	Internal flow
	NG-DRI EAF pathways	Coal	Technosphere

Electric arc furnace (EAF)		Natural gas	Technosphere
		Grid electricity	Technosphere
Electric smelting furnace	NG-DRI + Smelting + BOF pathway	Grid electricity	Technosphere
		Coke	Technosphere
Ladle metallurgy and continuous casting	BF-BOF, BF-BOF+H2 pathways	Electricity *(from coke oven)*	Internal flow
		BF-BOF pathway outputs used as energy input in the system: COG	Internal flow
	All other pathways	Grid electricity	Technosphere
		Natural gas	Technosphere
Co-generation plant	All BF-BOF pathways and NG-DRI + Smelting + BOF pathway	BF-BOF pathway outputs used as energy input in the system: Basic Oxygen Furnace gas (BOFG), BFG, smelter off gas,	Internal flow
Electrolyser	BF-BOF + H2 and the H-DRI pathways	Renewable electricity	Technosphere
Carbon capture plant	All pathways with CCS/ BECCS	Grid electricity	Technosphere
		Steam *(from BOF, electric boiler and co-generation plant)*	Internal flow
Electric boiler	All pathways with CCS/ BECCS	Grid electricity	Technosphere
Transport & Storage (T&S) of CO_2	All pathways with CCS/ BECCS	Grid electricity	Technosphere

In addition to energy inputs, several non-energy inputs are required in different steelmaking pathways. Where background datasets were not available in Ecoinvent, a proxy flow was used for those inputs by selecting an existing Ecoinvent flow based on technical similarities. Of particular interest:

- **Iron ore concentrate:** The assumption is that pellets are imported from Brazil. Therefore, the iron ore concentrate, which is the raw material for pellet production, is also assumed to be mined in Brazil. However, the Ecoinvent database only has a global process flow for iron ore concentrate, which was opted for and used in the analysis.
- **Coking coal:** The proxy used was a process flow for hard coal mined in Australia. The study assumption is that coking coal is imported from Australia. Therefore, a process flow focusing on this geographical area was selected for the analysis.
- **Sinter feed:** Sinter feed is similar to iron ore concentrate for pelletisation. The main difference between them is the iron content (generally smaller for sinter feed) and the size of the particles, that is larger for sinter feed. In the absence of a sinter feed process flow in Ecoinvent, the global process flow for iron ore concentrate was selected. As per Ecoinvent, iron ore concentrate is 65% iron on a dry basis.
- **Purchased scrap**: Within Cradle-to-gate system boundary this is assigned no environmental impact. When recycling is included within the system boundary, the recycling credit is applied to the system.

It should be noted that no catalysts have been modelled for hydrogen production in the electrolyser. Impacts of catalyst, once amortised over their lifetime would have a negligible impact on crude steel production.

Table 14: Non-energy inputs

Unit	Steelmaking pathway	Non-energy input to the unit	Origin

Pellet plant *(not onsite; assume pellets imported from Brazil)*	All pathways	Iron ore concentrate, limestone, water	Technosphere
Sinter plant	All BF-BOF pathways	Sinter feed, limestone, water	Technosphere
		Lime, return fines, mill scales	Internal flow
Coke oven	All BF-BOF pathways, and NG-DRI + Smelting + BOF pathway	Coking coal, water	Technosphere
Lime kiln	All pathways	Limestone	Technosphere
Air separation unit (ASU)	All pathways	Air	Biosphere
Blast furnace	All BF-BOF pathways except CCS and BECCS pathways	Lump ore, limestone, PCI, water	Technosphere
		Pellets, sinter, coke, oxygen	Internal flow
Oxy-blast furnace	BF-BOF + CCS and BF-BOF + BECCS pathways	Lump ore, limestone, PCI, water	Technosphere
		Pellets, sinter, coke, oxygen	Internal flow
Shaft furnace	All NG-DRI pathways	Pellets, oxygen, nitrogen	Internal flow
Basic oxygen furnace (BOF)	All BF-BOF pathways and NG-DRI + Smelting + BOF pathway	Purchased scrap, burnt dolomite	Technosphere
		Hot metal, home scrap, lime, oxygen	Internal flow
Electric arc furnace (EAF)	NG-DRI EAF pathways	Purchased scrap, burnt dolomite, graphite electrodes, refractory lining, water	Technosphere
		DRI, home scrap, lime, oxygen	Internal flow
DRI electric arc furnace	NG-DRI + Smelting + BOF pathway	Raw dolomite, Soderberg electrode paste, refractory lining	Technosphere
		DRI, lime	Internal flow
Ladle metallurgy and continuous casting	All pathways	Liquid steel, lime, oxygen	Internal flow
		Water	Technosphere
Electrolyser	BF-BOF + H2 and pathway,	Water	Technosphere
Carbon capture plant	All pathways with CCS/ BECCS	Amine solvent, water	Technosphere
		CO_2 to absorber	Internal flow
Transport & Storage (T&S) of CO_2	All pathways with CCS/ BECCS	CO_2 from capture plant	Internal flow

4.2.2 Transport

Transport of inputs from outside the system boundary to the steelmaking plant are included within the background dataset as an average transportation distance for that product sold on the 'market', i.e., not specific to transporting from supplier to a steelmaking plant. In case of pellets imported from Brazil, the emissions associated with the transportation of iron ore concentrates to the pellet plant are included in the Ecoinvent process flow as it is a 'market activity'. Given that this is a 'global' process flow, it is assumed that the process flow also covers the emissions associated with the transport of pellets to the steel plant in Europe. Internal transport and handling, i.e., within the steelmaking plant, was not included in the analysis.

4.2.3 Wastes and waste treatment

The different steelmaking pathways analysed in this study generate waste streams. However, the export of some of these waste streams outside the system boundaries is minimal due to steel producers' efforts to recycle and reuse materials within the production plant. These include:

- **Emissions to air due to flaring of process gases such as BFG, BOFG, COG (**released to biosphere): This is reduced as significant volumes are recycled on-site. However, there is still some flaring due to production dynamics and safety considerations. Process gases are fully oxidised when flared and there is no venting.

However, some waste streams are not recycled/reused before exiting the system boundary but are instead sold to other companies as substitute raw material. These include:

- **Steelmaking slag:** In the past, landfilling was the default treatment option for steelmaking slag, including BOF slag and EAF slag. With steel mill operators adopting best practices to make their operations more sustainable, the landfilling of steelmaking slag can be discontinued as is assumed here. Instead, it is sold to construction companies that use it as substitute for gravel.
- **Granulated blast furnace and electric smelter slag:** Steel mills sell granulated blast furnace slag to cement producers that use it as a substitute for clinker in cement production. It is expected that slag from the electric smelting furnace will have similar composition as blast furnace slag, and hence can also be used as a clinker replacement.

Finally, some waste streams are not recycled/reused before exiting the system boundary and are not sold to other companies. These are sent to landfill or enter the municipal wastewater stream following treatment on-site. These include:

- **Wastewater from pellet plant in Brazil**: The proxy process flow selected was that for the treatment of wastewater from pig iron production (Geography: Rest of the world)
- **Sludge from sinter plant, blast furnace**: The proxy process flow selected was that for "treatment of blast furnace sludge, residual material landfill" (Geography: Europe)
- **Wastewater from sinter plant, coke oven**: The proxy process flow selected was that for the treatment of wastewater from pig iron production (Geography: Europe)
- **Wastewater from blast furnace; ladle metallurgy and continuous casting; CO_2 capture plant:** The proxy process flow selected was that for the treatment of wastewater from ground granulated blast furnace slag production (Geography: Rest of the world). Similar process flow focusing on Europe was not available in Ecoinvent.
- **Dusts from Electric Arc Furnace:** Dusts mainly contain oxides of iron, calcium and zinc. The process flow selected is for treatment of "electric arc furnace dust, residual material landfill" (Geography: Switzerland)
- **Waste refractories from Electric Arc Furnace:** The proxy process flow selected was that for the treatment of "electric arc furnace slag, residual material landfill" (Geography: Rest of the world)
- **Ladle Metallurgy slag:** The proxy process flow selected was that for the treatment of "basic oxygen furnace secondary metallurgy slag, residual material landfill" (Geography: Global)
- **Mill scales from Ladle metallurgy and continuous casting:** The process flow selected is for treatment of "mill scale, residual material landfill" (Geography: Global)
- **Waste solvent from CO_2 capture plant:** The proxy process flow selected was that for the treatment of "spent solvent mixture, hazardous waste incineration" (Geography: Europe)
- **CO_2 seepage (emissions to soil/land) occurring during transport and storage of CO_2:** Seepage is the gradual and slow migration of CO_2 out of the confinement zone and into adjacent reservoirs (or maybe caprock if not completely impermeable). This is assumed to be 0.5% of CO_2 that is transported and stored.

In this study we have assumed that only carbon dioxide is emitted as any GHG emissions to air. For this we have assumed that other GHGs, such as methane, are fully oxidised and converted to carbon dioxide before being released from different units within the steelmaking plant. Non-GHG air pollutants, such as particulate matter (PM), NO_x or SO_x, are not included because there were no corresponding impact categories selected in the LCIA.

Table 15: Wastes and waste treatment

Unit	Steelmaking pathway	Wastes generated
Pellet plant *(not onsite; assume pellets imported from Brazil)*	All pathways	Wastewater, emissions to air (CO_2)
Sinter plant	All BF-BOF pathways	Sludge, wastewater, emissions to air (CO_2)
Coke oven	All BF-BOF pathways, and NG-DRI + Smelting + BOF pathway	Wastewater, emissions to air (CO_2)
Lime kiln	All pathways	Emissions to air (CO_2)
Air separation unit (ASU)	All pathways	Nitrogen (gas)
Blast furnace	All BF-BOF pathways except CCS and BECCS pathways	BF sludge, wastewater, emissions to air (CO_2)
Oxy-blast furnace	BF-BOF + CCS and BF-BOF + BECCS pathways	BF sludge, wastewater, emissions to air (CO_2)
Shaft furnace	All NG-DRI pathways	Emissions to air (CO_2)
Basic oxygen furnace (BOF)	All BF-BOF pathways and NG-DRI + Smelting + BOF pathway	Emissions to air (CO_2)
Electric arc furnace (EAF)	NG-DRI EAF pathways	Dusts, waste refractories, emissions to air (CO_2)
DRI electric arc furnace	NG-DRI + Smelting + BOF pathway	Dusts, waste refractories, emissions to air (CO_2)
Ladle metallurgy and continuous casting	All pathways	LM slag, wastewater, emissions to air (CO_2)
Co-generation plant	All BF-BOF pathways and NG-DRI + Smelting + BOF pathway	Emissions to air (CO_2)
Carbon capture plant	All pathways with CCS/ BECCS	Waste solvent, emissions to air (CO_2)
Transport & Storage (T&S) of CO_2	All pathways with CCS/ BECCS	CO_2 seepage (emissions to soil/land)

4.2.4 Co-products

As mentioned previously, steelmaking delivers more than one useful function. It delivers several other goods/products (such as blast furnace slag) or services (for instance, excess electricity) in addition to the main product – i.e., crude steel. These co-products are discussed below in Table 16.

Table 16: System expansion assumptions

System co-product	Steelmaking pathway	Unit where the co-product is generated
Excess Electricity	BF-BOF, BF-BOF+H2	Co-generation plant
Crude Tar	All BF-BOF pathways	Coke oven
Benzole	All BF-BOF pathways	Coke oven
Coke oven gas (COG)	All BF-BOF pathways	Coke oven
Blast Furnace Slag	All BF-BOF pathways	Blast furnace, Oxy-blast furnace
BOF Slag	All BF-BOF pathways and NG-DRI + Smelting + BOF pathway	Basic oxygen furnace
Smelter Slag	NG-DRI + Smelting + BOF pathway	DRI electric smelting furnace
EAF Slag	All NG-DRI and H-DRI pathways	Electric arc furnace

4.3 Lifecycle Impact Assessment and interpretation of results

The lifecycle impacts of the different steelmaking pathways are summarised in Table 17 and percentage change in impacts of each pathway compared to the BF-BOF baseline are summarised in Table 20. Subsequent sections consider each of the impact categories' results in more detail and identify processes driving the results for each.

Table 17: Summary of environmental impacts of each pathway *(please refer to sub-section 'LCIA and impact categories' in section 4.1.2 for details about the impact categories)*

Environmental impact category	BF-BOF	BF-BOF H2	BF-BOF CCS	BF-BOF BECCS	NG-DRI EAF	NG-DRI EAF CCS	H-DRI EAF	H-DRI EAF bio	NG-DRI smelting BOF
GWP (fossil) kg CO_2eq/ t CS	1,889	1,500	1,236	1,000	1,184	945	1,198	1,020	1,559
GWP (biogenic emissions CO_2 and CH_4) kg CO_2eq/ t CS	0.12	0.01	7.7	216	12	15	19	217	9.5
Fossil resource use GJ/ t CS	31	25	31	22	17	20	16	13	22

Metals and minerals resource use kg Sb eq/ t CS	8.05E-05	7.81E-05	8.57E-05	9.37E-05	5.54E-04	5.57E-04	5.62E-04	5.66E-04	1.04E-04

Table 18: Summary of percentage decrease in environmental impacts of each pathway compared to the BF-BOF baseline pathway[27]

Environmental impact category	BF-BOF H2	BF-BOF CCS	BF-BOF BECCS	NG-DRI EAF	NG-DRI EAF CCS	H-DRI EAF	H-DRI EAF bio	NG-DRI smelting BOF	Remark
GWP (fossil)	21%	35%	47%	37%	50%	37%	46%	17%	All pathways show reduction in impact
GWP (biogenic emissions CO_2 and CH_4)	91%	- 6,227%	- 177,222%	- 9,758%	- 12,145%	- 15,274%	- 178,018%	- 7,699%	All pathways except BF-BOF-H_2 show increased biogenic emissions, although the very low baseline distorts the percentage analysis
Fossil resource use	19%	2%	31%	44%	37%	49%	59%	27%	All pathways show reduction in impact
Metals and minerals resource use	3%	-6%	-16%	-588%	-592%	-598%	-603%	-520%	Other than BF-BOF+H2, all other pathways show higher impacts compared to the BF-BOF baseline

[27] A negative value reflects an increase in impact compared to the BF-BOF baseline. For example, based on the IPCC AR6 GWP100 life cycle impact assessment method, the total GWP100-biogenic emissions (CO_2 and CH_4) for the BF-BOF pathway are estimated at 0.12 kgCO_2e/t CS while that for BF-BOF BECCS are estimated at 216 kgCO_2e/t CS. The percentage change (increase in this case) is therefore -177,222%. Because GWP100-biogenic emissions (CO_2 and CH_4) for the BF-BOF pathway are very small, percentage changes show very high values. Comparison of absolute biogenic GWP in Figure 39 may be more relevant.

4.3.1 Global Warming Potential

Fossil GWP impacts (fossil emissions) are shown in Figure 38, while biogenic GWP impacts (biogenic emissions) are shown in Figure 39.

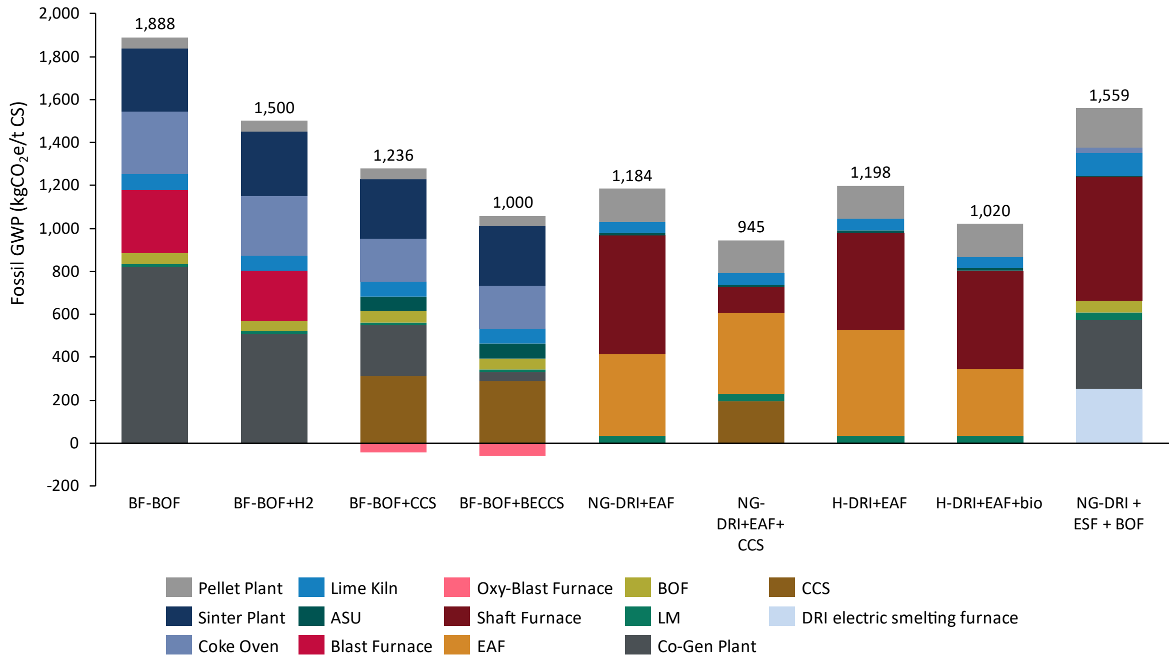


Figure 38: Global Warming Potential (GWP - Fossil) for steelmaking pathways

For the baseline BF-BOF steelmaking pathway, the co-generation unit is the largest contributor to fossil GWP, followed by the blast furnace. Large quantities of carbon dioxide are estimated to be emitted by the co-generation unit due to the blast furnace gas (BFG) and basic oxygen furnace gas (BOFG) input which in turn are associated with combustion of coal. It is assumed that during the combustion process the BFG and BOFG is converted completely into CO_2. For the BF-BOF pathway, the results for fossil GWP in the LCA are similar in value to the TEA results for direct emissions and indirect emissions associated with electricity and hydrogen use. The driver of this is the methodological decision to adopt a system expansion approach, whereby any co-products of the system are credited with an avoided emissions of the production of the product displaced. Of note, 188 kWh/t CS of excess electricity is assumed to displace grid electricity outside of the system boundary. This results in a credit of 107 $kgCO_2e$/t CS.

The LCA results show that transitioning from BF-BOF steelmaking can reduce the fossil GWP impact of the crude steel product, when accounting for embedded CO_2 emissions (e.g., from the upstream raw material processing) as well. However, it is evidenced that alongside dealing with residual direct emissions, decarbonisation of the supply of materials/energy and treatment of wastes will be required to drive down total GWP of crude steel production:

- The co-generation unit and the blast furnace remain the largest sources of fossil emissions in the BF-BOF with hydrogen injection pathway, though the absolute emissions in both decreases. The hydrogen (assumed to be renewable), displaces some of the PCI as an auxiliary reducing agent in the blast furnace, which drives the decrease in emissions arising from the blast furnace. Excess electricity is generated in the hydrogen pathway resulting in a credit of 89 $kgCO_2e$/t CS. Overall, the hydrogen injection pathway abates roughly 21% of fossil emissions compared to the BF-BOF baseline.
- In case of the BF-BOF-CCS, the blast furnace is replaced by an oxy-blast furnace with top gas recycling (TGR) and chemical absorption capture. The TGR alone results in a lower coke rate,

thus reducing emissions from the coke oven. Moreover, the captured process gases result in less direct CO_2 emissions from the oxy-blast furnace. The impact of the oxy-blast furnace is negative due to the reduced direct CO_2 emissions, use of recirculated energy and materials, and the avoided credit received for BF Slag produced as a co-product, which is assumed to displace cement.

- Replacing PCI coal with charcoal (BF-BOF+BECCS), fossil GWP is reduced by ~240 kgCO_2e/t CS compared to BF-BOF+CCS. However, Figure 39 shows biogenic emissions increase to ~220 kgCO_2e/t CS as a result of uncaptured biogenic CO_2. Note, assumptions were made as to the emissions source of the biogenic CO_2 for the purpose of modelling: in practise the process fuel gases are not separatable.
- The commercially mature natural gas-DRI route offers considerable reduction in fossil GWP compared to BF-BO. In NG-DRI, the shaft furnace is the largest contributor to fossil GWP due to the large consumption of natural gas (over 8,800 MJ/t CS). The transitional pathway, NG-DRI+ Smelt (ESF) + BOF, which is attractive to steel producers because it allows integrated BOS sites to transition a portion of their production over to the direct reduction route. However, as with the NG-DRI pathway, the smelting pathway consumes significant quantities of natural gas in the shaft furnace (10,300 MJ/t CS). NG-DRI+ ESF+ BOF offers the lowest reduction in fossil GWP compared to BF-BOF.
- More dramatic fossil GWP reductions are achievable when including CCS on NG-DRI, approximately 50% compared to BF-BOF, In this pathway, due to the reduction in direct CO_2 emissions from flaring of flue gas streams from the gas reformer, the relative contribution of the EAF increases, driven by the dependence on grid electricity and the refractory lining, As with the BOS CCS cases, there are additional emissions associated with an electric boiler required to generate sufficient steam for the CO_2 capture process.
- Unlike when considering only direct and indirect (electricity and hydrogen) CO_2 emissions, as was the case in Chapter 3, transitioning to hydrogen-DRI does not offer the same level of reductions when considering all embedded emissions associated with raw materials upstream and waste treatment. In fact, considering the fossil GWP, the H-DRI pathway has a higher fossil GWP than NG-DRI. This is driven by significantly higher electricity input (6 times) in the shaft furnace compared to NG-DRI routes and higher coal (10 times) consumption in the EAF. This suggests that H-DRI is only advantageous if renewable electricity can be used in the steelmaking facility. Substitution of coal with charcoal at a rate of 0.9 kg PCI/ kg charcoal, in the EAF in the H-DRI+EAF bioenergy pathway reduces the fossil GWP impacts of the EAF but emissions from the shaft furnace remain higher than for NG-DRI.
- Across all direct reduction pathways, there is a deficit of electricity within the system, therefore an external source of electricity is required. Grid electricity was assumed to satisfy the electricity demand of the pathways. The sensitivity analysis in Section 4.3.5 explores the impacts of substituting grid electricity with renewable electricity. In addition, pellet production has higher fossil GWP impact across all DRI-based pathways, as the amount of pellets required per tonne of crude steel increases because they are used as the sole iron ore input for the shaft furnace.

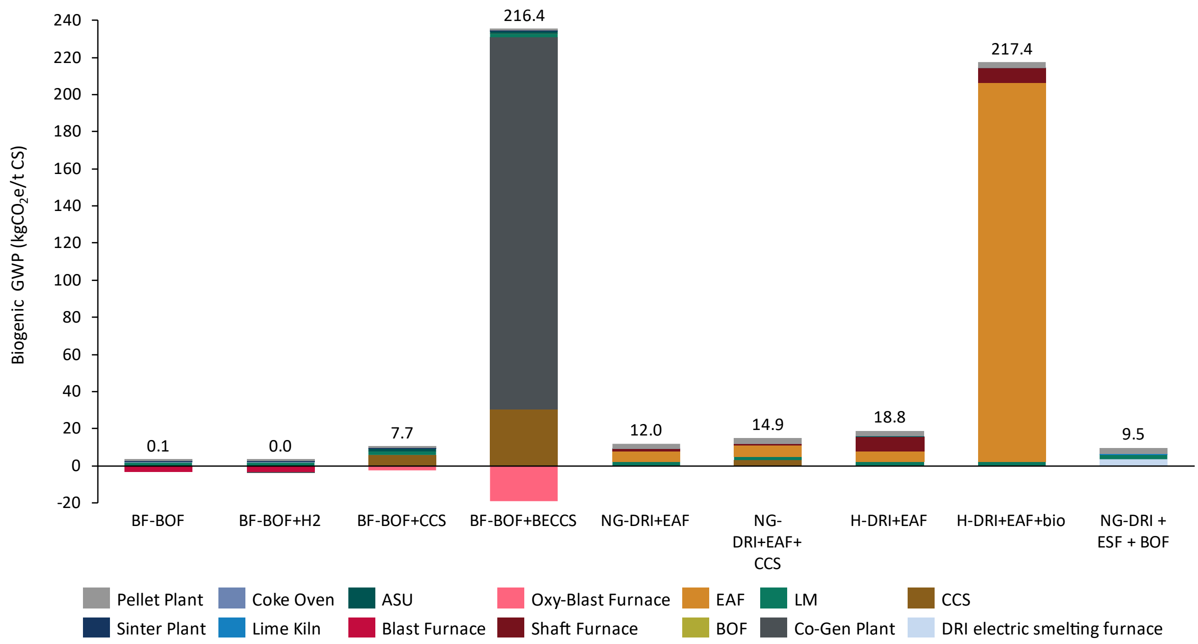


Figure 39: Biogenic GWP for steelmaking pathways

Box 3 – Infrastructure emissions of renewable electricity

While the impacts of infrastructure are not included in this study, it is important to consider how they might influence the results. This is of particular relevance for renewable electricity generation (i.e., emissions associated with the production of turbines, solar panels, and other components), which otherwise has very low emissions when infrastructure impacts are excluded.

One of the major challenges associated with quantifying infrastructure emissions of electricity is the lack of high-quality data. Moreover, where the data exists there are large uncertainties. This is compounded by the significant variability by electricity generation site. For instance, there can be variations in the capacity factor due to geographies or technologies. Nonetheless, some studies have been conducted which seek to quantify the embodied emissions of renewable electricity. For wind electricity ranges of between 12 - 26 $kgCO_2e/MWh$ (World Nuclear Association, 2011; Smoucha *et al.*, 2016) have been estimated; emissions for solar electricity are higher, between around 40 - 85 $kgCO_2e/MWh$ (Louwen *et al.*, 2016), though are expected to fall in the outlook to 2050 (Pehl *et al.*, 2017).

In this study the importance of sourcing renewable hydrogen for hydrogen-based pathways has been shown in terms of direct and indirect GHG emissions. However, significant quantities of renewable electricity are required to facilitate this. Almost 3 MWh/ t CS of renewable electricity is required in the H-DRI+EAF pathway for the hydrogen demand alone. Considering the emissions factors presented above, the inclusion of the infrastructure emissions of renewable electricity could increase the GWP of the H-DRI+EAF pathway by between 34 and 111 $kgCO_2e/t$ CS, depending on the source of the electricity. This is equivalent to a 3 - 9% increase compared to the fossil GWP presented in Figure 38.

In the case that renewable electricity is used to satisfy the total electricity demand of the H-DRI+EAF pathway, total electricity demand for the H-DRI+EAF pathway climbs to almost 4 MWh/t CS. The GWP of the H-DRI+EAF pathway could rise to an additional 48 - 159 $kgCO_2e/t$ CS, an increase of 4 - 13% compared to the fossil GWP presented in Figure 38.

4.3.2 Fossil Resource Impact

Fossil resource use is equivalent to the cumulative energy demand of fossil resources. It includes embedded energy demand associated with the extraction and processing of raw materials such as natural gas or coal. There is more variation between pathways for fossil resource impact than GWP, though all pathways offer a reduction in reliance on fossil resources compared with BF-BOF.

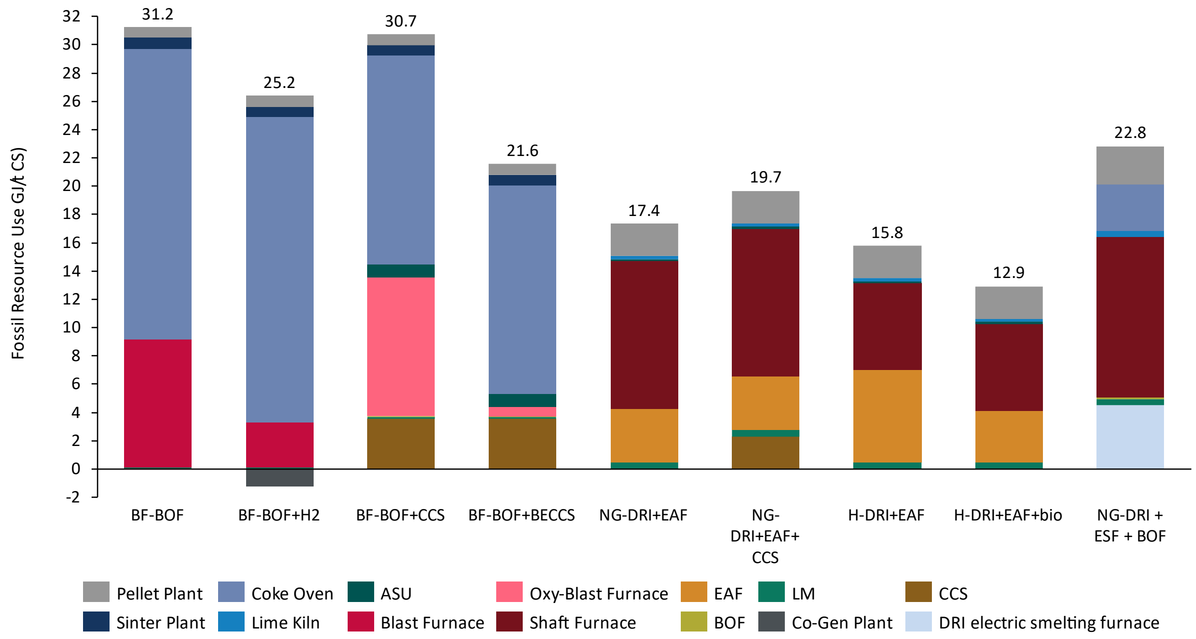


Figure 40: Fossil resource use of different steel production routes

The coke oven is the largest contributor to fossil resource impact across all BF-BOF pathways. This is due to the large quantities of coal used in the unit (300 to 400 kg /t CS) to produce the required quantities of coke. Hydrogen injection reduces the fossil resource impact of steelmaking by ~19% compared to BF-BOF, this is because renewable hydrogen helps displace 120 kg of PCI coal/ t CS. In addition, the excess electricity exported from the co-generation unit results in a negative fossil resource impact as it is reducing the dependence on fossil-derived grid electricity. This will diminish with increasing renewables penetration into the grid.

In the BF-BOF+CCS pathway, despite additional material and energy required for CO_2 capture, including an amine solvent and grid electricity-fuelled electric boiler to meet the steam demand, the lower coking coal demand in the coke oven, results in approximately the same total fossil resource use. The replacement of PCI coal with charcoal in the BF-BOF +BECCS pathway lowers fossil resource use of the pathway by 31% compared to BF-BOF.

All direct reduction pathways have a lower reliance on fossil resource, including the transitional NG-DRI+ESF+BOF pathway. With the exception of the ESF route, this is driven by the removal of the coke oven and results in a reduction in fossil resource use by 37 – 44%. The shaft furnace is the largest contributor to fossil resource impact across all NG-DRI pathways. This is due to the large quantities of natural gas used in this step (between 8,800 and 10,300 MJ/t CS). The EAF is the largest contributor to fossil resource impact in the H-DRI+EAF pathway due to the larger consumption of coal compared to the NG-DRI+EAF pathways. The shaft furnace is the largest contributor in case of the H-DRI+EAF bio pathway due to grid electricity consumption. H-DRI routes mitigate the fossil energy required for NG-DRI but this relies on the availability of significant quantities of hydrogen produced via electrolysis using renewable electricity.

4.3.3 Metals and Minerals Resource Impact

Minerals and metals resource use is used to assess non-renewable resource depletion. It is an EF3.0 impact category recommended by the Joint Research Centre of the European Union.

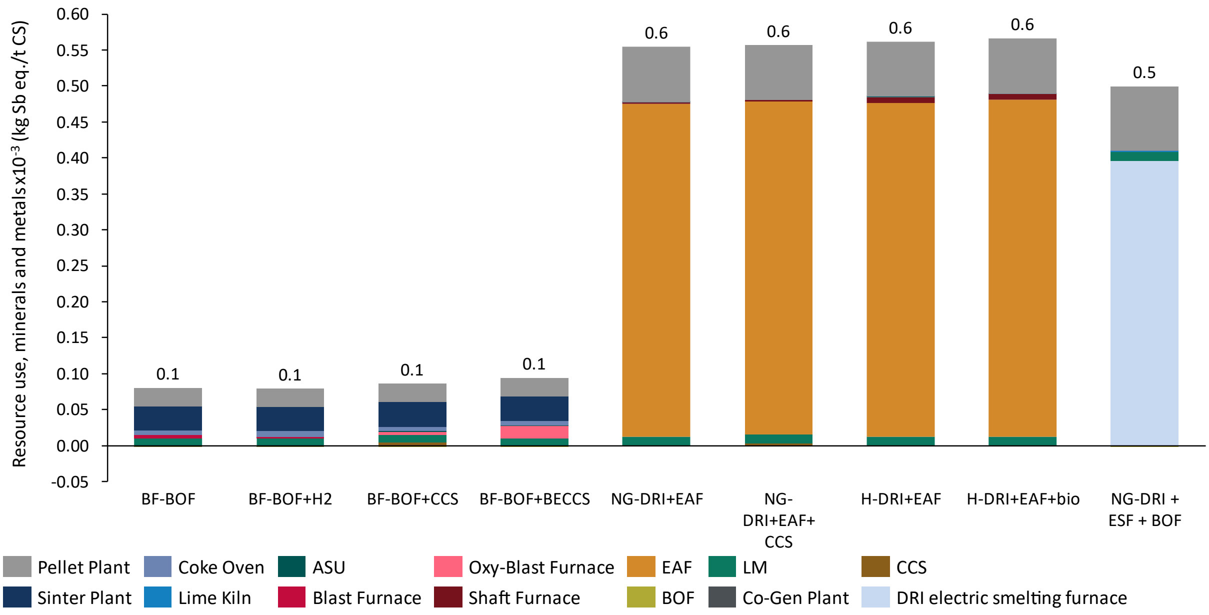


Figure 41: Minerals and metals resource use of different steel production routes

There is limited difference in mineral resource impact across all BF-BOF pathways and the NG-DRI smelting furnace pathway. The sinter plant is the largest contributor to metals and minerals resource impact in the BF-BOF pathways due to the large input of sinter feed (similar to iron ore concentrate, see section 4.2.1) and limestone. The smelting furnace is the largest contributor in case of the NG-DRI smelting furnace pathway due to the iron ore concentrate input, and absence of a sinter plant in this pathway. The impact of refractory lining in EAFs (and its disposal) drive the significantly higher impact seen across the DRI routes.

4.3.4 Inclusion of end-of-life recycling

As discussed in the goal and scope, two system boundaries were considered in this analysis: cradle-to-gate with and without recycling of scrap. All modelling and analysis up to this point of the report are presented without considering the impacts scrap recycling. When end-of-life recycling is included, a credit is applied to the product system, as discussed in Section 4.1.2.

In our analysis we have assumed that the share of recycled scrap in metallics input for crude steel production is 20% across all pathways. However, this comprises both home scrap (internal flow) and purchased scrap. The amount of purchased scrap varies slightly across the different pathways, resulting in slightly different recycling credits. On this basis, recycling credits which could be applied to the LCI of crude steel production are summarised in Table 19.

Table 19: recycling credits applicable for each pathway

Impact Category	BF-BOF pathways	DRI pathways	NG-DRI+ESF+BOF
Fossil GWP kgCO_2e/t CS	1,170	1,158	1,173
Fossil resource use *GJ /t CS*	11.2	11.1	11.2
Mineral and metal use *kg SB eq./ t CS*	3.03E-03	3.00E-03	3.04E-03

Figure 42 to Figure 44 shows the impact of expanding the system boundary to include scrap recycling on fossil GWP, fossil resource use and mineral and metal resource use, respectively.

As can be seen, the recycling credit can change the results and therefore the conclusions substantially, with net negative fossil GWP achievable across the NG-DRI+EAF+CCS, BF-BOF+BECCS, and H-DRI+EAF+bio due to the pathways' lower processing emissions. Even in the baseline BF-BOF pathway, inclusion of the recycling credit results in net emissions which are over 50% less than the cradle-to-gate emissions. This highlights the importance of reporting these credits separately.

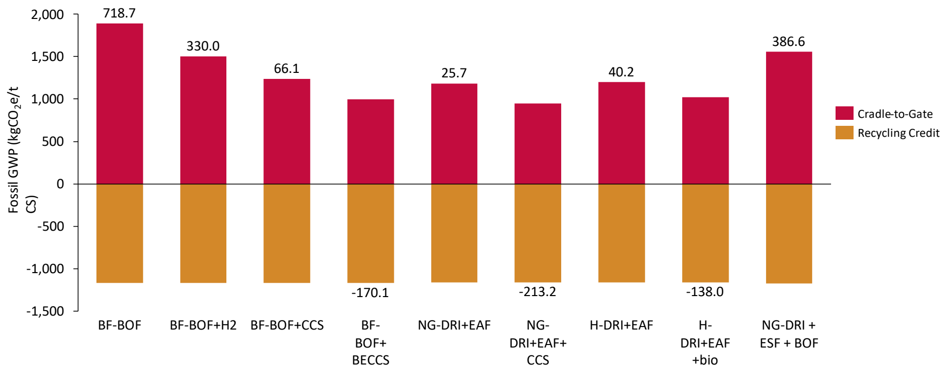


Figure 42: Fossil GWP for cradle-to-gate with recycling

Considering fossil resource use, the biggest impact is on the H-DRI pathways, where the recycling credit is of similar scale to the cradle-to-gate emissions, thus resulting in a net impact of between 1.9 and 4.7 GJ/t CS. For the pathways with a higher dependence on fossil resource, inclusion of a recycling credit reduces the overall fossil resource impact of the pathways by 36 – 50%. The recycling credit has a significant impact on mineral and metal resource use, yielding net negative impacts across all pathways. This is driven by the fact that including scrap in the process reduces the quantity of iron ore required to produce 1 tonne of crude steel.

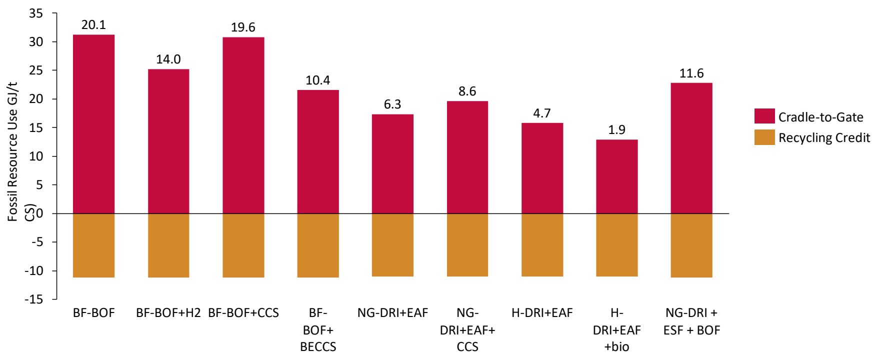


Figure 43: Fossil resource use for cradle-to-gate with recycling

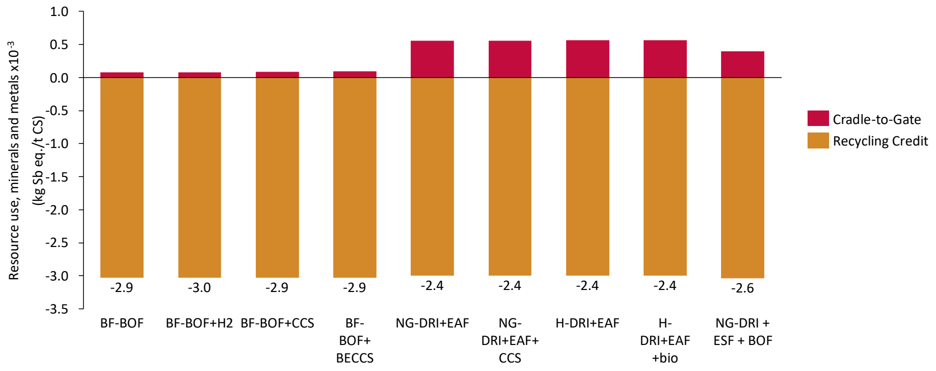


Figure 44: Mineral and metal resource use for cradle-to-gate with recycling

4.3.5 Sensitivity analysis

Impacts of electricity background data source

As discussed in Section 4.2.1, Ecoinvent data for the Netherlands and Brazilian grid does not represent the most recent data on grid emission intensity, provided by IEA. As only GWP can be evaluated using IEA, Ecoinvent was used in the baseline results. Figure 45 and Figure 46 show the impact of the value for grid electricity on the pathways modelled. The emissions factor for the Brazilian grid from Ecoinvent is 1.8x higher than the grid intensity calculated by the IEA for 2020. In the baseline results, the pellet plant accounts for 2.7 – 5.0% of total pathway emissions for BF-BOF based pathways and 11.7 - 16.4% for DRI pathways, due to larger pellet requirement and thus electricity demand in the latter pathways. However, there is only minor variation in grid emission intensity data provided by Ecoinvent and the IEA. Therefore, there is a negligible variation in overall fossil GWP impact of each steelmaking pathway using Ecoinvent or IEA grid emission intensity data, as evidenced in Figure 45.

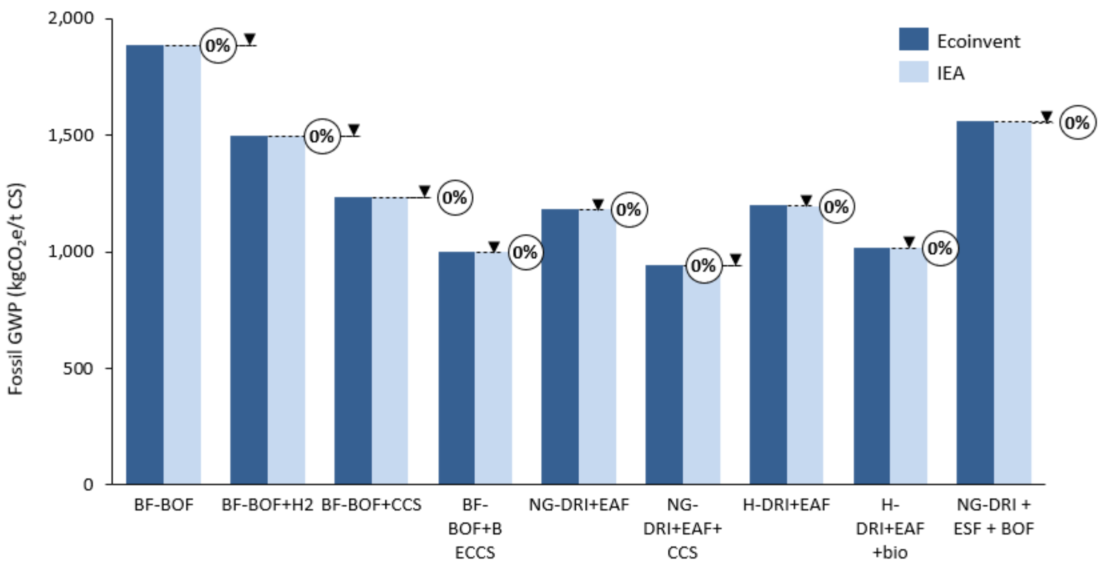


Figure 45: Impacts of using Ecoinvent dataset for fossil GWP compared to IEA 2020 for grid electricity consumption at the pellet plant facility in Brazil

For the steelmaking site itself, located in Northwestern Europe (Netherlands), the impact of the grid electricity impact factor (IEA value is 1.3x smaller than the Ecoinvent data) is more sizable for direct reduction routes than the blast furnace routes (Figure 52). This is driven by the electricity balance of the plant, with no direct reduction pathways holding capacity to generate electricity on-site. Therefore, total electricity demand is met through grid electricity (note this excludes electricity required for hydrogen production). There is a slight increase in fossil GWP for BF-BOF and BF-BOF with hydrogen injection due to the excess electricity and the reduced credit achieved for avoided emissions when displacing a less GWP intensive grid. The effect of the grid electricity impact factor is most pronounced in the hydrogen DR pathways. This suggests that siting H-DRI plants in regions with low grid electricity emissions could yield further reductions in fossil emissions of crude steel production, beyond that explored in this study.

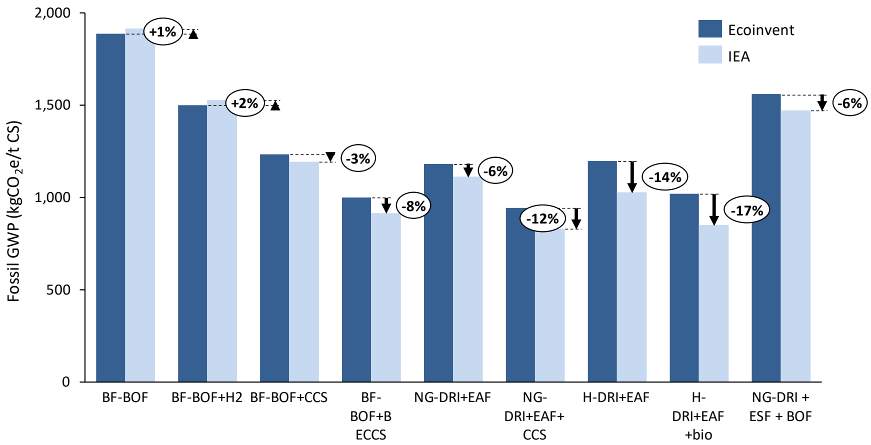


Figure 46: Impacts of using Ecoinvent dataset for fossil GWP compared to IEA 2020 for grid electricity consumption at the steelmaking facility in Northwestern Europe (Represented as the Netherlands)

Temporal changes

The results presented in Section 4.3.1 represent current steelmaking operations and do not include changes in foreground /background data expected to 2050. Notably, several key inputs are likely to decarbonise in the period to 2050. The most prominent GHG emission reduction potential comes from the decarbonisation of grid electricity. Figure 47 illustrates the emissions reduction potential of each pathway considering the decarbonisation of the local electricity grid (assumed to be the Netherlands).[28] Pathways which are more reliant on electricity benefit to a greater extent than those which do not, which is seen by the dramatic reduction in emissions for the DRI routes, where there is high electricity consumption in the shaft furnace and EAF, compared to other pathways. On the contrary, the life-cycle emissions of the BF-BOF routes do not significantly decrease over time with grid decarbonisation. For the BF-BOF baseline and BF-BOF with H_2 injection, an increase in fossil GWP is seen over time. This is owing to the excess electricity produced in the system, which is “exported”. Avoided emissions credited to the crude steel production system diminish over time, due to the excess electricity displacing increasingly decarbonised grid electricity. Further emissions reduction can be expected in line with the decarbonisation of the Brazilian grid, though to a lesser extent due to the already lower emissions intensity of the Brazilian grid compared to the Netherlands grid (see Section 4.2.1), a result of high hydroelectric, wind and solar energy.

Other energy inputs, for instance natural gas or coal, are likely to experience modest reductions in their associated GWP impacts, through improvements in upstream extraction and processing. However,

[28] Excludes decarbonisation of the Brazilian grid.

direct CO_2 emissions arising from the use of these inputs far outweigh the supply-related emissions and therefore have not been further explored in this study.

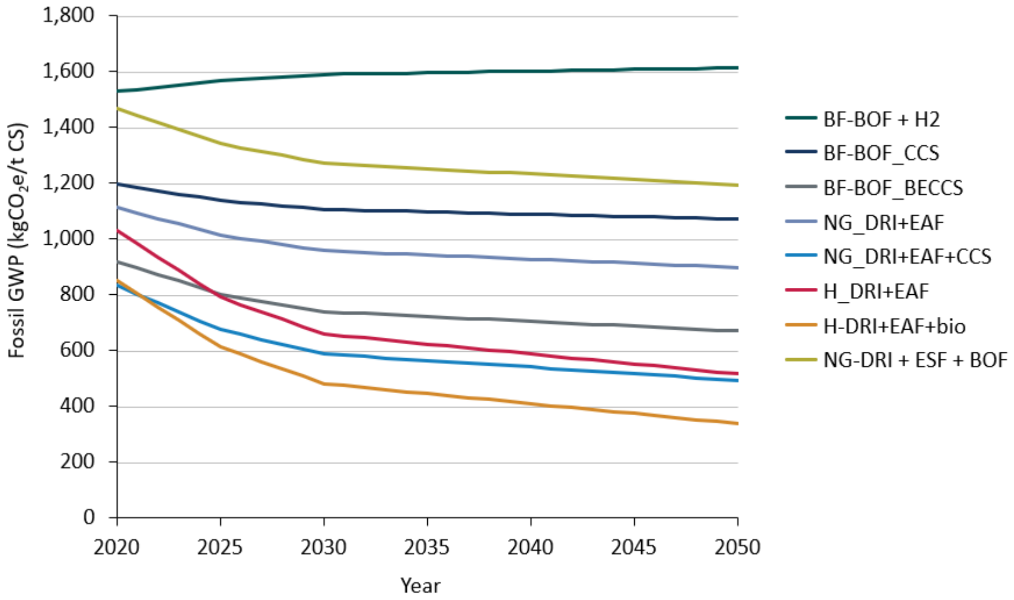


Figure 47: Emissions intensity of production pathways over lifetime based on grid decarbonisation (IEA grid factors used).

Impact of electricity source on environmental impact

As already discussed, grid decarbonisation is likely to have a positive impact on DRI routes due to their stronger reliance on grid electricity both at the pellet plant and steelmaking site. Facilities could explore the option to use renewable electricity, sourced via Power Purchasing Agreements (PPAs) or Guarantees of Origin (GOO) to achieve greater fossil GWP reduction in the near-term, while the grid carbon intensity remains high: this is likely to be most beneficial for the sites with the highest on-site electricity demand. Using renewable electricity could reduce fossil GWP impact of the H-DRI+EAF+bio to 338 $kgCO_2e$/t CS, as shown in Figure 48. This represents a reduction of approximately 82% compared to the GHG footprint of crude steel currently produced in BOS.

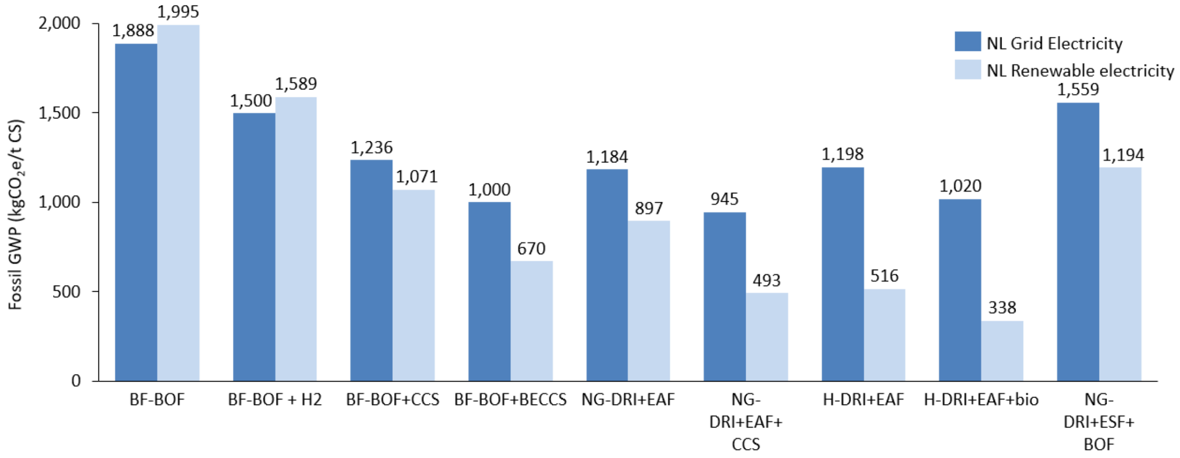


Figure 48: Fossil GWP impact of each pathway when using grid or renewable electricity (based on Dutch grid and renewable electricity emission factors available in Ecoinvent database v3.8)

Fossil resource impact follows the same trend as fossil GWP. The relative reduction of biogenic GWP is significant in the BF-BOF and BF-BOF + H_2 pathways: however, absolute values remain minimal. As shown in Figure 49, changing the source of electricity has limited impact on mineral and metal resources.

	Fossil GWP	Biogenic GWP	Fossil Resource use	Mineral and Metal Resource Use
BF-BOF	-5.6%	-1493.5%	-4.6%	-2.3%
BF-BOF + H2	-6.0%	-13753.7%	-4.8%	-2.0%
BF-BOF+CCS	13.3%	36.7%	7.3%	3.3%
BF-BOF+BECCS	33.0%	2.6%	0.0%	0.0%
NG-DRI+EAF	24.2%	40.9%	25.8%	1.0%
NG-DRI+EAF+CCS	47.9%	51.9%	19.8%	0.9%
H-DRI+EAF	56.9%	62.4%	38.9%	1.4%
H-DRI+EAF+bio	66.9%	5.4%	71.6%	2.1%
NG-DRI+ESF+BOF	23.4%	65.9%	40.6%	2.4%

Figure 49: Effects of replacing grid electricity with renewable electricity within a Dutch steelmaking facility on each impact category[29]

Source of coal

Coal is primarily used in the blast furnace (for PCI coal) and in the coke oven (coking): the coke oven dominates the fossil resource impact of BF-BOF pathways (48-86%), while both contribute significantly to fossil GWP. As discussed in Section 2.1, the coking coal and PCI coal are sourced from Australia. Australia has the third highest coal reserve globally, accounting for 14% of all reserves (BP, 2021). Europe as a whole accounts for 12.8% of coal reserves.

The fossil GWP for Australian coal is 1.3 times greater than that of European coal; this is mainly driven by the emissions arising from transport from Australia to European steelmaking facilities which accounts for 68% of fossil GWP for Australian coal imported in Europe. Substituting Australian coal with European coal could reduce the GWP of BF-BOF pathways by up to 4%. The fossil resource impact for Australian coal is almost 2 times higher than that of European coal. Therefore, replacing Australian coal with European coal could reduce the fossil resource use of BF-BOF pathways by as much as 55%.

[29] As mentioned at the start of this chapter, the LCA has been carried out for 9 different steelmaking pathways assuming that the plant is located in the Netherlands. It is also assumed that the pellets are imported from Brazil while coal is imported from Australia. In the current scenario, the LCA assumes use of grid electricity on-site and therefore the associated emission factors were used in the assessment. For the sensitivity analysis we assumed that all grid electricity used on-site was replaced with renewable electricity (for all 9 steelmaking pathways). This involved deducting the emissions impact associated with grid electricity from the overall impact of the steelmaking pathway, and adding the emissions impact associated with renewable electricity. The numbers mentioned in Figure 49 are the percentage difference between the overall steelmaking pathway impact using grid electricity vs impact using renewable electricity. Please note that this assessment does not consider points such as availability of dedicated/ intermittent electricity, with backup or base load provided by a power plant, or using grid as well as renewable electricity.

5 Supporting infrastructure

Over the past decades, integrated steel sites have taken incremental steps to reduce their specific energy consumption and to reduce their environmental impact. Despite these changes, the basic processes, feedstocks, and energy sources have remained virtually unchanged. As a result, the associated mass and energy flows, international trade flows, and supporting infrastructure have evolved around this configuration. A conversion to alternative low-carbon steelmaking pathways can present significant infrastructure and supply chain challenges because **infrastructure and supply chains have evolved around mass and energy flows resulting from integrated steel sites**.

The development of supporting infrastructure is critical to enable the transition to alternative low-carbon steelmaking pathways. Infrastructure needs and the use of new materials differ between routes. For instance, pathways relying on CCS will require CO_2 infrastructure to transport and permanently store CO_2, pathways relying on hydrogen will require connection to a hydrogen pipeline, and pathways that increase electricity demand will need new renewable generation to be added to the grid and likely upgrades to their connection capacity. Needs will be more acute for pathways involving new energy flows or feedstocks. This will be the case for production pathways that involve CCS, the use of hydrogen, electrification, or the use of biomass. Supply chains will also see new pressures: some pathways rely on an extensive use of biomass, whereas other pathways require a DR-grade ore supply. New supply chains will need to be established.

Mentioning the critical role of supporting infrastructure as an enabler for steel's sectoral decarbonisation is not just a theoretical digression: different stakeholders share the view that the bottleneck in the transition is the infrastructure. For instance, multiple stakeholders pointed out that, with CCS being already a technologically mature option, lack of deployment is a result of political and societal struggles and the absence of CO_2 transport and storage infrastructure.[30] A similar issue was found for direct reduction plants. Only one stakeholder identified the ability to build enough plants at the required pace as a potential issue; most stakeholders viewed the availability of renewable energy and low-carbon hydrogen to feed the direct reduction plant as the main bottleneck in the direct reduction transition. The same message was repeated for charcoal: use of sustainably sourced charcoal in blast furnaces can be an easy way to reduce net emissions, but all stakeholders mentioned that constraints in biomass availability can block the possibility of doing it a significant scale in Europe. This narrative only changed to a certain extent for DR-grade pellets. While some stakeholders expressed concerns that growth in supply of DR-grade pellets might be a barrier to the DRI-EAF route, others considered that electric smelting or fines-based reduction can alleviate the issue.

By drawing on outputs from the TEA, we identify the main pressure points arising from the large-scale deployment of different steelmaking pathways onto the supporting value chain. To do this, we provide an **assessment of the demand for hydrogen, primary renewable electricity, CO_2 transport and storage infrastructure, charcoal, and DR-grade pellets** that will be required to support the full decarbonisation of the steel industry with each pathway. For each logistical item, this results in an upper estimate of demand for steel production.

To complement the quantitative estimations, we explore low-carbon energy procurement strategies that steel producers might follow until the grid has fully decarbonised, such as power PPAs to operate EAFs or electrolytic hydrogen PPAs. We also discuss the implications of intermittent renewable generation on the steelmaking processes, and ways to mitigate these.

[30] Private conversation with stakeholders.

5.1 Pressure on supporting infrastructure and supply chains

Table 20 shows the demand on each logistical aspect for the different steel production pathways per tonne of crude steel. The maximum demand for each aspect is shown in bold.

Table 20: Quantification of demand on each logistical aspect for the different pathways

Logistical aspect	Units	BF-BOF+ CCS	BF-BOF+ BECCS	BF-BOF+H2	NG-DRI+EAF	NG-DRI+ EAF+CCS	H-DRI+EAF	H-DRI+ EAF+bio	NG-DRI+ Smelt+BOF
CO_2 for T&S	kg/t CS	**776**	**776**	-	-	410	-	-	-
Hydrogen	kg/t CS	-	-	25	-	-	**54**	**54**	-
Electricity (final)	MWh/t CS	0.6	0.6	-0.2	0.5	0.8	**1.2**	**1.2**	0.6
Electricity (primary)	MWh/t CS	0.6	0.6	1.1	0.5	0.8	**4.0**	**4.0**	0.6
Charcoal	kg/t CS	-	**199**	-	-	-	-	62	-
DR-grade pellets	kg/t CS	-	-	-	**1,312**	**1,312**	**1,312**	**1,312**	-

By identifying the pathway with the greatest demand for each logistical aspect it is possible to estimate upper boundaries for EU-wide demand on infrastructure networks and supply chains. Individual sites decarbonising will need to deal with pressures on their supporting infrastructure. Pressures could be even more acute at a regional level if all sites transition away from the BF-BOF route. Hence, demand estimates are presented on a unit basis, at a site level, and at an EU-wide level. Results are shown in Table 21. As an upper estimate, we have assessed the demand levels for different energy sources or infrastructure components assuming all EU sites transition by adopting the same decarbonisation route. Demand is scaled to EU-wide levels by normalising it to primary steel production in EU-27 countries in 2021, of 85.7 Mt crude steel distributed across 29 sites (World Steel Association, 2022). This is intentionally inaccurate, as a mix of pathways is likely to be deployed across Europe. Despite the inaccuracy, the upper estimate can be of value because it provides a cautious projection of what may be required reflecting the highest possible values.

Table 21: Upper estimate of demand on each logistical aspect at various aggregation levels

Logistical aspect	Unit basis (per t CS)	Site level (per year)	EU wide (per year)	Route
CO_2 for T&S	776 kg	2.6 Mt	66.5 Mt	BF-BOF+CCS
Hydrogen	54 kg	92 kt	4.6 Mt	H-DRI+EAF
Electrolyser capacity at 85% utilisation		*630 MW*	*32 GW*	
Electricity (final)	1.2 MWh	2.0 TWh	102 TWh	H-DRI+EAF
Electricity (primary)	4.0 MWh	6.7 TWh	340 TWh	H-DRI+EAF
Charcoal	199 kg	678 kt	17.1 Mt	BF-BOF+BECCS
DR-grade pellets	1.3 t	2.2 Mt	112 Mt	DRI+EAF

5.2 CO_2 transport and storage

The maximum CCS demand from steel plants will occur if all sites decarbonise via the BF-BOF+CCS route. Total demand from all EU-27 steelmaking plants if they follow this route is 66.5 $MtCO_2$/year, when normalised to 2021 production values. Compared to theoretical geological storage capacity, the amount to be stored per year is not large. The theoretical geological storage capacity across Europe ranges between 126 and 360 $GtCO_2$ (EU GeoCapacity, 2008) but much of this storage capacity is unlikely to be developed for a variety of technical, economic, legal and social reasons.

Announced CO_2 storage projects (blue diamonds, shown in Figure 50) within the EU-27 are used as a proxy for where geological storage capacity is most likely to be commercially developed (Clean Air Task Force, 2022). Announced projects include Porthos (Porthos, 2023), Greensand (State of Green, 2022), Ravenna (ENI, 2023), Prinos (Cavcic, 2022), Anrav (Anrav, 2023) and PyCasso (Lockwood and Bertels, 2022), as well as projects outside EU-27 countries, such as Northern Lights in Norway or the East Coast Cluster in the UK. Currently, these announced projects account for around 1,600 Mt CO_2 storage capacity. Assuming constant injection at 100% rate, **this would account for only 24 years of storage capacity for steel plants – and only if the iron and steel sectors has exclusive access to geological storage**. Therefore, if CCS is to be a viable decarbonisation option for steel plants, additional storage capacity must be developed.

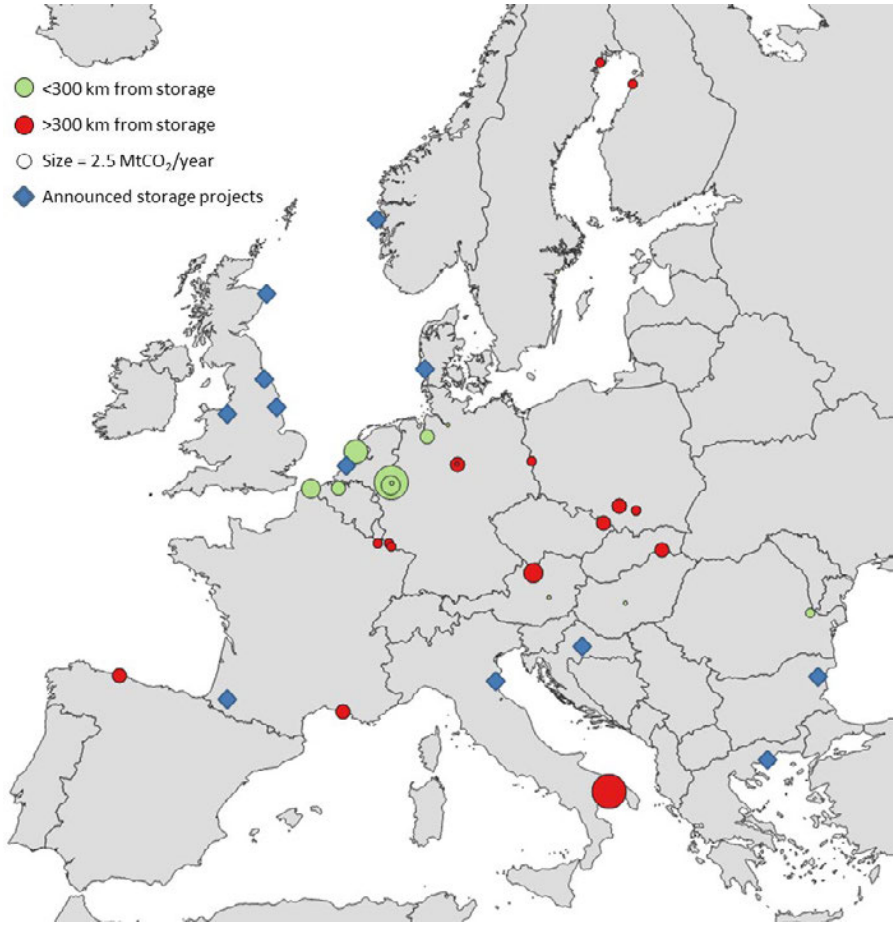


Figure 50: Mapping of EU-27 steel plants and announced CO_2 storage projects

To access geological storage capacity, CO_2 needs to be transported between the emission source and the storage injection well. Longer transport distances increase transport costs of CCS. For example, they lead to higher CAPEX costs associated with the construction of longer pipelines or to an increase in OPEX costs associated with shipping further. Longer distances also reduce the decarbonisation benefits of CCS: higher energy requirements for transport can reduce total avoided emissions and will also impact other LCA categories. Moreover, establishing a pipeline network will be more feasible over shorter distances due to a reduced need for permits and potentially fewer regulatory barriers. Developing long cross-border CO_2 pipelines may prove unfeasible and would require political and societal changes that would delay the transition. To illustrate the challenge of matching emitters (steel mills) with geological storage, sites that are more than 300 km away from an announced CCS project were identified. While this is an arbitrary distance, it is an example of a relatively short distance to storage that reduces the need for cross-border transfer and increases its feasibility of being built. **19 out of 29 integrated steel mills are more than 300 km away from an announced CCS project**. This greatly challenges the role that CCS can play for most of the EU-27 integrated steel mills. If onshore CO_2 storage was developed in the Upper Silesia Basin in Poland or in southern Italy (for instance, the Luna Gas field), in addition to announced projects, these distances could be reduced and more steel mills would be able to decarbonise using CCS.

5.3 Hydrogen

Hydrogen demand for primary steel production is maximised under the H-DRI pathways. Total hydrogen could reach almost 5 Mt hydrogen per year if all integrated mills transition towards these pathways. If this is met with electrolytic hydrogen, this represents an installed electrolyser capacity of 32 GW.[31] For reference, current hydrogen use in Europe is 10 Mt H_2/year (Hydrogen Europe, 2020), mostly from methane steam reforming without carbon capture and is utilised in oil refineries and for nitrogenous fertilisers.

Under the REPowerEU plan, renewable hydrogen supply in the EU will grow to 20 Mt H_2/year by 2030: 10 Mt would be produced in Europe and 10 Mt would be imported (European Commission, 2023b). The plan has renewable hydrogen targets and does not refer explicitly to CCS-enabled hydrogen. Hydrogen is considered renewable in REPowerEU when it meets the criteria set under the Renewable Energy Directive (RED III) to be considered as a renewable fuel of non-biological origin (RFNBO) – i.e., electrolysers are connected to new renewable electricity production, meeting the requirements for the principle of additionality.

Although current uses for hydrogen in refineries may slightly decrease because of lower demand for petrol and diesel for road transport, it can be estimated that approximately half of the EU target of 20 Mt of hydrogen by 2030 will allow the decarbonisation of hydrogen production for current hydrogen uses. As a result, 10 Mt of hydrogen would be available for new uses of hydrogen. Hence, **hydrogen demand for steelmaking in the EU could claim up to 50% of hydrogen supply for new applications**. Other sectors can also present high demand for hydrogen and will compete for supply with steel producers. For instance, the chemical sector, shipping and aviation sectors relying on hydrogen either as a fuel or as a feedstock for e-fuels, industries switching to hydrogen as a fuel for high-temperature industrial heat, or peaking power generators are all likely to present an increasing hydrogen demand.

The techno-economic modelling presented in Chapter 3 highlights that access to low-cost hydrogen is critical to close the cost gap between hydrogen-based pathways with other steelmaking pathways. Hydrogen Power Purchase Agreements (PPAs) can provide a way of securing hydrogen supply, in a context of undersupply of low-carbon hydrogen, and reduce the exposure to energy price volatility. However, entering a long-term PPA with a hydrogen supplier too early may lock in a higher-than-market hydrogen cost, as the steel producer would not be able to take advantage of progress in hydrogen production technologies that reduce the production cost.

As shown in Figure 51, European steel producers mostly benefit from being near to proposed and existing hydrogen transmission pipelines. **Proximity to transmission pipelines could reduce the hydrogen distribution cost component and improve the feasibility for using hydrogen**.

[31] For electrolysers with a high capacity factor of 85%. This does not include potential hydrogen use in reheating furnaces or other downstream processes.

Figure 51 : EU hydrogen infrastructure map showing transmission pipelines (Hydrogen Project *et al.*, 2023)

Electrolysers coupled with renewable electricity sources may result in intermittent hydrogen production. Thus, development of hydrogen storage will be necessary to cover fluctuations in production and demand. Access to hydrogen infrastructure and storage sites will also be necessary for sites opting for captive electrolysers. Initially, steel producers will blend increasing quantities of hydrogen with natural gas in shaft furnaces (or in blast furnaces). The blending of reductants in the shaft furnace could provide some flexibility to adapt for the intermittency of electrolyser operation. The extent to which this is possible in short periods of time may be limited by process characteristics, but this is an area for further work.

5.4 Renewable electricity

The maximum primary electricity demand (including electricity demand for electrolysers) from steel plants will occur if all sites decarbonise via the H-DRI route. Total demand from all EU-27 primary steel plants if they follow this route is 340 TWh/year, when normalised to 2021 production values. This is additional to demand from electric arc furnaces for existing secondary steel production. Additional demand would represent a significant increase in electricity use from the industrial sector. In 2021, electricity use by the industrial sector in EU-27 countries totalled 928 TWh (European Commission, 2023a). **Additional demand for steel production would represent an increase of 37% of European industrial electricity use**.

As covered in the LCA, the GHG footprint of electricity intensive pathways largely depends on the carbon intensity of electricity. The sensitivity analysis in Section 4.3.5 showed how H-DRI pathways can lead to large emissions reductions when operating on a decarbonised grid. Steel producers transitioning towards electricity intensive routes are likely to be willing to secure renewable energy sources via PPAs or Guarantees of Origin. Long-term electricity contracts such as PPAs can also reduce steel producers' exposure to energy price volatility. For steel producers to be able to claim the use of low-carbon electricity, it is important that PPAs lead to additional renewable electricity supply. Otherwise, claiming emissions reductions from PPAs results in a transfer of emissions to other electricity users who purchase from the electric grid. Because, of this renewable electricity generation will need to increase to meet additional demand from the steel sector.

Renewable generation in the EU in 2021 was 919 TWh, of which 545 TWh were from intermittent sources (European Commission, 2023a). Under the REPowerEU plan, renewable generation will increase by 1,072 TWh/year by 2030 (European Commission, 2022). **Additional primary electricity demand for steel production would claim over 30% of the planned increase in renewable generation by 2030**. This represents a very large share, as renewable generation is required both to replace existing fossil thermal generation for existing electricity uses and to cover an increase in demand as other sectors of the economy move towards electrification – for instance, electric vehicles and heat pumps.

Low-carbon electricity generation is only part of the electricity challenge: **significant grid upgrades are required** to integrate new generation capacity, to improve the electric connectivity between countries, and to allow new connections for users significantly increasing their power demand – such as steel producers under electricity-intensive pathways.

5.5 Biomass

Current charcoal consumption in European steelmaking is around 0.8 Mtpa and this demand could increase to 17 Mtpa assuming all steelmaking facilities transitioned to bioenergy. The starting material for charcoal is primarily wood, although other biomass can be used.

While it has been standard to assume biomass sourced charcoal is carbon neutral, this assumption is coming increasingly under criticism. It depends on the biomass species, on what happened to the underlying soil carbon (which can be damaged on harvest, with some carbon oxidizing), and on the carbon time debt as the biomass regrows. This may be only one year for agricultural residues, but hundreds of years for woody biomass sourced from trees (Hepburn *et al.*, 2019). In order to assess charcoal supply in Europe, we have referred to the sustainable biomass potential dataset developed in the European Commission's S2Biom project (S2Biom, 2017).[32] The S2Biom report estimates that over 340 Mtpa of agriculture lignocellulosic biomass (dry mass), including straw and orchard residues, will be available in Europe by 2030. This is after considering sustainable practices.

[32] S2Biom project was supported by the European Commission under the 7th Framework Programme between 2013 and 2016. The project supported the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through development of harmonised data sets, strategies, and roadmaps at local, regional, national and pan European level for EU28, Western Balkans, Ukraine, Moldova and Turkey. These can be accessed via the S2BIOM tool set.

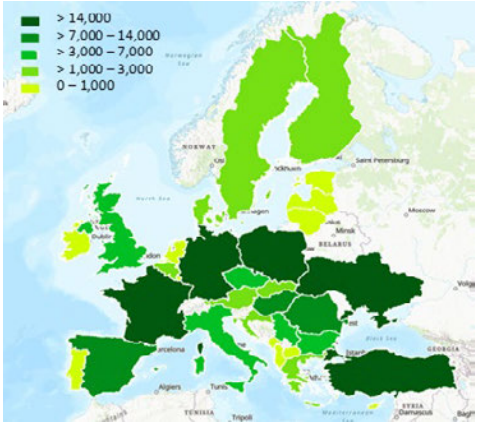


Figure 52: Sustainable potential of agriculture biomass by country (‘000 dry tonnes per year)

The same report estimates that 510 Mtpa of forest biomass (dry mass) will be available in Europe by 2030 under sustainable practices. Forest biomass includes: i) primary forestry production from thinnings & final fellings, stem and crown biomass from early thinnings, ii) logging residues and stumps from final fellings, iii) secondary residues from wood industries (sawmill and other wood processing).

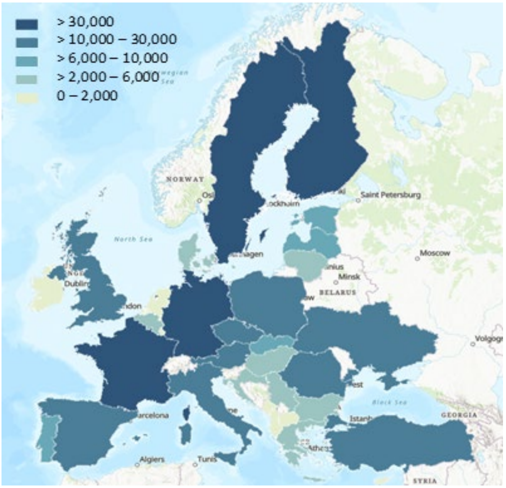


Figure 53: Sustainable potential of forestry biomass by country (‘000 dry tonnes per year)

The FAO estimates the average charcoal yield to vary from 16 to 30% of the weight of raw material. As charcoal is primarily produced using wood, we have considered forest biomass potential (sustainable) in our assessment. On this basis, European forest biomass (sustainable potential) in 2030 could yield between 81 and 153 Mtpa of charcoal. As mentioned previously, the charcoal demand from European steelmaking is estimated at 17 Mtpa which is well within the estimated range.

While there is potentially surplus biomass available for charcoal used in steel production, the commercial use of biomass/charcoal will require the establishment of supply chains. Biomass/charcoal supply chain is a network that links the raw material, conversion technologies and final market together. Pursuing efforts to optimise the biomass supply chain is critical as even small logistical improvements have the potential to considerably contribute to the cost effectiveness of the biomass conversion process. The following factors affect biomass/charcoal supply chain:

Sourcing radius: Optimising supply chain costs for feedstock production and energy conversion involves logistical challenges such as determining the optimal feedstock supply radius, i.e. sourcing radius. The sourcing radius refers to the economically viable distance between biomass collection point and the charcoal production plant that may or may not be integrated with a steel mill. Sourcing radius varies depending on the size of the plant, the type of feedstock used and the conversion costs. This also has implications for the overall steel GHG emissions.

Fragmentation of biomass sources: Land areas with forest or agricultural biomass are highly fragmented, adding challenges to the efficient collection and transportation of raw biomass.

Biomass densification: It should be noted that the bulk density of residues (especially agri-based) is relatively low, resulting in high transportation cost per km. Baling is a typical densification method for straw, however, other methods such as briquetting could increase the bulk density further. However, the costs of densification increase with increasing bulk density, and need to be considered against transport costs. Detailed investigation is needed to see whether densification could be considered attractive for a particular supply chain, taking into account the feedstock type, transport distance, volume and processing technology to be used downstream.

Current status of biomass/charcoal supply chains: Supply chains for biomass, especially residues, are fairly immature, therefore significant biomass supply infrastructure is needed to tap into the full sustainable potential. The maturity of the forest residue supply chain is heavily influenced by activity happening in the forest-based industry overall. Especially in the case of wood processing residues, traditional pulp and paper facilities act as the main driver for the deployment of this supply chain. Similarly, for harvesting residues, feedstock availability is influenced by forest management activities and logging practices. At European level, the maturity and activity of the forest-based industry varies considerably between individual countries. This is heavily influenced by the feedstock availability on the territory and the landscape (e.g. mountainous landscapes). The disparity between forest ownership can also impact the maturity of the supply chain. In Central Europe, a lot of private owners are small and independent and do not see themselves as part of the industry. This can make managing supply chain logistics considerably more challenging in those regions.

While there is indicatively enough sustainable biomass in Europe to comfortably satisfy charcoal demand in European Steelmaking, **competing uses must be taken into consideration**. There are multiple uses of lignocellulosic biomass as illustrated in Figure 54.

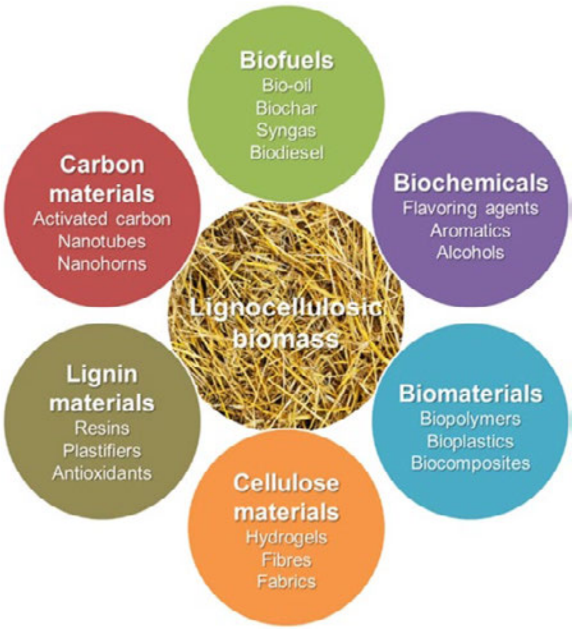


Figure 54: Multiple uses of lignocellulosic biomass (Okolie *et al.*, 2021)

The EU bioeconomy strategy aims to facilitate the development of 300 new or expanded sustainable biorefineries by 2030 focusing on bio-based products like chemicals, and energy (European Commission, Directorate-General for Research and Innovation, 2018). Lignocellulosic biomass will be among the various feedstocks required. Furthermore, with the launch of the Public Private Partnership (BioBased Industries Initiative Joint Undertaking) in 2014 in Europe, now succeeded by the Circular Bio-based Europe Joint Undertaking (CBE JU) (CBE JU, 2023), lignocellulosic biomass is expected to have a growing share in advanced pathways for non-energy industries such as biobased chemicals, bio-polymers and plastics and other bio-based materials replacing their fossil-based versions. BBI JU projects have three main focus areas: i) Feedstock, ii) Biorefineries and iii) Markets, products and policies.

While there is limited data on current/projected overall demand for lignocellulosic biomass in energy and non-energy applications, the competition for this feedstock is set to grow. Therefore, sustainable potential biomass (forest/agricultural) available for charcoal production will vary depending on competing uses.

Furthermore, while the section focuses on biomass available within Europe, steelmaking plants do have the option to import sustainably produced charcoal from countries such as Brazil. However, this will have cost and LCA implications associated with transportation.

5.6 DR-grade iron ore pellets

Demand for DR-grade pellets could reach 112 Mtpa in the EU if all production shifts towards DRI-based pathways, when normalised to 2021 production values. **This value is almost three times as large as the global DR-grade seaborne market in 2019**: out of a total seaborne pellet market of 115 Mt (Roy *et al.*, 2021), 43 Mt were DR-grade pellets (Barrington, 2021). In 2019, global pellet production was 463 Mt, with a large share (40%) used to meet domestic demand in China and India (Barrington, 2022). According to World Bank trade statistics for 2022, the EU currently imports 22 Mt of pellets per year (BF-grade) from outside the block. An additional 7 Mt of pellets are imported from Sweden, the only large iron ore producer in the block (World Integrated Trade Solution, 2023).[33] Figure 55 shows the scale of potential DR-grade pellet demand compared to current trade flows.

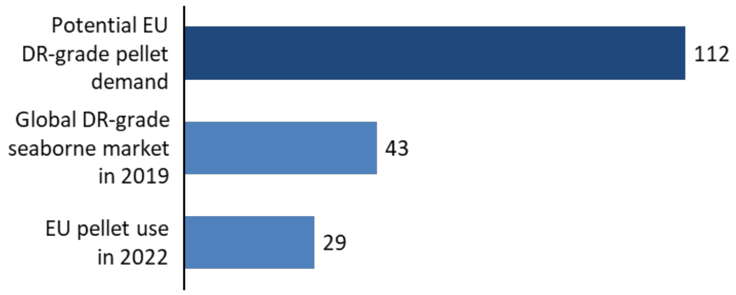


Figure 55: Comparison of potential DR-pellet supply with current market, Mtpa

The seaborne pellet market would need to expand significantly to meet increasing demand. More importantly, **steel producers will face a quality problem** as only a small share of seaborne iron ore meets the quality requirements for direct reduction. Significant investment by miners is required not only in pelletising capacity, but also in beneficiation of iron ore to achieve a DR-grade, with low-gangue content and a minimum Fe content of 66%. Beneficiation of iron ore to reduce the gangue content would not only require significant capital investment but would also result in substantial iron yield losses during the process (particularly for lower grade ores), increased water demand, and logistical challenges to handle mining tailings.

As demand for DR-grade pellet increases, supply by pellet producers needs to scale up. Analysis by the International Iron Metallics Association (IIMA) suggests there should be adequate supply by the middle of the 2020s given the capacity of existing pellet producers. However, as announced DR projects

[33] Mostly BF-grade pellets, given very small DRI capacity in the EU.

enter production **in the late 2020s and early 2030s there could be a significant shortfall in pellet supply** (Barrington, 2022). Depending on the evolution of the supply and demand balance, the availability of DR-grade pellets could become a bottleneck in the transition towards DRI-based pathways. Steel producers could address the challenge via diverse strategies. Firstly, a **higher degree of collaboration between iron ore producers and steel producers** is likely to be required. Examples are captive pellet supply with on-site pelletising plants (as Tata Steel Ijmuiden) or vertical integration (as is the case of LKAB, who have announced a long-term strategy to transition from supplier of pellets to supplier of HBI). Secondly, additional **research and development is needed for steel production pathways that do not require DR-grade pellets**. The electric smelting step between the DR plant and the steel shop, or the emergence of fines-based DR processes (not included in our analysis) could alleviate pressure on DR-grade ores.

6 Price premium for clean steel

Clean steel is currently a niche market. It is fairly new, with very limited production capacity able to meet the Near Zero threshold from the ResponsibleSteel standard.[34] Concurrently, demand for clean steel is growing. End-user pressure and ambitious supply chain carbon reduction targets from some steel purchasers have developed a growing demand. Under those conditions, customers may be willing to pay a premium for steel with a lower carbon footprint. The green premium is the **additional price above that paid for the equivalent conventional substitute** that the consumer will pay because of the lower GHG footprint associated with clean steel (Macnaughton and Poole, 2023).

A potential green premium on steel will depend on the **additional value customers attach to the reduced GHG footprint of clean steel** and on the **balance between supply and demand**, as scarcity is a key driver for the premium. Because the green premium refers to the additional price producers can obtain above *standard products*, and not above *production costs*, a green premium will only result in high producer margins if the green premium offsets any increase in production costs. The emergence of a premium means that additional costs incurred producing clean steel could be passed on to customers, but the extent to which this may happen, whether green premia can fully cover the additional production cost, and the time span over which green premia will materialise are questions that do not have well defined answers.

A green premium for clean steel will only develop as long as demand and supply remain unmatched and there is a supply shortage. The growing demand for clean steel is currently unmet, but whether this trend will continue into the future is unclear. Steel is largely a commodity (even though there are thousands of different steel grades), and it is hence a fungible good. Customers buying on international prices and without decarbonisation targets for their value chain will not be willing to pay a premium for clean steel. Therefore, as the supply of clean steel increases, and eventually when production of clean steel becomes a license to operate rather than a procurement choice, the premium over conventional steel will level off. The green premium will thus have a temporary effect only; the clean steel market may remain a small share of the overall steel market if the largest user segments are not willing to pay extra. This represents an advantage that can be grabbed by first movers, as identified by multiple stakeholders. With the **first mover advantage**, steel producers can secure a green premium, passing costs on to the customers before the market becomes saturated.

Estimating the evolution of green premia is a complex task. An estimation would require a market assessment of supply and demand for clean steel over time. This is beyond the scope of this study. However, it is possible to estimate an **upper boundary for green premia** based on the abatement cost customers are willing to pay. Steel customers aiming to decarbonise their value chain are likely to prioritise decarbonisation options with the lowest abatement cost. By assuming an indicative cap to the abatement cost customers are willing to face, we estimate an upper boundary for green premia and discuss its limitations. We compare this premium with the production cost gap between clean steel and steel from the conventional integrated route to determine whether additional costs can be fully passed on. Finally, we evaluate the impact that a premium on clean steel could have on end products such as buildings or automotives.

6.1 Demand and supply for clean steel

Demand for clean steel is growing. Sectors with a large steel consumption are facing increasing pressure from consumers, policymakers, and the finance sector to decarbonise their supply chains. The mounting pressure is explained by a combination of increasing policy incentives to decarbonise, greater

[34] The ResponsibleSteel standard sets a different GHG emissions threshold, including a Near Zero emissions intensity threshold that accounts for direct CO_2 emissions and GHG emissions associated with the generation of electricity imported to the site and with imported materials (ResponsibleSteel, 2022).

scrutiny from finance players that have committed to climate-aligned portfolios, and modifications to consumer behaviour arising from increasing awareness of environmental impacts of consumption. The key steel-using sectors need to address this pressure to decarbonise their supply chains. However, not all demand sectors are equally positioned to drive the offtake of clean steel. Sectors that purchase high volumes of steel, that face higher pressure to decarbonise and that operate in concentrated markets purchasing directly from steel producers are better positioned to lead the way (Energy Transitions Commission, 2021).

The automotive sector is currently the most active sector in championing demand for clean steel. As discussed in Chapter 2, demand from construction and from the automotive sector represents almost two thirds of global steel demand. The automotive sector has a high demand volume and a highly concentrated market with original equipment manufacturers (OEMs) usually dealing directly with steel producers. Moreover, the sector is pressed to decarbonise as LCAs become ever more important for electric vehicles. For instance, BMW Group has signed agreements with steel producers Salzgitter and H2 Green Steel for delivery of clean steel, and has invested in Boston Metal, a startup developing electrolytic steelmaking (BMW Group, 2022). Other sectors with large steel demand are not as advanced in leading clean steel demand. While the construction sector represents the largest demand sector, it does not meet the other favourable conditions: it has a relatively fragmented value chain and, as explained in Section 2.1.2, construction largely uses secondary steel. A sub-sector of construction, the renewable energy market, is better placed to become a first mover in increasing demand for clean steel. Although renewable energy is perceived as cleaner than fossil fuel-based thermal generation, it is increasingly scrutinised to lower its carbon footprint when considering complete LCA. The market is set to grow rapidly over the next decade and manufacturing of solar panels and wind turbines is fairly concentrated.

Multiple steel consumers are already committing to future purchases of clean steel. Most publicly reported deals on clean steel to date belong to the automotive sector, as shown in Table 22. By making the commitments public, companies send an early demand signal to steel manufacturers and contribute to creating confidence in the future market. Alternatively, buyers can engage in buyers' initiatives such as SteelZero. SteelZero is a global initiative run by the Climate Group that brings together more than thirty companies that purchase large volumes of steel and that have committed to a minimum of procuring 50% clean steel by 2030 and 100% by 2050 (Climate Group, 2023). By aggregating individual commitments, the campaign maximises the potential impact, showing a strong signal to steel producers that there is a demand for clean steel across a variety of sectors. SteelZero includes energy producers, construction companies, and automotive OEMs. On the public procurement side of the market, there is also an increasing number of national, federal and municipal governments committing to and designing sustainable steel procurement approaches. For instance, the US through its Federal Buy Clean Initiative (US Council on Environmental Quality, 2021) (initially introduced in California in 2017) or the EU through Green Public Procurement (GPP) programmes, even if implementation and uptake have been problematic (Lewis *et al.*, 2023).

Table 22: Publicly reported deals on clean steel[35]

Clean steel consumer	Clean steel supplier	Industry
BMW	H2 Green Steel	Automotive
Mercedes	H2 Green Steel	Automotive
Scania	H2 Green Steel	Automotive
Polestar	SSAB/Hybrit	Automotive
Volvo	SSAB/Hybrit	Automotive
Ford	Tata Steel	Automotive
BMW	Boston Metal	Automotive

[35] Own research on press releases from either steel producers or customers.

Mubea	ThyssenKrupp	Automotive
BMW	Salzgitter	Automotive
Miele	Salzgitter	Automotive
Stahlo Steel Service Center	Salzgitter	Mixed
Mendritzki Group	Salzgitter	Mixed
General Motors	ArcelorMittal	Automotive
Gestcamp	ArcelorMittal	Automotive
Ford	Salzgitter	Automotive

The supply and demand relation of clean steel will create a market-based green premium. This green premium will form as long as there is an undersupply of clean steel. In Europe, it is expected that the market for clean flat steel will remain undersupplied until 2030,[36] as shown in Figure 56. Hence, in the short and medium term, the **supply and demand relation could create a higher willingness to pay and result in a significant green premium**. Only through increased production and additional clean steel projects will this market driven green premium reduce. In the long term, the green premium will likely fade out as supply catches up with demand. There is thus a 'first mover advantage' – the first movers will be able to claim large green premia until the market becomes saturated and supply meets demand. Given the high barriers to enter the market, the clean steel green premium may be more persistent than premia for other green commodities.

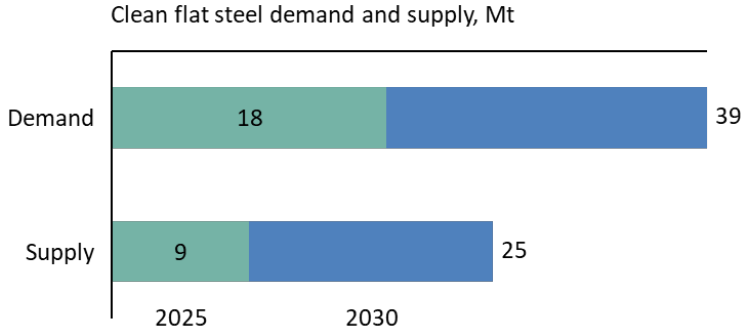


Figure 56: European supply and demand of flat clean steel by 2025 and 2030 (Azevedo *et al.*, 2022)

6.2 Green premium estimation

The additional value customers attach to the reduced GHG footprint of clean steel is a key driver for the green premium. Hence, **shadow carbon prices can offer an insight into the willingness of companies to pay a green premium**. A shadow price is a form of internal carbon pricing that sets a hypothetical price for carbon emissions, used as a tool to evaluate risks and opportunities in supply chains and future capital investment. Shadow pricing can support low-carbon investment decision making, drive energy efficiency, help changing internal behaviour, and back supplier engagement. Apart from that, it can be used to manage the risk of an increase in the price of emissions (CDP, 2021).

The shadow carbon price a steel consumer has adopted can represent the **upper bound of the marginal abatement cost it will be willing to face to decarbonise its value chain**. Steel consumers may already be accounting for expected price increases by considering a shadow carbon price. In theory, options to decarbonise the value chain that present a lower marginal abatement cost than the shadow price will be prioritised over those with a higher abatement cost. It is possible to derive the

[36] Flat steel products, including steel sheets, coils and plates, are typically produced by integrated steel mills as they have stricter tolerances on the inclusion of tramp elements.

green premium a consumer will be ready to pay for by linking the marginal abatement cost with the specific emissions reductions enabled by procuring clean steel.

Internal prices on carbon adopted by companies vary largely by region and emissions scope coverage, and by the type of price. In 2020, the median price in Europe was \$28/t CO_2 (or €25/t CO_2). Globally, the median price for the manufacturing and infrastructure sectors was \$28/t CO_2 and \$35/t CO_2. The variance in internal carbon prices can be high: the maximum shadow price reported to Carbon Disclosure Project (CDP) in 2020 was \$459/t CO_2 (CDP, 2021). By comparison, the EU ETS price in 2020 ranged between €16/t CO_2 and €32/t CO_2 (Ember, 2023). As shadow pricing can be used to manage risks from carbon pricing regulations, prices are likely to track the evolution of the EU ETS carbon price with some company specific nuance. More recently, the price of emissions allowances traded on the EU ETS has oscillated between €80/t CO_2 and €100/t CO_2 (Ember, 2023). To estimate an upper boundary for the green premium a median shadow carbon price for steel consumers of €100/t CO_2 was assumed.

Steel produced under the conventional integrated route has a GHG footprint of 1.89 t CO_2/t crude steel, according to results from the LCA.[37] For steel consumers with a **shadow carbon price of €100/t CO_2**, this would represent an additional cost of €189/t crude steel to be considered for procurement decisions. A shadow carbon price would also apply to the low emissions from clean steel. Assuming that clean steel meets the ResponsibleSteel's Near Zero threshold, for a 20% scrap content the emissions intensity would be 0.33 t CO_2/t crude steel.[38] This would add a cost of €33/t crude steel for procurement decisions. As a result, conventional steel would have a net shadow carbon price of €156/t crude steel.

Historically steel prices exhibit significant fluctuations. For the purposes of this study, we may compare the net shadow carbon price to a lower representative steel price of \$500 (€457) and a higher price of \$1,000 (€914) per ton of steel (Trading Economics 2024).[39] **The shadow carbon price of €100/tCO_2 then represents a green premium between 17% to 34%**, meaning that steel consumers would be willing to pay a maximum of 17%-30% more for clean steel compared to conventional steel.

[37] When procuring clean steel, it is likely that buyers will follow the ResponsibleSteel standard. In the ResponsibleSteel standard direct CO_2 emissions and GHG emissions associated with the generation of electricity imported to the site and with imported materials are included, but not other embedded GHG emissions. The value of 1.89 tCO_2/t crude steel acts as a reference for the green premium estimation purposes.

[38] The ResponsibleSteel standard uses a sliding scale to determine the Near Zero threshold depending on the scrap share of metallics input (ResponsibleSteel, 2022, p. 118).

[39] Prices from Trading Economics are for US Midwest domestic hot-rolled coil steel. While this differs from crude steel in Northwestern Europe, they are considered as equivalent for this high-level estimation.

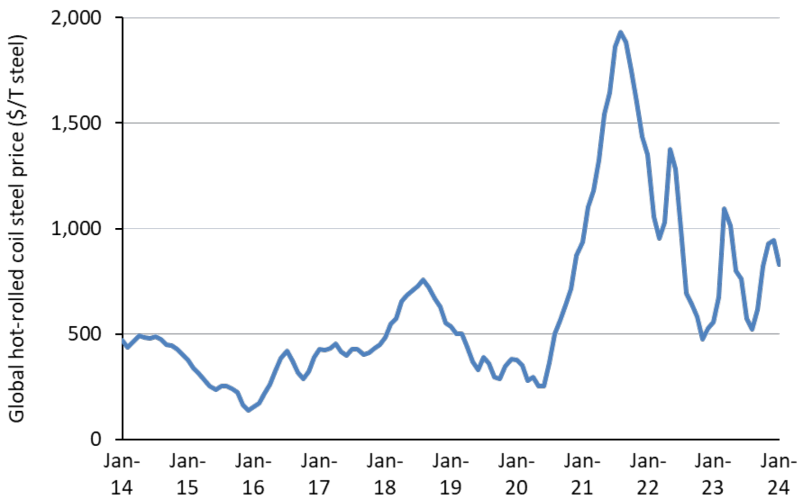


Figure 57: Historic global hot-rolled coil steel prices (Trading Economics, 2024)

Naturally, this green premium varies with the shadow carbon price as illustrated in Figure 58. Green premium makes a much smaller piece of overall costs when base steel prices are higher.

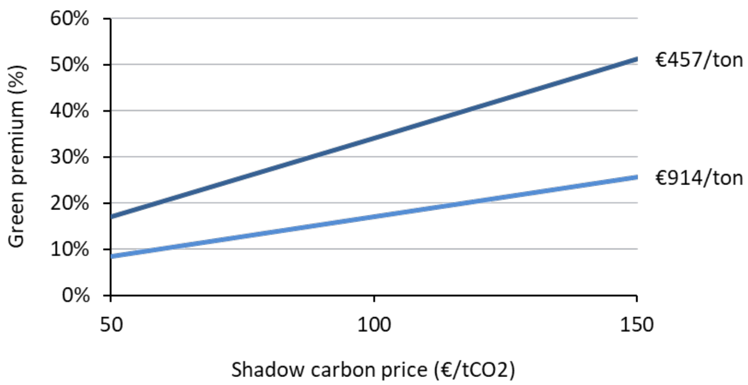


Figure 58: Green premium dependence on shadow carbon price and price of non-green steel at €457 and €914 per ton

By itself, **a green premium of €156/t crude steel is not enough to achieve cost parity** between conventional integrated steelmaking and steelmaking compatible with ResponsibleSteel's Near Zero threshold. Figure 59 shows the levelised costs of production for BF-BOF steel and the H-DRI with bioenergy pathway under a shadow carbon price of €100/t CO_2.[40] Even after including the shadow carbon price (which reflects the willingness of consumers to pay up to €156/t steel extra for clean steel), the H-DRI+EAF+bio pathway presents higher costs than conventional steelmaking. H-DRI steel would require an increase in the green premium from conventional steel to make it cost competitive, but most consumers are unlikely to be prepared to pay for a larger premium. Over time, the drop in production costs for clean steel and the increase in production costs for conventional steel due to rising carbon prices will tend to narrow the cost differential, and the green premium may be sufficient to cover the remaining difference. Before then, **additional support for either producers or consumers will be necessary to support uptake of clean steel**. Alternatively, consumers may be able to pass costs on to end users and thus accept a higher green premium.

[40] To avoid double counting of emissions pricing, this assumes a flat price of €100/t CO_2 and does not include EU allowances.

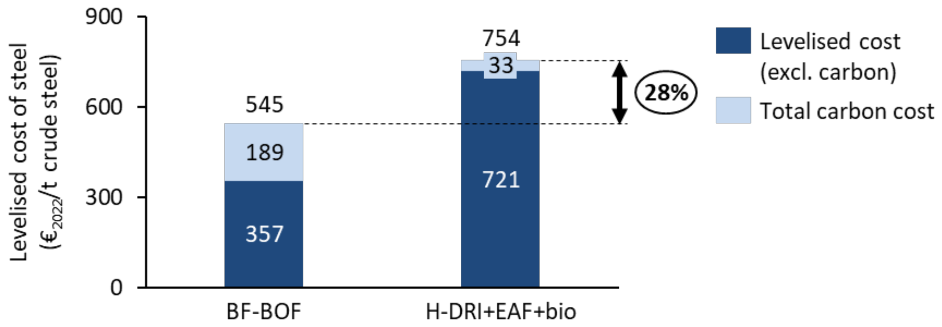


Figure 59: Levelised costs of production for conventional and clean steel (total carbon cost includes shadow carbon price of €100/t CO_2)

While green premia can increase the cost of clean steel for customers, their **impact on the end-product costs will be minimal**. Because the cost of steel represents only part of the end-product cost, the impact of green premia gets diluted down the value chain. The cost impact on each consumer of clean steel will be dependent on the percentage that steel costs represent in the end-product. For instance, for a car with a market price of €30,000 using 1.5 t of steel at a price of €530/t HRC, the cost of steel represents 2.6% of the market value of the final product. If the €156/t crude steel green premium is passed on to consumers, the impact on the market price would be a 0.8% increase. The Energy Transitions Commission have detailed similar small scale price increases for end users despite an increase in steel production costs, as illustrated in Figure 60 (Energy Transitions Commission, 2021).

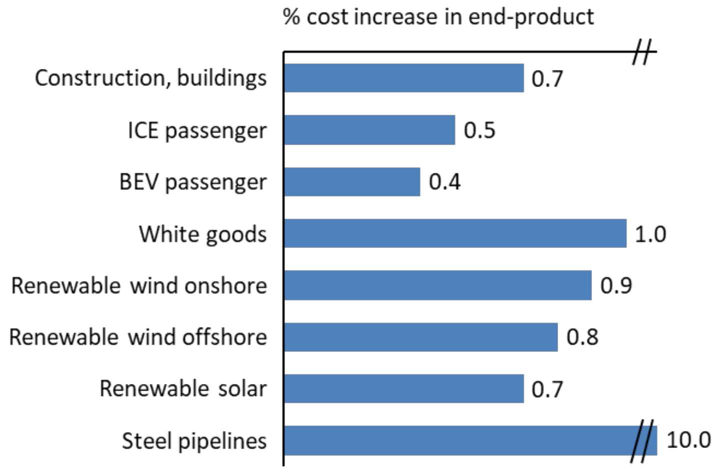


Figure 60: Cost increase in end-products due to shift to clean primary steel

The very low impact on end-products has telling consequences. If steel consuming sectors are able to pass on costs to end consumers they would not absorb the total cost of green premia. **By passing on the green premium costs, steel consumers can be ready to accept green premia in excess of what their internal carbon price dictates**. This is a limitation of the method used to estimate the upper boundary for the green premium. Passing on green premia may only be possible for sectors with short value chains, where the steel consumer acts as a direct intermediary between the steel producer and the end user.

7 Conclusions

Steel is a critical commodity in modern day society and will play an increasingly important role in the energy transition. Today, using the technologies deployed to date, steel production accounts for 8% direct CO_2 emissions, globally. Business as usual in terms of technologies used would therefore result in growing emissions when considering increased demand for steel products.

There are a number of alternative steelmaking technologies which could offer routes to the decarbonisation of steel. Some technologies which could present the opportunity of achieving the most radical decarbonisation are currently at very low maturity. Therefore, the focus of this study was on technologies that have the potential to **achieve commercial deployment by 2030,** and their applicability for integrated sites. Of the selected technologies, the study shows that all have the potential to reduce emissions (both direct and embedded) compared to traditional BF-BOF. However, the results also show that there is no zero emissions steelmaking. Residual emissions within the steelmaking facility and throughout the supply chain will need to be dealt with.

All pathways evaluated have higher production costs compared to BF-BOF, which is the pathway producing steel at the lowest cost: production costs are generally higher with increasing levels of decarbonisation. Nonetheless, **doing nothing is not a cost-neutral scenario**. Managing and eliminating emissions (operating and embodied) is becoming a core part of business and procurement, and not decarbonising will in the future lead to loss of market share and revenue reduction.

CCS retrofitted to an integrated BOS steel mill could add little additional cost to steelmaking, but, unless this is accompanied by very high levels of charcoal use, GHG emissions reductions are not compatible with deep decarbonisation. However, CCS on a DR plant could still be attractive compared to hydrogen-based routes largely due to the additional electricity and coal required in hydrogen-based pathways. Therefore, hydrogen- and electricity-intensive pathways can achieve low GHG emissions and fossil resource use, but this is strongly dependent on sourcing of low-carbon hydrogen and electricity. Sensitivity analysis showed that in the long-term H-DRI+EAF with bioenergy could achieve the lowest fossil GWP as the electricity grid decarbonises. In the future, the cost gap will close as effective carbon prices increase and energy costs (electricity and hydrogen) decrease, making **H-DRI pathways increasingly attractive**.

Supporting infrastructure could be a bottleneck in the transition to clean steel technologies. This study has shown the vital role infrastructure will need to play for the successful roll out of alternative steel technologies:

- The capacity of existing CO_2 storage projects developing in Europe today would be sufficient to account for **24 years of CO_2 storage capacity**, if all steel mills in the EU transitioned to CCS-based pathways – assuming storage is dedicated to the iron and steel sector.
- Hydrogen demand for steelmaking in the EU could claim **up to 50% of hydrogen supply for new applications**, facing competition from other sectors including transport and chemicals.
- All alternative steel technologies have a higher electricity demand than the traditional integrated steel mill. **Additional renewable generation** capacity and **grid reinforcements** will be needed to support the transition. 30% of the planned increase in renewable generation in the EU by 2030 could be claimed by primary steel production, if all steel mills were to transition to H-DRI based pathways.
- Pairing bioenergy with H-DRI could lead to the greatest reduction in fossil emissions. Substitution of PCI coal with charcoal at all EU steel mills would require 17 Mtpa charcoal. While this is well within the estimated potential from forestry-based biomass, **true availability may be significantly less** due to accessibility, immature supply chains and competing uses.

The solution for steelmaking facilities to transition to cleaner steelmaking could vary substantially by geography even within Europe. Sites in Northwestern Europe (study focus) are likely to be better suited for adopting CCS technologies due to the location of developing CO_2 transport and storage projects. Sites in Central or Southern Europe may find transitioning to hydrogen-based routes more attractive due to existing hydrogen pipelines. However, without PPAs and until widespread renewable hydrogen production, the location of H-DRI projects is likely to be dictated by steel mills in close proximity to developing hydrogen projects, ultimately driven by access to low-cost renewable electricity. Hence, existing H-DRI projects are currently developing in Northwestern Europe.

While increased effective carbon price could increase the cost competitiveness of alternative steelmaking technologies compared to BF-BOF in the near-term, the coexistence of carbon pricing and free allowances does not incentivise decarbonisation. To compensate for higher production costs, **further incentives are required to drive the roll-out of clean steel production capacity**. These incentives could take the form of policy support mechanisms or could stem from the ability to claim a green premium on clean steel. The analysis has shown that green premia would have a low impact on the final product cost (less than 1% impact for a car), therefore if costs could be passed along the supply chain to the end consumer, the direct consumers of steel, like OEMs, may be willing to pay a higher price.

Based on these conclusions, it is recommended that future work focuses on 4 areas:

- **Extending the analysis**: multiple technologies, including nascent technologies such as electrolytic reduction or alternative CCS configurations, were excluded from the analysis. Further assessment, including the application of learning rates to emerging technologies, can offer a more complete picture of future costs and associated impacts. Moreover, the LCA could be extended to cover other environmental and social impact categories, which could highlight unforeseen environmental hotspots in the pathways. Further assessment of decarbonisation options for upstream mining and downstream processing of crude steel, not included within the scope of this study, could also help to identify ways to reduce embedded emissions and costs. Given the high potential for biomass use that was identified, thorough evaluation of true availability of biomass for steel and the impacts its use may have in process parameters are needed.
- **Steel and iron decoupling and its societal impacts**: this study has identified that high energy costs in Europe may adversely affect the cost structure for steel producers transitioning towards H-DRI pathways. Steel producers could potentially lower production costs by importing HBI to charge it into an electric arc furnace. Extending the analysis to other regions, bringing in wider geopolitical factors which may influence the roll out of technologies across the globe, is required to identify regions where transitioning to H-DRI presents a competitive advantage. It is also crucial to assess the impacts that steel and iron decoupling could have in terms of direct and indirect jobs and value added in different regions and at a local level, and how this affects the just transition.
- **Exploring commercial arrangements and business models**: securing access to low-price and low-carbon electricity and hydrogen and being able to claim a green premium are vital for steel producers transitioning towards clean steel pathways. Exploring the commercial arrangements and business models that could underpin the different pathways is required. For instance, future studies can assess whether steel producers can access cheaper electricity and hydrogen by participating in demand side response measures. A more complete understanding of the bargaining power of steel producers and customers in determining the green premium is also needed to understand the extent to which costs could be passed on to end-users.
- **Assessing barriers and enablers in the transition**: the supporting infrastructure plays a critical role in facilitating uptake of steel decarbonisation technologies. Moreover, further policy support is likely required to facilitate the transition. A fuller understanding of barriers and enablers for different technology pathways is required, as this study has mainly focused on economic and environmental metrics that offer a partial picture only. Exploring the advantages and disadvantages of different policy mechanisms to drive the deployment of decarbonisation

technologies is also needed, including an assessment of the effect that the Carbon Border Adjustment Mechanism (CBAM) could have on European steel production.

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9 Appendix

9.1 Key modelling assumptions

9.1.1 End of life recycling credit

In this study, it is assumed that 20% of material input is scrap steel (with 80% iron ore/pellets/fines). Therefore, treatment of recycled products must be considered within the LCA. As discussed in Section 4.1.2, and aligning with World Steel, the selected system boundary is cradle-to-gate with and without recycling. When recycling is included in the system boundary, the study makes use of the **closed material loop recycling methodology** defined by World Steel which is shown by the following equation.

$$\boldsymbol{LCI\ for\ 1\ kg\ of\ crude\ steel\ product\ including\ recycling = X\ - (RR - S)\ \times Y(X_{pr} - X_{re})}$$

- X is the cradle to gate LCI of the product
- (RR-S) is the **net** amount of scrap
    - RR = recycling rate of the steel product. In this study this value was assumed to be 85%.
    - S is the scrap input to the steelmaking process
- $Y(X_{pr} - X_{re})$ is the value of scrap
    - Y = process yield of an EAF – ratio of steel output to scrap input
    - X_{Pr} = Theoretical LCI for 100% primary metal production via BF-BOF route (0% scrap input)
    - X_{re} = Theoretical LCI for 100% secondary metal production from scrap in the EAF (100% scrap input)

World Steel recommend reporting the recycling credit separate from the main results for transparency, this approach has been adopted in this study.

9.1.2 Carbon and energy pricing

Year	EU ETS (CO_2) (€2022/t)	Coking coal (€2022/t)	Electricity (€2022/MWh)	NG (€2022/GJ)	H_2 (€2022/kg)
2024	83	219	68	17.1	4.7
2025	85	202	66	13.1	4.6
2026	87	183	63	9.7	4.5
2027	89	173	60	8.8	4.5
2028	91	173	58	8.3	4.4
2029	93	173	55	7.8	4.3
2030	94	173	52	7.3	4.3
2031	95	173	52	7.2	4.2
2032	104	173	52	7.1	4.2
2033	112	173	52	7.1	4.1
2034	120	173	52	7.0	4.0
2035	129	173	52	6.9	4.0
2036	137	173	52	6.8	3.9
2037	145	173	52	6.8	3.9
2038	154	173	52	6.7	3.8
2039	162	173	52	6.6	3.7
2040	170	173	52	6.5	3.7
2041	173	173	52	6.5	3.6
2042	175	173	52	6.4	3.6
2043	178	173	52	6.3	3.5
2044	180	173	52	6.3	3.5
2045	182	173	52	6.2	3.4
2046	185	173	52	6.1	3.3
2047	187	173	52	6.0	3.3
2048	190	173	52	6.0	3.2
2049	192	173	52	5.9	3.2
2050	195	173	52	5.8	3.1

9.2 LCI

9.2.1 LCI – BF-BOF baseline scenario

Pellet plant *(Not onsite; assume pellets imported from Brazil)*

Material/ energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Iron ore concentrate	Iron ore concentrate {GLO}|market for iron ore concentrate| Cut-off, U	This activity represents the global supply of iron ore concentrate (65% Fe, dry basis) to consuming activities in iron and steelmaking. It includes transport emissions that have been used as proxy for the transport of pellets from Brazil to the Netherlands.
	Limestone	Limestone, crushed, for mill {RoW} | Market for limestone, crushed, for mill | Cut-off, U	
	Natural gas	Natural Gas, High Pressure {BR} | market for natural gas, high pressure| Cut-off, U	Natural gas entry under 'Inputs from technosphere: materials/fuels' is in m^3 and not MJ. Used following assumption: "A cubic metre of natural gas contains approximately 38.3 MJ/m^3" So, 1MJ natural gas = 1/38.3 = 0.0261 m^3
	Electricity	Electricity, medium voltage {BR}|market group for electricity, medium voltage|Cut-off, U	Brazilian grid electricity selected here as pellet plant is off-site and it is assumed that the pellets are imported from Brazil. Note: Emissions data associated with this appear to be outdated in Ecoinvent 3.8 – higher emissions compared to 2020 estimated emissions (IEA, 2022a).[41] This has been discussed in section 4.3.5 of the report.
	Water	Water, deionised {RoW} | market for water, deionised | Cut-off, U	Water entry under '*Inputs from technosphere: materials/fuels*' is in kg and not m^3. "Water, distilled weighs 1 g/cm^3 or 1,000 kg/m^3, i.e. density of water; at 25°C (77°F or 298.15K) at standard atmospheric pressure." So, 1m^3 deionised water = 1,000 kg
Outputs	Pellets		
	Wastewater	Wastewater from pig iron production {RoW}|treatment of, capacity 5E9l/year|Cut-off,U	
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, including CH_4, are converted to CO_2 before being emitted.

[41] IEA (2022). Emission factors 2022. Available at: https://www.iea.org/data-and-statistics/data-product/emissions-factors-2022

Sinter plant

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Sinter feed	Iron ore concentrate {GLO}|market for iron ore concentrate| Cut-off, U	Sinter feed is iron ore concentrate or fines with iron content assumed to be ~58% for sinter. The SimaPro entry is for iron ore concentrate with 65% iron, dry basis.
	Limestone	Limestone, crushed, for mill {CH} | Market for limestone, crushed, for mill | Cut-off, U	Swiss process flow selected as this is the only European-specific process flow on market for limestone.
	Lime	No Ecoinvent entry selected	Input from lime kiln (on-site)
	Water	Water, deionised {Europe without Switzerland} | Market for water, deionised | Cut-off, U	
	BOF slag	No Ecoinvent entry selected	Input from the BOF
	BF return fines	No Ecoinvent entry selected	Input from the BF
	BF dust	No Ecoinvent entry selected	Input from the BF
	Coke breeze	No Ecoinvent entry selected	Input from the coke oven
	COG	No Ecoinvent entry selected	Input from the coke oven
	Electricity	No Ecoinvent entry selected	From 'Coke oven' and 'Co-generation plant'
Outputs	Sinter		
	Sludge	Blast furnace sludge {Europe without Switzerland}|treatment of blast furnace sludge, residual material landfill|Cut-off,U	No Ecoinvent entry for sinter plant sludge. BF sludge assumed to be the most appropriate proxy
	Wastewater	Wastewater from pig iron production {Europe without Switzerland}|treatment of wastewater from pig iron production, capacity 5E9l/year|Cut-off,U	Most suitable process flow in Ecoinvent V3.8
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, including CH_4, are converted to CO_2 before being emitted.

Coke oven

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Coking coal	Hard coal {AU}| market for | Cut-off, U Hard coal {Europe, without Russia and Turkey}| hard coal, import from AU | Cut-off, U	Also known as metallurgical coal. The rank is often bituminous coal or black coal, but some grades of anthracite coal or hard coal might be used.

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
	Water	Water, deionised {Europe without Switzerland} | Market for water, deionised | Cut-off, U	
	BFG	No Ecoinvent entry selected	Input from the BF
	COG	No Ecoinvent entry selected	Input from the coke oven
	Electricity	No Ecoinvent entry selected.	Process flow for "Electricity_GeneratedInCokeOven" used here
	Steam	No Ecoinvent entry selected.	We have assumed that this is steam from BOF
Outputs	Coke		
	Coke breeze	No Ecoinvent entry selected.	Coke breeze is used in the sinter plant. Coke breeze contains coke dust/particles, mixed with iron ore fines - same composition as coke
	COG	COG_UsedInternally (no emissions linked)	Assumption: Some COG is used in other units and remaining is exported out of the system boundary, but used within the integrated steel plant. It serves as a substitute for natural gas.
		Natural gas, high pressure {DE}|natural gas production| Cut-off, U *(Avoided product)*	
	COG flared	No Ecoinvent entry selected.	CO_2 emissions in the 'emissions to air' section of the model.
	Electricity	No Ecoinvent entry selected.	Electricity generated in coke oven is assumed to be used within the system boundary
	Crude tar	Bitumen seal {RER}|production|Cut-off,U *(Avoided product)*	Crude tar is a byproduct, not used any further in the system. Crude tar is a blend of tar and naphthalene.
	Benzole	Benzene {RER}|production|Cut-off,U *(Avoided product)*	Benzole is a byproduct, not used any further in the system. It is also known as BTX (benzene, toluene and xylene)
	Wastewater	Wastewater from pig iron production {Europe without Switzerland}|treatment of wastewater from pig iron production, capacity 5E9l/year|Cut-off,U	Most suitable process flow in Ecoinvent V3.8
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, including CH_4, are converted to CO_2 before being emitted.

Lime kiln

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Limestone	Limestone, crushed, for mill {CH} | Market for limestone, crushed, for mill | Cut-off, U	Chosen Switzerland as only European-specific flow.
	COG	No Ecoinvent entry selected .	Input from coke oven
	Electricity	No Ecoinvent entry selected	Input from coke oven
Outputs	Lime		
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, including CH_4, are converted to CO_2 before being emitted.

Air separation unit (ASU)

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Electricity	No Ecoinvent entry selected	Input from co-generation plant
	Air	No Ecoinvent entry selected	
Outputs	Oxygen		
	Nitrogen	Selected "Nitrogen, atmospheric" in Ecoinvent	

Blast furnace

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Pellets	No Ecoinvent entry selected	Input from pellet plant (Brazil)
	Sinter	No Ecoinvent entry selected	Input from sinter plant
	Lump ore	Iron ore concentrate {GLO}|market for iron ore concentrate| Cut-off, U	No 'Lump ore' entry in Ecoinvent.
	Limestone	Limestone, crushed, for mill {CH} | Market for limestone, crushed, for mill | Cut-off, U	
	Coke	No Ecoinvent entry selected	Input from coke oven
	PCI	Hard coal {AU}| market for | Cut-off, U Hard coal {Europe, without Russia and Turkey}| hard coal, import from AU | Cut-off, U	Also known as metallurgical coal. We have used the same Ecoinvent entry as for coking coal.
	Oxygen	No Ecoinvent entry selected	Input from Air Separation Unit (ASU)
	BFG	No Ecoinvent entry selected	This is an input from the blast furnace
	Electricity	No Ecoinvent entry selected	From the blast furnace and the co-generation plant.

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
	Steam	No Ecoinvent entry selected	This is steam from BOF
	Water	Water, deionised {Europe without Switzerland} | Market for water, deionised | Cut-off, U	
Outputs	Hot metal		
	BF slag	Cement, Portland {Europe without Switzerland}| production| Cut-off,U *(Avoided product)*	Avoided product
	BFG	No Ecoinvent entry selected.	BFG generated is re-circulated within the system boundary
	BFG flared	No Ecoinvent entry selected.	CO_2 emissions in the 'emissions to air' section of the model.
	BF sludge	Blast furnace sludge {Europe without Switzerland}|treatment of blast furnace sludge, residual material landfill|Cut-off,U	
	Electricity	No Ecoinvent entry selected	Electricity generated in blast furnace is re-circulated here
	Waste water	Wastewater from ground granulated blast furnace slag production {RoW}|treatment of|Cut-off,U	
	Emissions to air (CO_2)	Carbon dioxide	

Basic oxygen furnace

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Hot metal	No Ecoinvent entry selected	Input from blast furnace
	Home scrap	On-site (0 impact associated in model)	
	Purchased scrap	Burden associated with this is in the credit calculated using World Steel Association data (0 impact associated in model) and will be presented separately from the main results	
	Lime	No Ecoinvent entry selected	Input from lime kiln
	Burnt dolomite	Lime {Europe without Switzerland}|lime production, milled, loose|Cut-off,U	
	Oxygen	No Ecoinvent entry selected	From Air Separation Unit (ASU)
	Electricity	No Ecoinvent entry selected	From 'Co-generation plant'. Used process flow "Electricity_Co-generation plant"

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Outputs	Liquid steel		
	BOF slag	Recycled in system - 0 impact	
	BOF slag for sale	Gravel, crushed{CH}|production|Cut-off,U *(Avoided product)*	Avoided product
	BOFG	No Ecoinvent entry selected.	Used in co-generation plant.
	BOFG flared	No Ecoinvent entry selected.	CO_2 emissions in the 'emissions to air' section of the model.
	Steam	Most of the steam from BOF is used internally in coke oven and blast furnace. No emissions associated with that. Some steam is dissipated on site.	
	Emissions to air (CO_2)	Carbon dioxide	

Ladle metallurgy and continuous casting

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Liquid steel	No Ecoinvent entry selected	Input from BOF
	Lime	No Ecoinvent entry selected	Input from lime kiln
	Oxygen	No Ecoinvent entry selected	Input from ASU
	COG	No Ecoinvent entry selected	Re-circulated from coke oven
	Water	Water, deionised {Europe without Switzerland} | Market for water, deionised| Cut-off, U	
	Electricity	No Ecoinvent entry selected	From the coke oven
Outputs	Crude steel		
	Home scrap	No Ecoinvent entry selected	Recirculated in BOF
	LM slag	Basic oxygen furnace secondary metallurgy slag {GLO}|treatment of basic oxygen furnace secondary metallurgy slag, residual material landfill|Cut-off,U	Goes to landfill
	Wastewater	Wastewater from ground granulated blast furnace slag production {RoW}|treatment of|Cut-off,U	Most suitable process flow in Ecoinvent V3.8
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, incl. CH_4, are

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
			converted to CO_2 before being emitted.

Co-generation plant

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	BFG	No Ecoinvent entry selected	Re-circulated from blast furnace
	BOFG	No Ecoinvent entry selected	Re-circulated from BOF
Outputs	Electricity	No Ecoinvent entry selected for nearly half of the electricity generated (see assumption). Surplus electricity generated in co-generation plant features as ‘avoided product' (Electricity, high voltage {NL}|production mix|Cut-off,U)	Nearly half of the electricity generated in co-generation plant is used on-site.
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, incl. CH_4, are converted to CO_2 before being emitted.

9.2.2 LCI – BF-BOF + H2 scenario

The LCI for the BF-BOF hydrogen scenario has some similarities with the baseline scenario, as well as differences. These are explained in the table below.

BF-BOF + H_2 scenario - Processes	Similarities/ differences
Pellet plant	Input and output data same as in BF-BOF baseline scenario
Sinter plant	Similar to BF-BOF baseline scenario with different coke breeze and COG input, and higher CO2 emissions
Coke oven	Input and output entries similar (e.g. coking coal, COG) but data very different from BF-BOF baseline scenario
Lime kiln	Input and output data same as in BF-BOF baseline scenario
Air Separation Unit (ASU)	No Air separation unit (ASU) considered as it is assumed that oxygen will be available from the electrolyser plant
Electrolyser	This unit is unique to this route
Blast furnace	Main difference is the hydrogen input from electrolyser unit. Also, data associated with several entries are different from the baseline scenario.
Basic oxygen furnace	Input and output data same as in BF-BOF baseline scenario, except for steam re-circulated within the system boundary and steam dissipated. Also, oxygen input is from the electrolyser and not the ASU.
Ladle metallurgy and continuous casting	Input and output data same as in BF-BOF baseline scenario

BF-BOF + H_2 scenario - Processes	Similarities/ differences
Co-generation plant	Input and output data same as in BF-BOF baseline scenario, except for cogen electricity used within the system boundary and surplus electricity that is an 'Avoided Product'

On this basis, only the electrolyser unit is described below.

Electrolyser (off-site)

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Water	Water, deionised {Europe without Switzerland} | Market for water, deionised | Cut-off, U	Emissions associated with transportation of hydrogen to the site have not been included here.
	Electricity	Electricity, high voltage {NL}|electricity production, wind, 1-3MW turbine, onshore|Cut-off,U	Renewable electricity used
Outputs	Hydrogen		
	Oxygen		

Note: The LCA only considers market renewable hydrogen (see Table 6 for details)

9.2.3 LCI – BF-BOF + CCS scenario

The LCI for the BF-BOF + CCS scenario has some similarities with the baseline scenario, as well as differences. These are explained in the table below.

BF-BOF + CCS scenario - Processes	Similarities/ differences
Pellet plant	Input and output data same as in BF-BOF baseline scenario
Sinter plant	Input and output entries similar (e.g. sinter feed, COG) but data very different from BF-BOF baseline scenario
Coke oven	Input and output entries similar (e.g. coking coal, COG) but data very different from BF-BOF baseline scenario
Lime kiln	Input and output data same as in BF-BOF baseline scenario, except for electricity source (co-generation plant instead of coke oven)
Air Separation Unit (ASU)	Input and output entries similar but data very different from BF-BOF baseline scenario
Oxy-blast furnace	Input and output entries similar but data very different from BF-BOF baseline scenario. Main difference is the generation of OBF-PG instead of BFG, and CO_2 emissions from the OBF being sent to the CO_2 capture plant.

BF-BOF + CCS scenario - Processes	Similarities/ differences
Basic oxygen furnace	Input and output data same as in BF-BOF baseline scenario, except for steam and electricity input
Ladle metallurgy and continuous casting	Input and output data same as in BF-BOF baseline scenario, except for electricity input which is from the co-generation plant instead of coke oven.
CO_2 capture plant	This unit is unique to this route and the BECCS route
Electric boiler	This unit is unique to this route and the BECCS route
Co-generation plant	Input and output entries similar but data very different from BF-BOF baseline scenario
Transport and storage (T&S) of CO_2	This unit is unique to this route and the BECCS route

On this basis only the following three sub-units are described below.

CO_2 capture plant

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	CO_2 to absorber	No Ecoinvent entry selected	Process flow attached is 'BF-BOF_OBF-PG CO_2 emissions'
	Amine solvent	Monoethanolamine {GLO} market for|Cut-off,U	
	Water (for solvent dilution)	Water, deionised {Europe without Switzerland} | Market for water, deionised | Cut-off, U	
	Steam	No Ecoinvent entry selected	Steam is re-circulated from BOF, electric boiler and co-generation unit
	Electricity	Electricity, medium voltage {NL}| market for| Cut-off, U	NL electricity data in Ecoinvent V3.8 is from 2014. This is 30% higher than IEA's reported data for 2020. A sensitivity analysis has been done in section 4.3.5.
Outputs	CO_2 stream for T&S	No Ecoinvent entry selected	Linked with the CO_2 transport and storage (T&S) step
	Waste solvent	Spent solvent mixture {Europe without Switzerland} |treatment of	

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
		spent solvent mixture, hazardous waste incineration|Cut-off,U	
	Emissions to air (CO_2)	Carbon dioxide	

Electric boiler

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Electricity	Electricity, medium voltage {NL}| market for| Cut-off, U	See previous comments regarding NL grid.
Outputs	Steam		

Transport and storage (T&S) of CO_2

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	CO_2 from capture plant	No Ecoinvent entry selected	Re-circulated from CO_2 capture plant
	Electricity for injection	Electricity, medium voltage {NL}| market for| Cut-off, U	See previous comments regarding NL grid.
Outputs	CO_2 from capture plant	No Ecoinvent entry selected	After accounting for 0.5% seepage
	CO_2 seepage (emissions to soil/land)	Carbon dioxide, to soil or biomass stock	Seepage is the gradual and slow migration of CO_2 out of the confinement zone and into adjacent reservoirs (or maybe caprock if not completely impermeable). This is assumed to be 0.5% of CO_2 being subjected to T&S.

9.2.4 LCI – BF-BOF + BECCS scenario

The LCI for the BF-BOF + BECCS scenario has some similarities with the baseline and CCS scenarios, as well as differences. These are explained in the table below.

BF-BOF + BECCS scenario - Processes	Similarities/ differences
Pellet plant	Input and output data same as in BF-BOF baseline scenario

BF-BOF + BECCS scenario - Processes	Similarities/ differences
Sinter plant	Input and output data same as in BF-BOF + CCS scenario
Coke oven	Input and output data same as in BF-BOF + CCS scenario
Lime kiln	Input and output data same as in BF-BOF baseline scenario, except for electricity source (co-generation plant instead of coke oven)
Air Separation Unit (ASU)	Input and output data same as in BF-BOF + CCS scenario
Oxy-blast furnace	Input and output data same as in BF-BOF + CCS scenario except for PCI coal input (0 kg/t CS) and Charcoal input (x kg/t CS). Ecoinvent entry for charcoal -> Charcoal {GLO}|market for|Cut-off, U
Basic oxygen furnace	Input and output data same as in BF-BOF baseline scenario, except for steam and electricity input
Ladle metallurgy and continuous casting	Input and output data same as in BF-BOF baseline scenario, except for electricity input which is from the co-generation plant instead of coke oven.
CO_2 capture plant	Input and output data same as in BF-BOF + CCS scenario
Electric boiler	Input and output data same as in BF-BOF + CCS scenario
Co-generation plant	Input and output data same as in BF-BOF + CCS scenario
Transport and storage (T&S) of CO_2	Input and output data same as in BF-BOF + CCS scenario

9.2.5 LCI – NG-DRI EAF scenario

The LCI for the NG-DRI EAF scenario has some similarities with the baseline scenario, as well as differences. These are explained in the table below.

NG-DRI EAF scenario - Processes	Similarities/ differences
Pellet plant	Input and output data same as in BF-BOF baseline scenario
Lime kiln	Input and output data same as in BF-BOF baseline scenario, except for electricity source (NL grid)
Air Separation Unit (ASU)	Input and output data same as in BF-BOF + CCS scenario, except for the circulation of nitrogen from the ASU to the shaft furnace
Shaft furnace	This unit is unique to the NG-DRI routes
Electric arc furnace (EAF)	This unit is unique to the NG-DRI EAF route
Ladle metallurgy and continuous casting	Input and output data same as in BF-BOF baseline scenario, except for electricity input which is from the co-generation plant instead of coke oven.

On this basis only the following sub-units are described below.

Shaft furnace

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Pellets	No Ecoinvent entry selected	Input from pellet plant (Brazil)
	Oxygen	No Ecoinvent entry selected	This is an input from the ASU
	Nitrogen	No Ecoinvent entry selected	This is an input from the ASU
	Natural gas	Natural gas, high pressure {NL}| market for | Cut-off, U	
	Electricity	Electricity, medium voltage {NL}| market for| Cut-off, U	See previous comments regarding NL grid.
Outputs	DRI		
	Emissions to air (CO_2)	Carbon dioxide	

Electric arc furnace (EAF)

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	DRI	No Ecoinvent entry selected.	Input from shaft furnace
	Home scrap	On-site (0 impact associated in model)	
	Purchased scrap	Burden associated with this is in the credit calculated using World Steel Association data (0 impact associated in model) and will be presented separately from the main results	
	Lime	No Ecoinvent entry selected.	Input from lime kiln
	Burnt dolomite	Lime {Europe without Switzerland}|lime production, milled, loose|Cut-off,U	
	Graphite electrodes	Synthetic graphite, battery grade {RoW}| market for synthetic graphite, battery grade | Cut-off, U	As per Steppich, D. (2021), "within every EAF are graphite electrodes composed of synthetic graphite" There is no option in SimaPro for synthetic graphite that is not battery grade and specific for EAF application.

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
	Refractory lining	Refractory, basic, packed {GLO}| market for | Cut-off, U	
	Coal	Hard coal {AU}| market for | Cut-off, U Hard coal {Europe, without Russia and Turkey}| hard coal, import from AU | Cut-off, U	
	Oxygen	No Ecoinvent entry selected.	Input from Air Separation Unit (ASU)
	Natural gas	Natural gas, high pressure {NL}| market for | Cut-off, U	
	Electricity	Electricity, medium voltage {NL}| market for| Cut-off, U	NL electricity data in Ecoinvent V3.8 is from 2014.
	Water	Water, deionised {RoW} | market for water, deionised | Cut-off, U	
Outputs	Liquid steel		
	EAF slag	Gravel, crushed{CH}|production|Cut-off,U *(Avoided product)*	Avoided product
	Dusts	Electric arc furnace dust {CH}| treatment of electric arc furnace dust, residual material landfill | Cut-off, U	
	Waste refractories	Electric arc furnace slag {RoW}| treatment of electric arc furnace slag, residual material landfill | Cut-off, U	Sent to landfill (although other valorisation options could be available). Smaller than refractory lining as part of refractories is lost to slag. No Ecoinvent entry for waste refractory.
	Emissions to air (CO_2)	Carbon dioxide	

9.2.6 LCI – NG-DRI EAF + CCS scenario

The LCI for the NG-DRI EAF + CCS scenario has some similarities with the NG-DRI EAF scenario, as well as differences. These are explained in the table below.

NG-DRI EAF + CCS scenario - Processes	Similarities/ differences
Pellet plant	Input and output data same as in NG-DRI EAF scenario
Lime kiln	Input and output data same as in NG-DRI EAF scenario
Air Separation Unit (ASU)	Input and output data same as in NG-DRI EAF scenario
Shaft furnace	Input and output data same as in NG-DRI EAF scenario. Main difference is that the CO_2 emissions from the shaft furnace are sent to the CO_2 capture plant.
Electric arc furnace (EAF)	Input and output data same as in NG-DRI EAF scenario
Ladle metallurgy and continuous casting	Input and output data same as in NG-DRI EAF scenario
CO_2 capture plant	Similar to unit in the BF-BOF + CCS scenario, except for the source of steam
Electric boiler	Similar to unit in the BF-BOF + CCS scenario, except for the input of steam from waste heat recovery
Transport and storage (T&S) of CO_2	Similar to unit in the BF-BOF + CCS scenario

9.2.7 LCI – H-DRI EAF scenario

The LCI for the H-DRI EAF scenario has some similarities with the NG-DRI EAF scenario, as well as differences. These are explained in the table below.

H-DRI EAF scenario - Processes	Similarities/ differences
Pellet plant	Input and output data same as in NG-DRI EAF scenario
Electrolyser	This unit is similar to that in the BF-BOF + H2 scenario, but data vary
Lime kiln	Input and output data same as in NG-DRI EAF scenario
Air Separation Unit (ASU)	Input and output data same as in NG-DRI EAF scenario
Shaft furnace	Input and output entries similar to NG-DRI EAF scenario but some data vary. Main difference is the use of hydrogen.
Electric arc furnace	Input and output entries similar to NG-DRI EAF scenario but coal input and CO_2 emissions vary.
Ladle metallurgy and continuous casting	Input and output data same as in NG-DRI EAF scenario

9.2.8 LCI – H-DRI EAF + bio scenario

The LCI for the H-DRI EAF + bio scenario has some similarities with the NG-DRI EAF and H-DRI EAF scenarios, as well as differences. These are explained in the table below.

H-DRI EAF + bio scenario - Processes	Similarities/ differences
Pellet plant	Input and output data same as in NG-DRI EAF scenario
Electrolyser	Input and output data same as in H-DRI EAF scenario
Lime kiln	Input and output data same as in NG-DRI EAF scenario
Air Separation Unit (ASU)	Input and output data same as in NG-DRI EAF scenario
Shaft furnace	Input and output data same as in H-DRI EAF scenario
Electric arc furnace	Input and output entries similar to H-DRI EAF scenario but there is charcoal input and CO_2 emissions vary.
Ladle metallurgy and continuous casting	Input and output data same as in NG-DRI EAF scenario

9.2.9 LCI – NG-DRI + Smelting + BOF scenario

The LCI for the NG-DRI + Smelting + BOF scenario has some similarities with the NG-DRI EAF scenario, as well as differences. These are explained in the table below.

NG-DRI + Smelting + BOF scenario - Processes	Similarities/ differences
Pellet plant	Input and output entries similar to the NG-DRI EAF scenario but data vary
Coke oven	This unit is unique to this route
Lime kiln	Input and output entries similar to the NG-DRI EAF scenario but data vary
Air Separation Unit (ASU)	Input and output entries similar to the NG-DRI EAF scenario but data vary
Shaft furnace	Input and output entries similar to the NG-DRI EAF scenario but data vary
DRI Electric smelting furnace	This unit is unique to this route
Basic oxygen furnace	This unit is unique to this route
Ladle metallurgy and continuous casting	Input and output data same as in NG-DRI EAF scenario except for CO_2 emissions
Co-generation plant	This unit is unique to this route

On this basis only the following sub-units are described below.

Coke oven *(Not onsite; assume pellets imported from Poland)*

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Coking coal	Hard coal {AU}| market for | Cut-off, U Hard coal {Europe, without Russia and Turkey}| hard coal, import from AU | Cut-off, U	Also known as metallurgical coal. The rank is often bituminous coal or black coal, but some grades of anthracite coal or hard coal might be used.
	COG	No Ecoinvent entry selected.	This is an input from the coke oven in the Polish steelmaking plant
	Electricity	No Ecoinvent entry selected.	This is electricity generated in the coke oven in the Polish steelmaking plant (re-circulated)
	Steam	No Ecoinvent entry selected.	We have assumed that this is steam from BOF of the Polish steelmaking plant
Outputs	Coke		
	Coke breeze	No Ecoinvent entry selected. Coke breeze is used in the sinter plant.	Coke dust/particles, mixed with iron ore fines - same composition as coke
	COG	This has been split into: COG_UsedInternally (no emissions linked) and COG_ReplacesNaturalGas_OutsideSysBoundary (Natural gas, high pressure {DE}|natural gas production| Cut-off, U)	For NL, Ecoinvent V3.8 has natural gas import options (from DZ, GB, RU); "Natural gas, high pressure {NL}| petroleum and gas production, off-shore| Cut-off, U (another flow but 'on-shore' production). However, the difference in impact is relatively small.

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
	COG flared	No Ecoinvent entry selected.	CO_2 emissions in the 'emissions to air' section of the model.
	Electricity	No Ecoinvent entry selected. Electricity generated in coke oven is assumed to be used within the system boundary.	
	Crude tar	Bitumen seal {RER}|production|Cut-off,U *(Avoided product)*	Crude tar is a byproduct, not used any further in the system. Crude tar is a blend of tar and naphthalene.
	Benzole	Benzene {RER}|production|Cut-off,U *(Avoided product)*	Benzole is a byproduct, not used any further in the system. It is also known as BTX (benzene, toluene and xylene)
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, including CH_4, are converted to CO_2 before being emitted.

DRI electric smelting furnace

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	DRI	No Ecoinvent entry selected.	Input from shaft furnace
	Lime	No Ecoinvent entry selected.	Input from lime kiln
	Raw dolomite	Dolomite {RER}| Market for dolomite | Cut-off, U	
	Soderberg electrode paste	Anode, paste, for aluminium electrolysis {GLO}| market for | Cut-off, U	Soderberg Electrode Paste also known as Anode Paste. No Ecoinvent entry for "Anode paste for electric smelting furnace", only for aluminium electrolysis.
	Refractory lining	Refractory, basic, packed {GLO}| market for | Cut-off, U	
	Coke	No Ecoinvent entry selected.	Input from coke oven

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
	Electricity	Electricity, medium voltage {NL}| market for| Cut-off, U	NL electricity data in Ecoinvent V3.8 is from 2014.
Outputs	Hot metal		
	Smelter slag for sale	Cement, Portland {Europe without Switzerland}|production|Cut-off,U *(Avoided product)*	Avoided product
	Dusts	Electric arc furnace dust {CH}| treatment of electric arc furnace dust, residual material landfill | Cut-off, U	
	Waste refractories	Electric arc furnace slag {RoW}| treatment of electric arc furnace slag, residual material landfill | Cut-off, U	Sent to landfill (although other valorisation options could be available). Smaller than refractory lining as part of refractories is lost to slag. No Ecoinvent entry for waste refractory.
	Smelter off gas	Carbon dioxide	

Basic oxygen furnace

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Hot metal	No Ecoinvent entry selected.	Input from DRI electric smelting furnace
	Home scrap	On-site (0 impact associated in model)	
	Purchased scrap	Burden associated with this is in the credit calculated using World Steel Association data (0 impact associated in model) and will be presented separately from the main results	
	Lime	No Ecoinvent entry selected.	Input from lime kiln
	Burnt dolomite	Lime {Europe without Switzerland}|lime production, milled, loose|Cut-off,U	
	Oxygen	No Ecoinvent entry selected.	Input from Air Separation Unit (ASU)
	Electricity	Some electricity is from 'Co-generation plant' and the remaining is from the NL grid (Electricity, medium voltage {NL}| market for| Cut-off, U)	

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Outputs	Liquid steel		
	BOF slag for sale	Gravel, crushed {CH} | production | Cut-off,U *(Avoided product)*	Avoided product
	BOFG	No Ecoinvent entry selected.	Used in co-generation plant.
	BOFG flared	No Ecoinvent entry selected.	CO_2 emissions in the 'emissions to air' section of the model.
	Steam	All steam dissipated on site.	
	Emissions to air (CO_2)	Carbon dioxide	

Co-generation plant

Material/energy source		Background data (Ecoinvent)	Notes and assumptions
Inputs	Smelter off gas	No Ecoinvent entry selected	Re-circulated from DRI electric smelting furnace
	BOFG	No Ecoinvent entry selected	Re-circulated from BOF
Outputs	Electricity	No Ecoinvent entry selected	Electricity generated in co-generation plant is used on-site.
	Emissions to air (CO_2)	Carbon dioxide	Only CO_2 considered as it is assumed that all other gases, incl. CH_4, are converted to CO_2 before being emitted.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org