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Revisiting investment costs for green steel: Capital expenditures, firm level impacts, and policy implications

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2082

Discussion
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Implications

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Revisiting investment costs for green steel: Capital expenditures, firm level impacts, and policy implications

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Abstract

The transition of the steel sector to carbon neutrality requires significant investment. In this study, we aim to better understand the scale of investment required for a transition to hydrogen-based steelmaking and the ability of listed steelmakers to finance this investment. First, we analyze how capital expenditures are estimated in the academic literature and compare them with reported investment costs of green steel projects. Second, we focus on how a targeted transition to carbon neutrality would affect the balance sheet and leverage of listed steelmakers operating in the EU-27 and compare the required investments with the companies' past capital expenditures. The study concludes that capital expenditure may be underestimated in the academic literature and derives recommendations for referencing and contextualizing capital expenditure estimates. Based on the identified impacts at the company level, we conclude with a discussion of the capabilities of listed steel producers to achieve carbon-neutral production, also from an industrial policy perspective.

Keywords

Steel, investment cost, capital expenditure, CAPEX, decarbonization

JEL classification

G31,32, L61, Q54,55

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1 Introduction

To achieve carbon neutrality, the steel sector will need to make significant investments to convert large parts of its production to green technology. While the comparatively higher operating costs (OPEX) of green steelmaking have been identified as the main barrier to net zero investment (e.g., OECD (2023a)), less attention has been paid to the scale of investment required and the ability of steelmakers to finance it. In this study, we therefore seek to understand the required capital expenditure (CAPEX), how it compares to companies' historical CAPEX, and its potential impact on companies' balance sheets, in order to gain insights into the industry's ability to achieve the transition to net zero.

In both the academic and grey literature, estimates of the OPEX and CAPEX of green steelmaking via the direct reduced iron and electric arc furnace (DRI-EAF) route are frequently made (see e.g., Devlin et al. (2023), Medarac et al. (2020), and Valentin Vogl et al. (2018)). However, to our knowledge, authors only explain their choice of CAPEX assumptions in more detail in isolated cases (e.g., Jacobasch et al. (2021)) only in isolated cases, leading to some uncertainty about the assumptions made. By reviewing the literature on CAPEX estimates and contrasting the range of estimates with those of implemented or planned full-scale green steel projects, this study attempts to gain a more nuanced understanding of the net zero investment costs that the steel sector will have to bear.

As a second step in our analysis, we seek to understand the factors influencing the total CAPEX for green steelmaking facilities and the implications of the investments needed to decarbonize the steel sector. To do this, we extrapolate the total investment costs required to convert 30% of production capacity to DRI-EAF steelmaking by 2030 - in line with the European scenarios and targets for the steel sector transition - on companies' current balance sheets under different investment scenarios and CAPEX assumptions. As an indicator of the industry's ability to bear the investments, we derive the impact of the investments on the companies' debt. In addition, we compare the required CAPEX with the company's previous annual CAPEX.

The study focuses on listed steel producers operating in the European Union for which operational data are available, as these producers have significant leverage in supporting the EU industry's transition to climate neutrality. We focus on seven listed companies that account for 91% of the EU-27's emission-intensive primary steel capacity and about half of the EU-27's total crude steel production capacity (Global Energy Monitor, 2023b).

With the Green Deal, the current EU Commission has taken a progressive role in mitigating climate change, paving the way for steel producing companies to transform their business activities (Hien & Cecchin, 2021). Therefore, in this study, we seek to better understand the preconditions for policy support for the transformation of the steel sector and to provide a source from which informed policy advice can be derived.

We focus on the investments needed until 2030, as this is the timeframe in which massive (re)investments will be required in the EU in the face of ageing production facilities (Valentin Vogl et al., 2021). Moreover, uncertainties about sectoral decarbonization pathways can be better assessed over a shorter time horizon (see e.g., the note from the Network for Greening the Financial System (2023)), allowing for more reliable estimates of how the decarbonization efforts required in this decade will affect the steel sector.

2 Background

2.1 (Green) steel production

Steelmaking is one of the world's most carbon-intensive industries, contributing around 7% of global carbon emissions (International Energy Agency, 2020). There are currently two dominant steelmaking routes, the first being more emission intensive than the second: Blast Furnace Basic Oxygen Furnace (BF-BOF) steelmaking and Electric Arc Furnace (EAF) steelmaking.

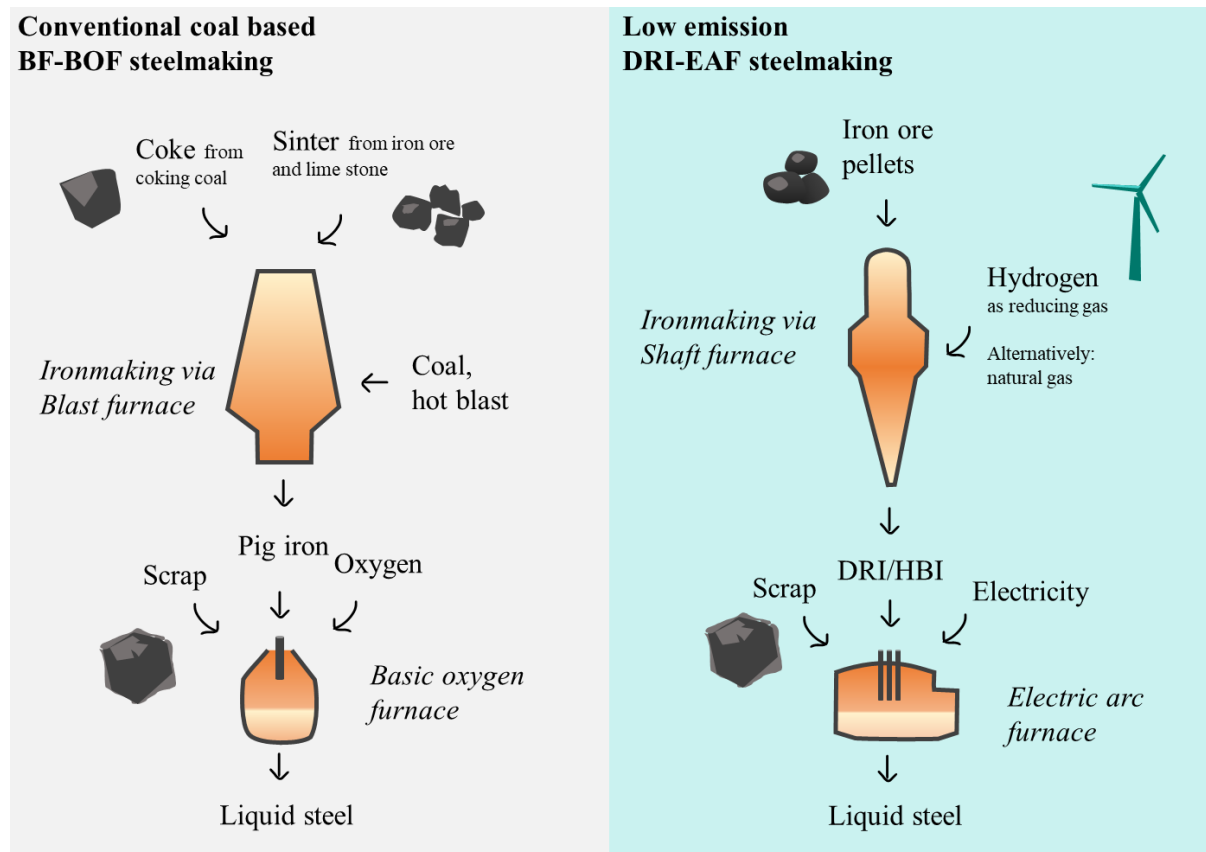
In BF-BOF steelmaking, iron ore is first melted in a blast furnace and converted into molten pig iron. Coke is added in the process to reduce the carbon content of the iron ore, which is a major source of carbon emissions in the process. Secondly, the pig iron, plus up to 30% (recycled) steel scrap, is fed into a basic oxygen furnace. By blowing oxygen through the feed materials, the molten iron is further purified and converted into crude steel.

EAF steelmaking, powered by electricity, is currently mainly used for secondary steel production using scrap steel as feedstock (Wang et al., 2021). Secondary steelmaking is less carbon intensive than primary steelmaking (emitting about one ton or less – if powered by green electricity – versus two to three tons of carbon dioxide equivalent per tonne of steel produced, see Wang et al. (2021)) and cost competitive. However, the lower quality of finished steel and the limited availability of steel scrap, particularly in Europe, limit a more widespread secondary steel production.

As an alternative to steel scrap, direct reduced iron (DRI) can be used as a feedstock for EAFs. Primary steel production via the DRI-EAF route can significantly reduce emissions as compared to the BF-BOF route (Wang et al., 2021). The DRI production process, usually via shaft furnace technologies (e.g., Energiron/HYL and Midrex), has been developed using natural gas as the main fuel and reductant, but can be adapted to operate on hydrogen (H-DRI-EAF route) to produce lower emission steel. DR shaft furnaces require higher quality iron ore than the BF-BOF route in order to produce the same high quality steel. To prevent re-oxidation, DRI must be fed directly into the EAF or pelletized into hot briquetted iron (HBI). The green H-DRI-EAF route can reduce emissions by up to 90-95% compared to conventional steelmaking (Shahabuddin et al., 2023; Zang et al., 2023). However, the H-DRI-EAF route is highly electricity intensive; therefore, operational flexibility of steel production could be important to reduce electricity costs (Toktarova et al., 2022) (requiring hydrogen storage facilities).

Alternative technologies for low or zero carbon steel production are currently being explored (see e.g., Kim et al. (2022) and Shahabuddin et al. (2023)), including CCUS solutions, biomass-based options, BF improvement, and electrolysis-based iron and steelmaking. However, the H-DRI-EAF route is considered in the scientific literature to be the most promising option for decarbonizing the steel sector (Devlin et al., 2023; Shahabuddin et al., 2023; Weigel et al., 2016). Reasons for this include its potential to reduce emissions, the success of pilot projects, and commercial readiness.

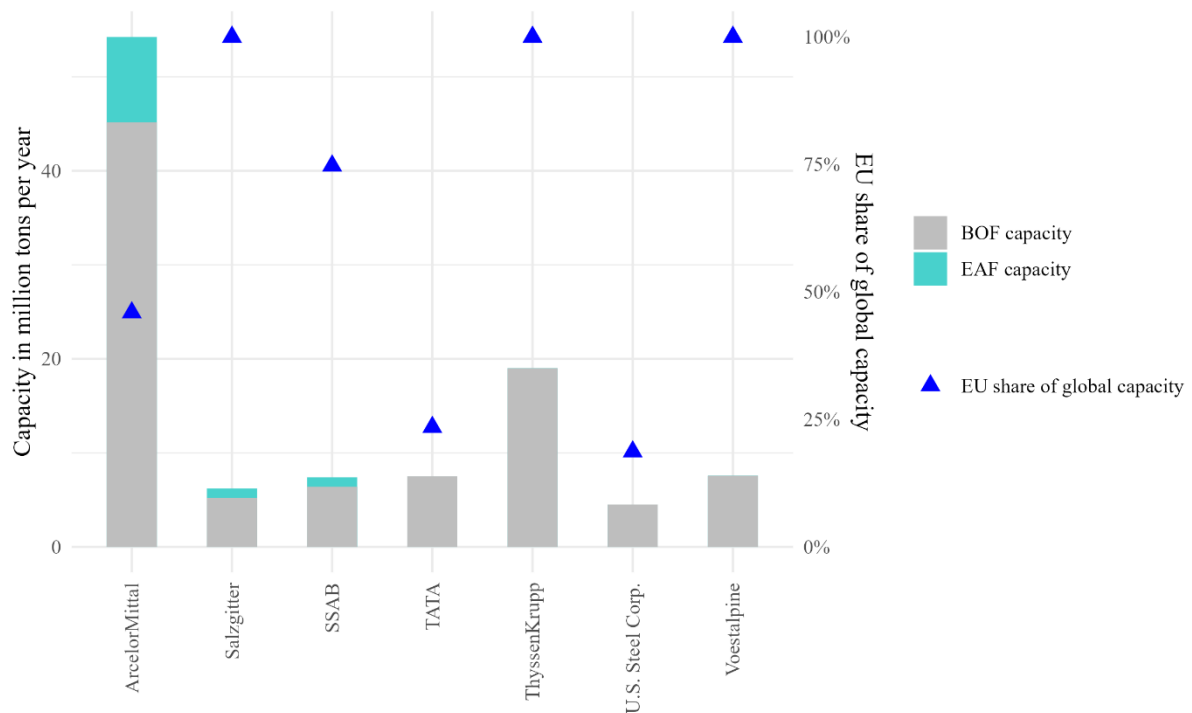
Figure 1: Main input materials and process steps for conventional and low-emission iron and steel production



Note: Authors' illustration. Finished steel is produced by continuous casting and rolling. The production of low-carbon steel via the DRI-EAF route requires the supply of electricity from renewable energy sources for hydrogen production via electrolysis and the operation of the EAF, e.g., Wang et al. (2021).

There are currently 26 BOFs in operation in the EU-27 Member States with a total capacity of 112 million tons per year, while EAFs provide a capacity of 81 million tons per year (EUROFER, 2020; Global Energy Monitor, 2023b). The BOFs can operate for a significant lifetime, with some plants in the EU already operating for more than 80 years (Global Energy Monitor, 2023a, 2023b). As can be seen in Figure 2, listed steelmakers operating in Europe produce a large proportion of their crude steel via the conventional BF-BOF route. Most EAFs are operated by smaller, non-listed EU-27 steelmakers. If the EU-27 steel sector is to achieve climate neutrality by 2050, many of the BOFs will have to be replaced by additional DR plants and EAFs or closed down (Valentin Vogl et al., 2021). So far, green steel production based on DRI plays only a minor role in the EU-27 as well as globally (600 thousand and 125 million tons production in 2022; World Steel Association (2023)).

Figure 2: Crude steel production capacities of listed steelmakers and their EU-27 share of global production capacities



Source: Global Steel Plant Tracker (Global Energy Monitor, 2023b), authors' calculations.

2.2 Decarbonization scenarios for the steel sector

According to EU climate legislation, steel production in the EU-27 countries must become carbon neutral by 2050. Academic studies and industry reports have proposed pathways for the EU steel sector's transition to climate neutrality (Bataille et al., 2021; International Energy Agency, 2020; Kempken et al., 2021; Strategic Perspectives, 2023; van Ruijven et al., 2016). As a common element, all scenarios suggest higher overall shares of EAF scrap production for Western Europe (e.g., from currently about 40% to about 60% in 2050, International Energy Agency (2020)). Regional scrap availability - as a factor limiting increased scrap-based production - is expected to increase in the EU, but to a lesser extent than in other regions of the world (Xylia et al., 2018), where current steel recycling rates are comparatively lower.

The GreenSteel for Europe report (Kempken et al., 2021) provides a comprehensive assessment of transition pathways for primary steel production in the EU-27, taking into account national and regional frameworks, including investment cycles. Kempken et al. (2021) formulated three scenarios for the year 2030: a "mixed implementation scenario" considering the currently most plausible technology shares, a scenario with increased hydrogen availability, and a delayed transition scenario (leading to a CO₂ reduction of only 17% compared to 25% in the other two scenarios, base year 2015). The first two scenarios assume that 22% of primary steel production will be converted to DR technologies by 2030, of which 9% and 23% respectively will be hydrogen-based (the remainder being natural gas-based). The two scenarios also assume optimized BF-BOF production and about 15% post-combustion of BF-BOFs with CCUS technologies.

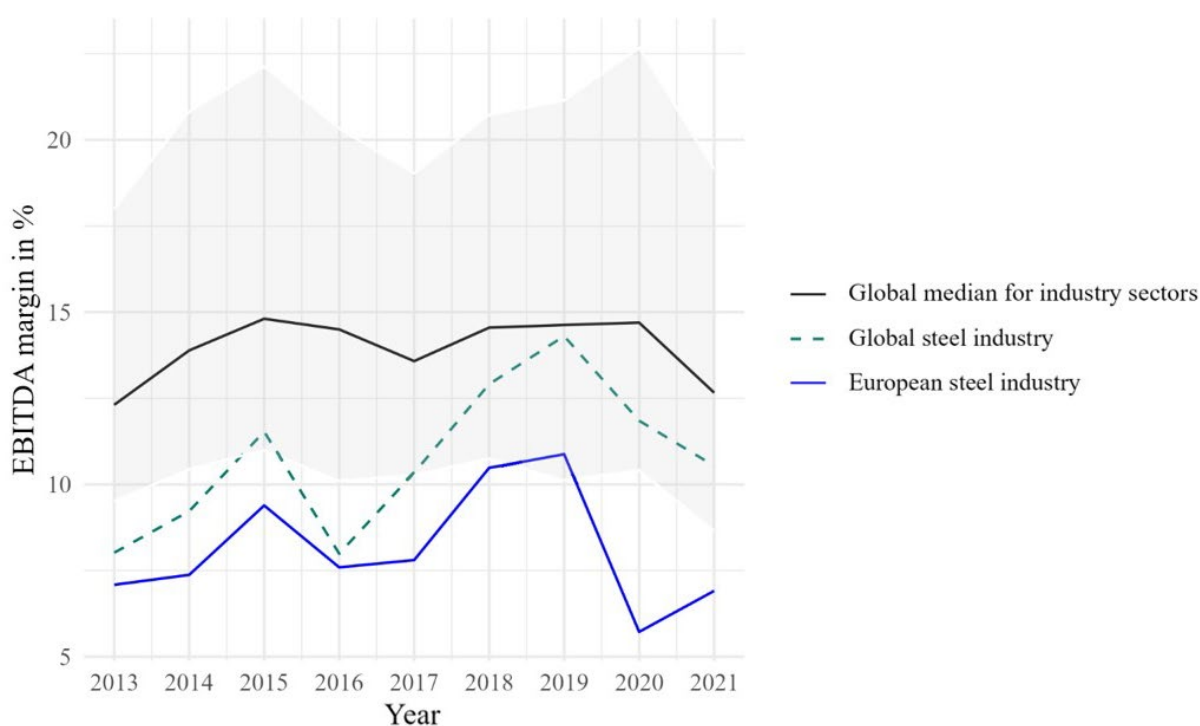
For 2050, Kempken et al. (2021) predict that 29% to 46% of primary steelmaking in the EU-27 nations will be converted to DRI-EAF steelmaking based solely on hydrogen (three

different scenarios). These shares would imply that 17% to 28% of total EU-27 steelmaking in 2050 will be based on the DRI-EAF route; these ranges roughly reflect the estimates for Europe by the International Energy Agency (2020) and the Net-zero Steel Project (Bataille et al., 2021).

2.3 Financial situation of the EU-27 steelmaking industry

After experiencing economic difficulties from 2010 to 2016 (OECD, 2016), with its profitability well below the average of the other industries, global steel production was able to increase its margins from 2017 to 2019 (see Figure 3). A reduction in overcapacity (see OECD (2016)), leading to higher global steel prices and margins, was seen as the main reason for the improved performance of the industry over this period. However, European steelmakers' margins have consistently been lower than those of the global sector (see Figure 3 and for individual listed companies operating in the EU-27, Figure A1 in the Annex), although higher margins have been achieved compared to steelmakers in Japan and the US (OECD, 2023a).

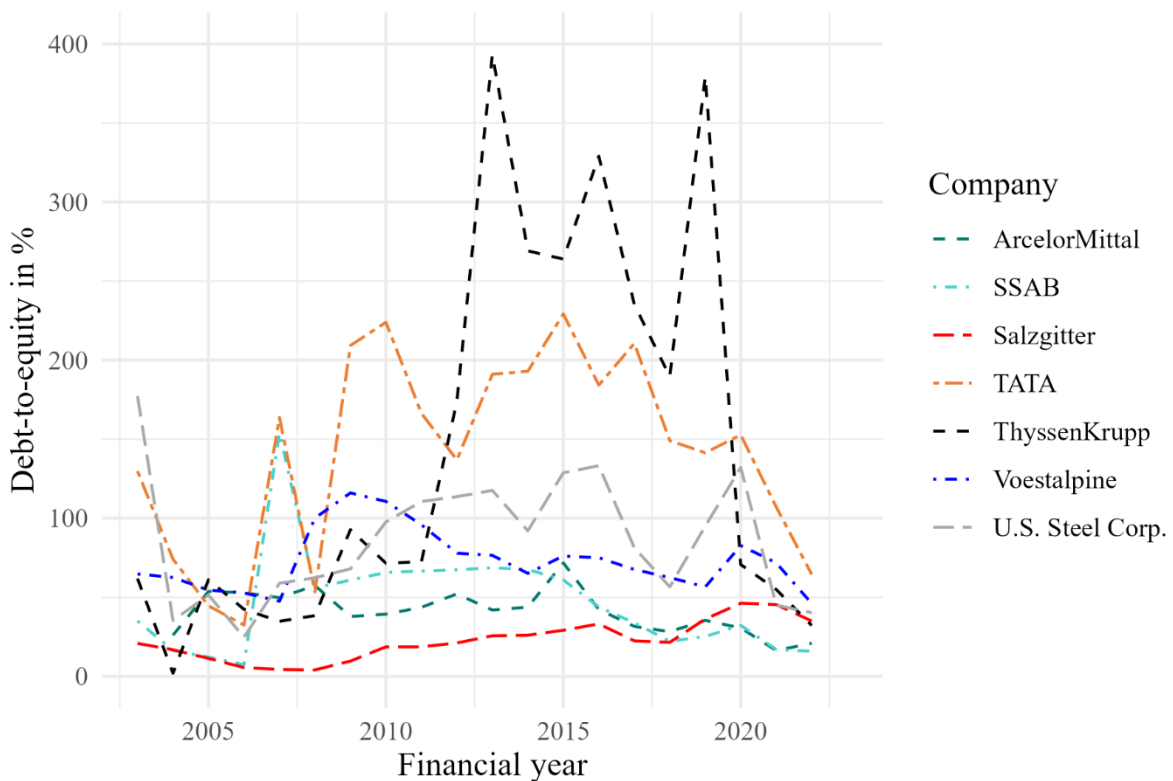
Figure 3: Profitability of the European steel industry as compared to the global steel industry and profitability of global industries



Note: Authors' illustration based on Damodaran data for global and European industries. The global data comprises the EBITDA margins for 95 different industrial sectors; the shaded area shows the interquartile range across these sectors, i.e., the range of EBITDA margins between the 25th and the 75th percentiles.

The economic downturn following the start of the coronavirus pandemic in 2020 affected steel producers in Europe and globally with declining demand resulting in a fall in EBITDA margins of around a third between 2019 and 2021 (see Figure 3). However, despite the economic difficulties in these years, have been able to deleverage steadily since 2016, with an average debt-equity ratio of 37% among listed steelmakers according to their latest financial reports (see Figure 4). In general, this could be a good starting point for a period of significant investment. However, the impact of the war in Ukraine, high energy prices and inflation have posed challenges for EU-27 steelmakers in recent years (The European Steel Association, 2023), which may also inhibit investment in more costly green production processes.

Figure 4: Historical debt-to-equity ratio of listed steelmakers operating in the EU-27 countries



Notes: Calculations based on Bloomberg data. Total debt comprises long and short-term debt. Total equity is the balance sheet total of the company minus its total liabilities (total of common stock, minority interest, and preferred stock). Financial year periods may differ from calendar years and may vary between companies.

3 Investment needs for green steelmaking

3.1 Information search and data

Switching from coal-based BF-BOF steel production to the DRI-EAF route requires major plant modifications and therefore significant investment. In order to obtain information on the scale of investment required for steelmakers to switch to carbon-neutral production, we carried out a) a literature review - also to obtain information on the assumptions associated with the CAPEX estimates - and b) an evaluation of the investment costs of implemented or planned green steel projects. Both analyses include the most recent articles and projects as of December 2023.

Literature search. We searched the academic and grey literature for original estimates of installation-based CAPEX for DR plants, EAFs and/or hydrogen production by electrolysis. A detailed description of the search methodology can be found in the supplementary materials.

Steelmaking project data. Second, we searched for project investment volumes of full-scale implemented or planned green steel projects, based on the Green Steel Tracker (V. Vogl et al., 2023), the Global Steel Plant Tracker (Global Energy Monitor, 2023b), and data from the OECD (2015). The Green Steel Tracker and the Global Steel Plant Tracker currently provide information on 43 and 61 planned full-scale green steel projects (including DRI production) worldwide, respectively. The OECD data includes information on steelmaking projects in OECD countries as of 2015, including 176 planned or operational projects in 23 non-European member countries related to DR or EAF technologies. For the projects

identified, we manually checked for information on production capacity (for either iron and/or steel production) and investment size. Where these were available, we calculated the CAPEX in euro per ton of annual DRI/crude steel production capacity. Currency conversions were based on the average exchange rates of the year in which the project information was published or the project started (OECD data).

Both the CAPEX estimates from the literature and the investment volume data of the announced green and OECD-listed steel projects have been adjusted for inflation using the OECD Europe producer price indices (year 2022) (OECD, 2024). In the following, inflation-adjusted currency values are indicated by a subscript for the reference year (2022) after the currency expression.

3.2 Results

Literature search. We identified 15 articles that provide original values for plant-related CAPEX for the (H-)DRI-EAF route, see Figure 5 for a visual overview and Table A1 in the appendix for the exact values and sources. The CAPEX estimates are also referred to as "overnight investment costs" or "total investment costs" and are usually expressed in currency values per ton of annual steel production capacity; in a few cases the currency values are linked to a base year (e.g., van Wortswinkel and Nijs (2010)). Referenced CAPEX values are adjusted for inflation only in a few cases (e.g., Pinegar et al. (2011)). CAPEX estimates are generally not linked to the world region and typically refer to greenfield investments for the (H-)DRI-EAF route. Capital costs are usually only considered (or made explicit) when annualized CAPEX is provided; in which context interest rate and plant lifetime assumptions vary (e.g., 12 versus 25 years lifetime and a two versus eight percent interest rate: compare Mayer et al. (2018) and the International Energy Agency (2020)).

For EAFs and DR shaft furnaces, a vast majority of articles were found to cite the studies by Fishedick et al. (2014) and Valentin Vogl et al. (2018), which provide a techno-economic assessment of steelmaking technologies (see e.g., the studies by Bataille et al. (2021), Devlin et al. (2023), Lopez et al. (2023)). Vogl et al. and Fishedick et al. give values of 230 and 184 euros per ton of annual steelmaking capacity as CAPEX for DR shaft furnaces and EAFs, respectively. As both studies refer to Wörtler et al. (2013) for the CAPEX assumptions, a large number of secondary citations were found. Wörtler et al. (2013) relate the CAPEX values to assumptions of the Steel Institute VDEh, a project team analysis of the Boston Consulting Group (BCG), and the conference proceedings of the InSteelCon (Diemer et al., 2011). Accordingly, most common CAPEX estimates reflect 2011 estimates. Taking 2011 as the base year, the inflation-adjusted values are 324 euros₂₀₂₂ for a direct reduction plant (DRP) and 259 euros₂₀₂₂ for EAFs (totaling 583 euros₂₀₂₂ for the integrated DR-EAF pathway).

In general, CAPEX assumptions for DR plants have been assumed to be similar regardless of whether the plants are operated on coal, natural gas, syngas, or hydrogen (see also Trinca et al. (2023)). Implemented DR technologies (such as Energiron/HYL and Midrex) are typically not specified; CAPEX is assumed to vary little by technology (Lockwood Greene Technologies, 2000). For EAFs and DRPs, Jacobasch et al. (2021) compare literature-derived correlations between steelmaking capacity and TCI. In a few cases, studies also refer to or provide CAPEX for the production of DR pellets (HBI) (e.g., 20 euros for storage per ton DRI per year, Haendel et al. (2022), and 62 euros per ton per year for pellet production, Xylia et al. (2018)), which enables the storage and transport of DRI. Although few authors make this explicit (Devlin & Yang, 2022), the cost of other CAPEX components, such as engineering,

construction, and land purchase, do not appear to be commonly included. It is generally assumed that DR-EAF prices will remain stable in the future (see e.g., Lopez et al. (2022)), as the technologies are perceived to be relatively mature.

For the CAPEX associated with H2 electrolyzers, several literature reviews and cost projections exist (see e.g., Jacobasch et al. (2021) and Reksten et al. (2022)). CAPEX for the electrolysis technologies alkaline (ALK), polymer electrolyte membrane (PEM), and solid oxide (SOEC) electrolysis are expected to decrease significantly over the next decade, particularly as production scales up. Authors often give CAPEX ranges for the installation of electrolyzers (e.g., Bhaskar et al. (2022) and Krüger et al. (2020)). In addition to CAPEX for hydrogen production, the authors also consider CAPEX for hydrogen storage (e.g., Bhaskar et al. (2022), Devlin & Yang (2022), and Toktarova et al. (2022)) and investment in electricity generation capacity (Elsheikh & Evely, 2023; Galitskaya & Zhdaneev, 2022; Toktarova et al., 2022). Cihlar (2020) notes that CAPEX for system integration costs can be a significant part of the investment costs for hydrogen production; it remains unclear whether these are included in the literature in many cases.

Investment data for steel projects. Steelmaking investment data was found for 21 announced green steel projects (see Appendix A2) and 52 projects listed by the OECD (2015), for instalments of individual DRPs and EAFs, as well as the combined (H-)DR-EAF route. Among the announced green steel projects, four projects also include instalments of hydrogen production capacities, coupled with comparatively high total CAPEX values of up to 4,000 euros₂₀₂₂ per ton of annual crude steel production capacity. In terms of annual steelmaking capacity, the projects in the OECD data are smaller than the announced green steel projects.

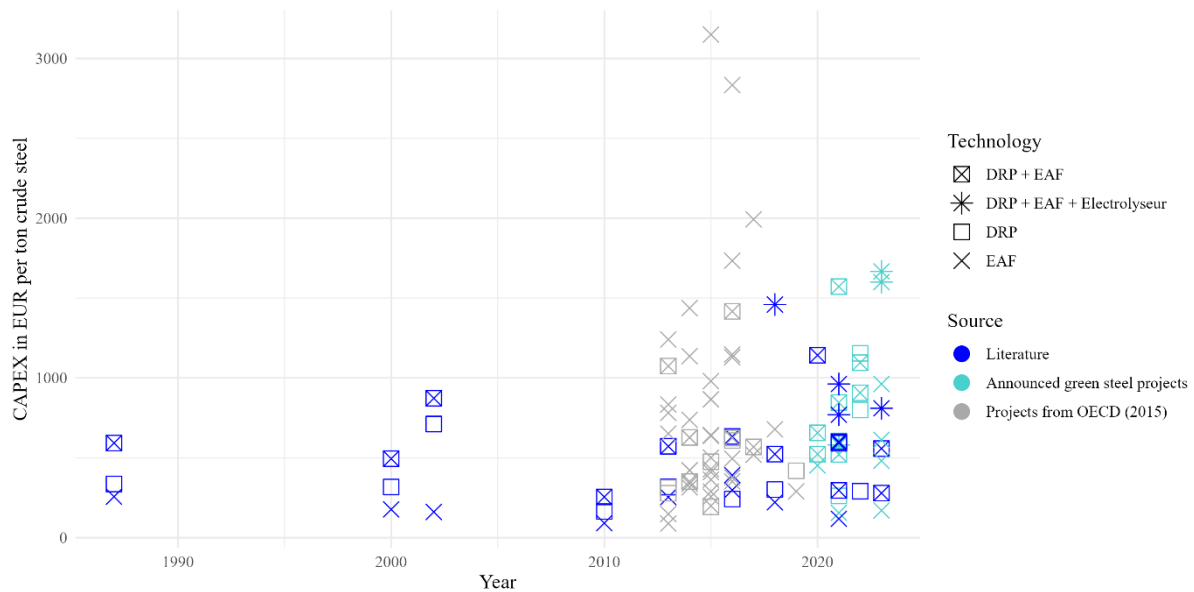
Combined analysis. Figure 5 and Table 1 show the CAPEX information gathered from the literature review and analysis of project data for (H)-DRI-EAF steelmaking. For most of the technology categories (individual DRP and EAF, integrated route, integrated route with electrolyser installation), a limited number of observations per source are available. As a result, a comparison of medians across sources must be treated with caution. However, it is noticeable that across all technology categories, the CAPEX information from green steel projects is significantly higher than literature estimates. For example, for an integrated installation of DRP and EAF, the information from the announced green steel projects suggests a value of around €750₂₀₂₂, while the literature reports a median value of €592₂₀₂₂.

Table 1: Comparison of CAPEX information for the (H)-DRI-EAF steelmaking route; literature review and project data

Source	Median CAPEX in € ₂₀₂₂ per ton DRI/steelmaking capacity per year and number of observations			
	DRP	EAF	DRP and EAF	Including electrolyser
Literature search	299(10)	254(11)	592(11)	886(4)
Announced green steel projects	800(3)	467(6)	751(8)	1600(3)
Projects listed by the OECD (2015)	366(6)	573(40)	626(6)	-

Notes: All values from the underlying observations (in brackets) are adjusted for inflation (producer prices in 2022). Literature values are based on the search results in Appex A1.

Figure 5: CAPEX information by year for the (H)-DRI-EAF steelmaking route; literature review and project data



Notes: All values are adjusted for inflation (producer prices in 2022). Literature values are based on the search results in Appex A1. The x-axis refers to the year of start or announcement of (planned) green projects and, for the literature search, to the year of publication or base year given for the CAPEX estimate. Projects with separate information for DRPs and EAFs appear under the respective technologies and the integrated pathway.

If the CAPEX information is adjusted for inflation, no general cost trend can be assumed for the (components of) DR-EAF steelmaking. As previously observed by authors (Jacobasch et al., 2021), we find that production capacities for DRPs are positively correlated with CAPEX per ton of annual crude production (see Appendix Figure A3 for correlations between CAPEX and installed capacities). For EAFs, contrary to previous observations, negative correlations were found between crude steelmaking capacities and CAPEX per ton of annual crude steel. For the integrated DRI-EAF route, CAPEX per ton of crude steel per year seems to be relatively independent of installed capacity (slightly negative correlation).

4 The impact of green steel investments on companies' financial situation

4.1 Scenarios, assumptions, and data

In order to assess the impact of the required decarbonization investments on European primary steel producers, we first estimate the expected investment costs at company level, defined as the Total Cost of Investment (TCI) capitalized on the assets side of a company's balance sheet.

In general, we assume that listed steel producers will invest in converting 30% of their current production volume (year 2022) to the DRI-EAF route by 2030. The assumed decarbonization share is higher than the 25% suggested by Kempken et al. (2021); however, given that CCUS technologies do not appear to be implemented rapidly (see Green Steel Tracker, V. Vogl et al. (2023)), we focus more on the implementation of the DRI-EAF route. The Science Based Targets (2022) also propose an emission reduction of around 30% by 2030 for primary steel producers, which is roughly in line with the ambitions of EU-27 steel producers (see Table 2).

Table 2: EU-27 steelmakers' net zero (interim) targets

Company	Country ^a	2030 target			2050 target
		Emission reduction	Baseline year	Emission scope ^b	
Aperam	Luxembourg	30%	2015	1 & 2	Climate neutrality
ArcelorMittal	Luxembourg	35% ^c	2018	1 & 2	Climate neutrality
Dillinger	Germany	Not stated	Not stated	Not stated	Climate neutrality
Outokumpu	Finland	Not stated	Not stated	Not stated	Climate neutrality
Salzgitter	Germany	50%	2018	1	Climate neutrality
SSAB	Sweden	35% ^d	2018	1, 2 & 3	Climate neutrality
Stahl Holding Saar GmbH	Germany	55%	Not stated	Not stated	Not stated
Techint Group	Italy	30%	2018	1 & 2	Not stated
Thyssenkrupp	Germany	30%	2018	1, 2 & 3	Climate neutrality
Voestalpine	Austria	30%	Not stated	Not stated	Climate neutrality

Source: Green Steel Tracker (V. Vogl et al., 2023)

Notes: Emerging companies that are not yet operational are not included in the table. SSAB aims to be carbon neutral as early as 2045.

^a Where company is headquartered

^b Scope 1 refers to direct emissions from operations, scope 2 to indirect emissions from purchased electricity, and scope 3 to other indirect emissions along the value chain

^c For production in Europe

^d For the year 2032

We include several investment scenarios in our analysis. First, as we have seen from our analysis of the literature and information from green steel projects that estimates of investment requirements vary, we consider an upper and a lower bound for CAPEX for DRI-EAF steel production. A lower bound value of 600 euros per ton of annual crude steel capacity roughly reflects the most cited inflation-adjusted value in the scientific literature (Wörtler et al., 2013). An upper bound value of 750 euros per ton of annual crude steel capacity reflects the median of announced green steel projects (adjusted for inflation).

Second, we consider - in addition to the DRI-EAF steelmaking investments - whether or not on-site hydrogen production capacity via electrolysis is installed. While the other investment scenarios do not specify whether the DRI plants are operated with natural gas, syngas or hydrogen, this investment scenario assumes the latter option (integrated H-DRI-EAF). We assume that steelmakers will build on-site hydrogen production capacity due to the lack of hydrogen transport infrastructure, the large volumes of hydrogen required and to gain flexibility (Boldrini et al., 2024). For the cost of installing the electrolysis capacity, we use a value of €250 per ton of annual steelmaking capacity, which corresponds to the approximated trend lines of Jacobasch et al. (2021) for PEM and ALK technologies in 2023 and is in line with common assumptions in the literature (see Table A1).

In summary, we assume that CAPEX can be as low as 600 euros per ton of annual steelmaking capacity (lower bound estimate for installation of DRP and EAF) and as high as 1000 euros per ton of annual steelmaking capacity (upper bound estimate for installation of DRP, EAF, and electrolysis unit); accordingly, an average plant with two million tons of annual steelmaking capacity would require an investment of 1.2 to two billion euros.

Third, we consider a scenario where listed steelmakers convert not only 30% of their EU production to DRI-EAF, but also 30% of their global production. Global steel producers are likely to decarbonize their operations first in areas with more stringent climate policies and stronger support mechanisms, such as the EU, as evidenced by the majority of planned full-scale green projects to be implemented in the EU-27 countries. However, we also seek to consider the impact of global primary steel producers converting 30% of their production by

2030. We do not make specific CAPEX assumptions by region, as there is assumed to be little geographical variation in investment costs (International Energy Agency, 2020).

Depending on these investment specifications, a firm's total cost of investment (TCI) is calculated by multiplying 30% of the firm's total steel production in the last financial year, either in Europe or globally, by the lower or upper bound CAPEX estimate (including or excluding the installation of electrolyzers). EU-27 crude steel production data were not directly available for all the listed companies analyzed and were therefore calculated by multiplying the share of company's EU-27 steel production capacity of its global capacity (as provided by the Global Steel Plant Tracker) by its global steel production (assuming uniform capacity utilization).

In a second step, we estimate the **firm-level impact of steel decarbonization investments**. We focus on the listed steel producers with production in the EU-27 (Arcelor Mittal, Salzgitter, SSAB, TATA Steel, ThyssenKrupp, U.S. Steel Corp and Voestalpine), which account for about 91% of the EU-27's emission-intensive primary crude steel production (according to the Global Energy Monitor (2023b)). There will be limits to the investments that companies can make, linked to the profitability of the projects, but also to their financial situation. In the following section, after comparing the required investments with the companies' previous year's CAPEX, we focus on the companies' debt-equity ratio as a common valuation metric that indicates the company's dependence on external funds. For the purposes of the analysis, we assume that firms make the investments under the various scenarios outlined above overnight and that they are financed on the balance sheet. We assume that the TCI are fully financed by debt (corporate loans or project finance). We do not consider cash flow, potential grants, subsidies received or equity financing. For each of the investment scenarios, we derive the change in a firm's debt-equity ratio by dividing the sum of the firm's total debt and the respective TCI by the firm's total equity. Information on firms' total debt and equity was obtained from the latest available balance sheets as of August 2023.

4.2 Results

Projected investment costs for green steel: Figure 6 and Table A3 in the Annex show the results of the analysis of the TCI in relation to the different investment scenarios.

If the seven listed steelmakers were to convert 30% of their European crude steel production to the (H-)DRI-EAF route, investments of between 12.1 and 20.2 billion Euros would be required, depending on the scenario. The average TCI for the companies is between 1.7 and 2.9 billion euros. These investments would exceed by a factor of 1.2 to 2.0 the average annual investments of the listed companies over their last 20 financial years (total operations, adjusted for inflation). Based on information on the companies' average free cash flow (balance sheet information as of August 2023), 84% and 50% of the TCI could be covered by free cash flow in the low and high EU-27 investment scenarios, respectively. However, the ability of the companies to rely on free cash flow to finance the required investments varies, with one of the companies having a number of negative free cash flows.

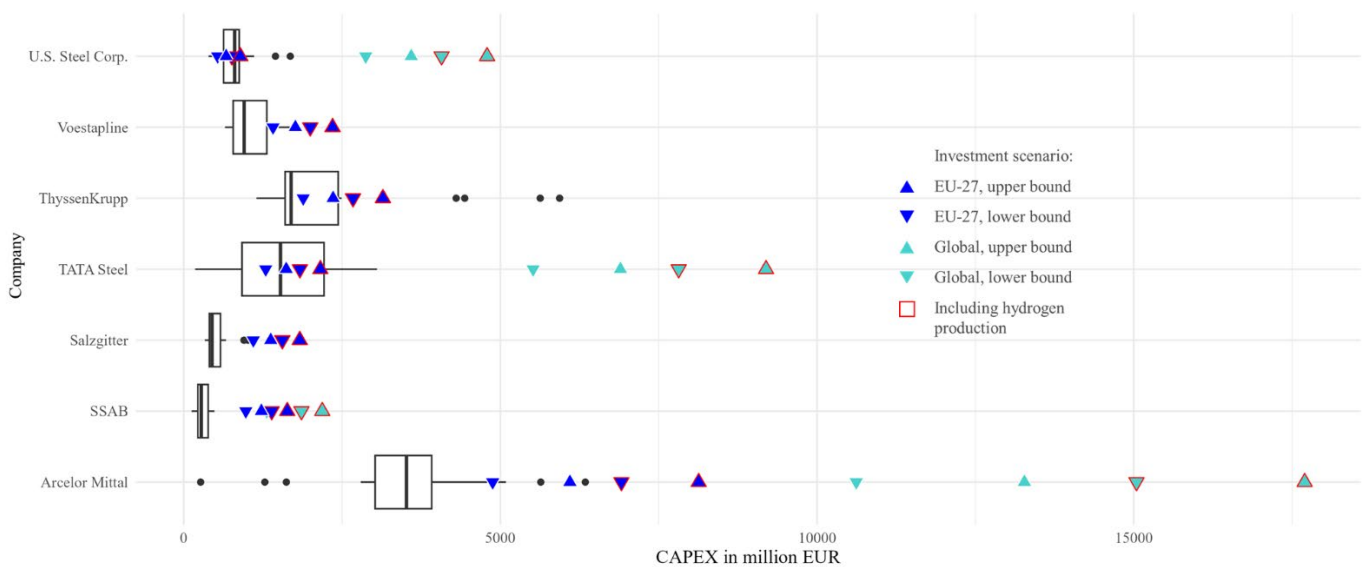
For the companies to convert 30% of their total (global) crude steel production, between EUR 24.7 billion and EUR 41.2 billion would be required, depending on the scenario. As this is 3.3 to 5.4 times higher than the average annual capital expenditure of listed companies with global steel production (over their last 20 financial years, adjusted for inflation), significant additional investment is required in the global scenarios. Approximately 30-50% of the

required investment could be financed by the average free cash flow (based on the latest balance sheet information from August 2023) of the companies with global steel production.

For the global companies U.S. Steel Corp and Tata Steel, as well as ThyssenKrupp (with historically high CAPEX), the estimated TCI for a 30% transformation of European production is in the range of their historical CAPEX over the last 20 years. However, to transform the entire production of global companies, the TCI would be much higher than their previous CAPEX. For example, Arcelor Mittal alone would need to invest almost as much to decarbonize 30% of its total crude steel production (10.6 to 17.7 billion euros) as would be needed to transform 30% of EU-27 crude steel production.

In addition to the scale of transformation (European or global decarbonization), the TCI is mainly determined by the decision whether or not to integrate hydrogen production with DRI-EAF steelmaking. In addition, the TCI varies depending on whether a lower or upper bound CAPEX estimate for DRI-EAF steelmaking is applied.

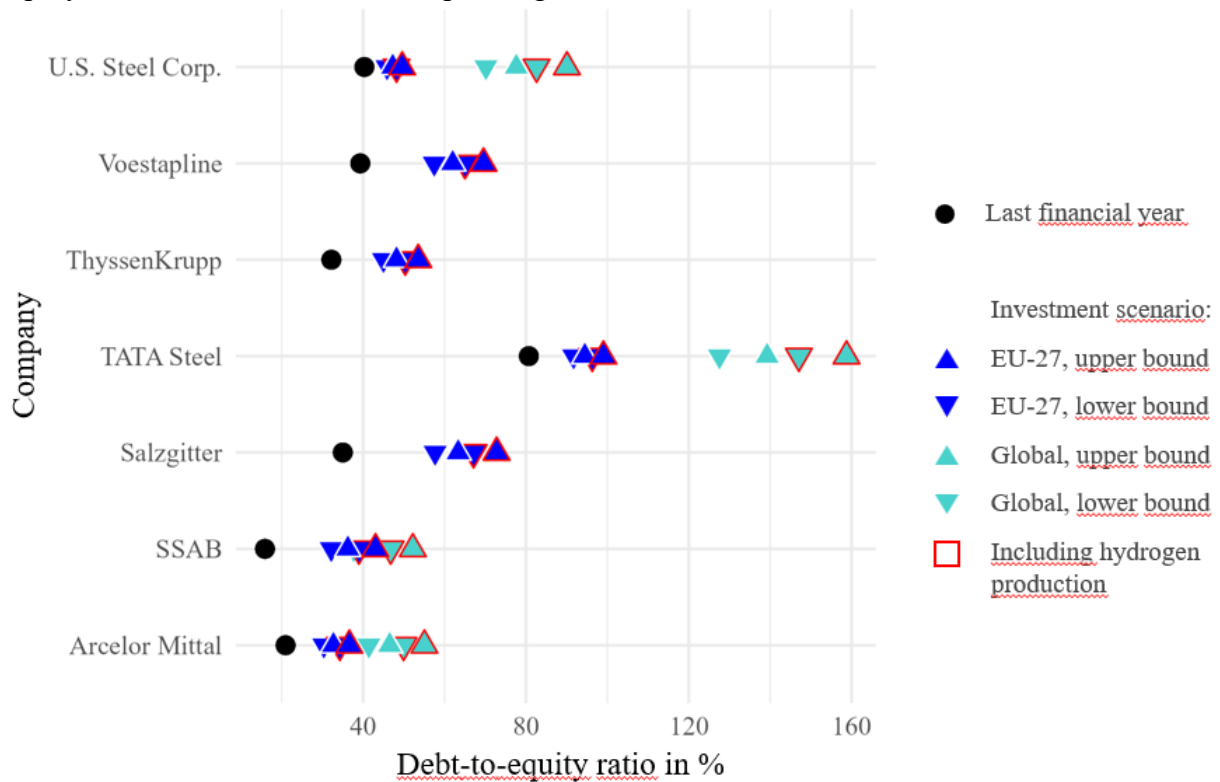
Figure 6: TCI for listed steelmakers operating in the EU-27 countries for converting 30% of their current production to DRI-EAF compared to their historical CAPEX.



Note: The box plots (outliers are shown as black dots) show the companies' past CAPEX over their last 20 financial years, adjusted for inflation.

Firm-level impacts of green steel investments: As shown in Figure 7, in all investment scenarios and under the conservative assumption that the TCI is financed by debt only, the firm's debt-equity ratio remains below the critical threshold of 200%. With the exception of TATA Steel in the global scenarios, debt levels do not exceed the firms' equity in the different investment scenarios, as was the case for three of the firms in the more financially challenging years from 2012 to 2016 (see Figure 4). Across all companies, the debt-equity ratio increases on average by 14 to 23 percentage points (from around 38% to 52-61%) when converting 30% of their European production to (H)-DRI-EAF. When companies convert 30% of their total (global) production, more substantial changes in debt-equity ratios are observed, increasing on average by 30 to 50 percentage points (from around 39% to 69-89%).

Figure 7: Impact of the TCI for converting 30% of current production to DRI-EAF on the debt-equity ratio of listed steelmakers operating in EU-27 countries



Notes: The TCI is assumed to be financed by debt only. Table A3 in the annex shows the average change in the debt ratio in percentage points and in percent.

5 Discussion and implications

5.1 Estimates of net zero investment costs for steelmakers

While we find that the overall range of estimates in the literature for the DRI-EAF route is rather narrow after adjusting for inflation (i.e., close to 600 euros per ton of steelmaking capacity for the integrated DRI-EAF route), the analysis of information from (announced) green steel projects suggests that the actual investment costs could be higher than indicated in the literature. In most cases, CAPEX in the literature seems to include only the process equipment for DRI-EAF steelmaking. However, total as-spent CAPEX also includes facility, engineering, and construction costs (see e.g., Schmitt et al. (2022)). According to Santis et al. (2021), the integration of green steelmaking with brownfield plants can involve significant additional CAPEX, as production chains need to be adapted in terms of raw materials, residues and by-products, and energy supply. For example, Agora Industry et al. (2022) use an integration factor of 1.8 for the CAPEX for the installation of DRPs and EAFs in their steel transformation cost calculator. As these additional costs do not seem to be commonly taken into account in the literature, the estimated investment needs for decarbonizing steel production may be lower than the actual investment needs.

When making CAPEX assumptions, good scientific practice would therefore to recognize the limitations of using common greenfield CAPEX assumptions or to consider slightly higher costs. A CAPEX of around 750 euros per ton of steelmaking capacity (cost for the integrated DR-EAF route) is more in line with figures from recently implemented or

planned green steel projects. However, it should be noted that publicly reported information on investment values may also be biased upwards (e.g., to obtain subsidies).

When referencing CAPEX estimates in the literature, adjustment for inflation is warranted, e.g., via the CE plant cost index (Vatavuk, 2002). When referring to CAPEX for electrolyzers, projected cost reductions should be taken into account (see e.g., Jacobasch et al. (2021)). In addition to the unit costs of the electrolyser, CAPEX for balance of a plant, system integration costs, and hydrogen storage should ideally be considered (Cihlar, 2020). While the CAPEX per ton of annual crude steel capacity for the integrated DRI-EAF route appears to be relatively independent of the installed capacity, the CAPEX values for the installation of individual DRP and EAF should be referenced according to the projected size of the installations for each component.

5.2 TCI and influencing factors

This study considers a scenario in which the seven listed steel producers responsible for 91% of the EU-27's emission-intensive primary crude steel production (according to Global Energy Monitor (2023b) data) invest to shift 30% of their current production to the DRI-EAF route, in line with the European scenarios and targets for the steel sector transition. As the TCI is more than twice as high in the global as in the European investment scenarios (i.e., 12 to 20 billion euros versus 25 to 41 billion euros), the geographical scale of decarbonization is the main determinant of the TCI. Second, the TCI is particularly influenced by the decision of steel producers whether or not to integrate on-site hydrogen production (leading to upper bound estimates of up to 1,000 euros per ton of crude steel capacity). The current lack of infrastructure for hydrogen transport requires on-site hydrogen production. However, flexibility potentials (see e.g., Boldrini et al. (2024)) could also argue in favor of integrating hydrogen production (and storage) with green steelmaking in the future. As prices for electrolysis units are expected to decrease significantly (e.g., Jacobasch et al. (2021)), a smaller part of the TCI will be determined by CAPEX for hydrogen production in the future. Thirdly, the results are affected by whether the lower or upper bound of the CAPEX estimate is applied, which increases the need for more elaborate projections or assumptions of CAPEX.

5.3 Can listed steelmakers operating in the EU-27 nations make the necessary net zero investments?

For primary steelmakers, the decarbonization of their operations requires a large-scale transformation of their assets. In general, the listed companies analyzed in this study may be well prepared for a period of significant investment, given their capital structures, which are currently relatively high compared to previous periods.

In the scenarios where 30% of the listed steelmakers' European primary production is converted to green steelmaking, the required TCI exceeds the average annual investment of the last 20 years for most companies. However, it should be noted that the average BF-BOF plants of the European-based steelmakers were built in the 1960s (see Global Energy Monitor (2023b)) and, with a few exceptions (e.g., Thyssen Krupp's investment in a steel plant in Santa Cruz, Brazil), the companies have not made large investments during this period. Given the comparison with previous investments, the ability of companies to service the investments from cash flow, and the impact on leverage, the required net zero investments by 2030 therefore appear manageable. However, the required investments would be in addition to the regular investments needed for companies to remain competitive in high value, high margin products.

Global companies in particular appear to have the leverage to transform European production, as the TCI for the European transformation would be broadly in line with previous investments. However, capital will not be fully flexible for global companies, which would likely prevent a major shift of investment to the EU-27 area.

While it could be concluded from the adopted CAPEX perspective that a 30% transformation of EU steel production facilities to the DRI-EAF route is possible, it is also apparent that margins in the EU steel sector are comparatively low and that some of the companies are facing economic challenges. As green steel production involves significantly higher OPEX (e.g., for Europe eight to 50% additional OPEX, see Gielen et al. (2020)), the business case for green steel production is a key challenge, even if green premium prices are to be achieved. By leading to higher interest expenses, the green steel investments will further reduce margins and, consequently, profitability. Accordingly, political support and targeted financing solutions will be needed to enable the transformation of the steel sector in the EU-27 to net-zero.

With regard to a shift of 30% of global production to green steelmaking, a timely transition to the DRI-EAF route appears to be a major challenge for the listed companies analyzed in terms of the impact on debt-equity ratios, prior investments and the ability to service investments from cash flows. Given the ongoing construction of new coal-based BF-BOFs, particularly in Asia - including by Arcelor Mittal and TATA Steel (OECD, 2023b) - limiting the construction of conventional coal-based iron and steel plants in this context may therefore be a priority.

5.4 Implications for targeted policy support for the steel sector transition

The results of this study show that major investments are needed for the transition to green steel in the EU-27 countries. Based on their current balance sheets, the analyzed steel producers appear to be in a position to make these investments. However, industrial policies are needed to ensure the viability of green steel production.

Green steelmaking only becomes cost-competitive with conventional, coal-based steelmaking under conditions of low electricity and/or higher carbon prices (e.g., Valentin Vogl et al. (2018)). Therefore, rapid deployment of renewable energy capacity will be the first step to support the transition. In addition, it will be important for companies to hedge against volatile carbon and electricity prices. One tool to do this is Carbon Contracts for Difference (CCfDs), which are contracts between a regulator and a firm that pay out the difference between a fixed strike price and the actual carbon price per emission saved by an investment (Richstein & Neuhoff, 2022). Several countries are currently exploring CCfDs as a tool to support the deployment of low-carbon solutions. In addition, significant funding has been provided or announced for individual steel producers operating in the EU (around EUR 8.7 billion of funding in the EU according to GMK Center (2023)).

Apart from these support mechanisms, sustainable finance measures and regulations, such as through product carbon requirements that set near-zero emission limits for the production of basic materials (Gerres et al., 2019), could complement an EU policy package to stimulate the net zero transition in the steel sector.

As most green steel projects are currently located in the EU, it will be important to encourage companies to deploy green steel solutions also in countries with less stringent climate policies and to establish appropriate policy frameworks to support the transition – in particular through international cooperation (see e.g., Hermwille et al. (2022) and Lüpke et al.

(2022) for discussions on international climate clubs and alliances). In addition to public-private partnerships, international standards and benchmarks for green steel will help to establish common ground and create lead markets (see Muslemani et al. (2021)) for green steel internationally.

6 Future research and limitations

On the scientific side, this study provides recommendations on how to make CAPEX for green steel production more rigorous. In addition, future research could further investigate commonly made OPEX assumptions, including their actuality and sensitivity, apart from commonly considered factors (such as electricity prices). In terms of CAPEX for green steelmaking, the cost evolution of hydrogen production in particular should be further monitored; in addition, further examination of investment figures from green steel projects could help to better understand the level of investment required.

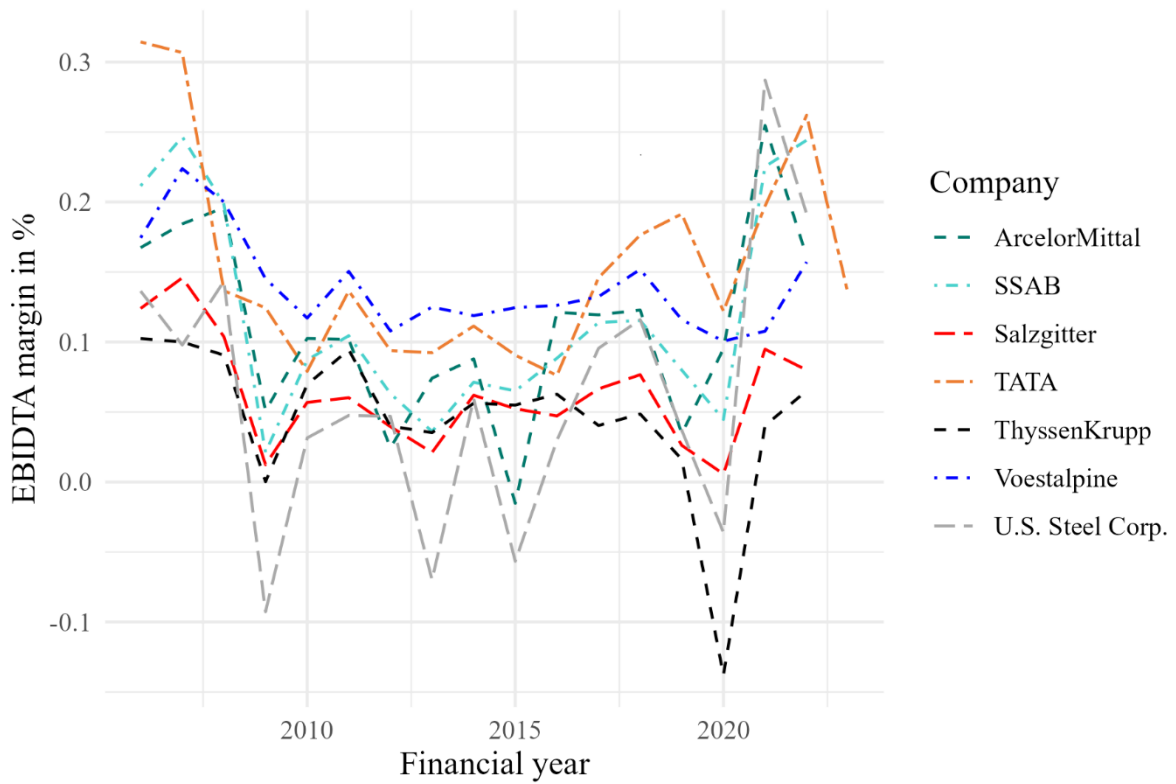
As a theoretical exercise, this study models how the first phase of the transition to net zero by 2030 would affect the financial position of listed steel producers in terms of their debt-to-equity ratio. This research could be taken further by modelling how increased OPEX would affect the financial position of companies, following the example of Richstein and Neuhoff (2022). Ideally, in doing so, studies would also consider how banks and financial markets would react to companies' green steel activities.

A limitation of this study is that we omit a larger part of the European steel production by excluding non-listed (secondary) steel producers from our analysis. In Italy, for example, more than half of production comes from small and medium-sized enterprises (SMEs) (OECD, 2023a), which may face very different challenges compared to listed companies. In addition, future studies could take into account the heterogeneity within the EU-27. Pathways and solutions to net-zero will vary across Member States, as illustrated, for example, by comparisons of the steel sectors in Germany, Italy and France by the OECD (2023a). Germany, for example, has a national net zero target by 2045. According to national decarbonization scenarios, the German steel sector needs to decarbonize much faster than at the EU level (Prognos, Öko-Institut, Wuppertal-Institut, 2021).

Finally, we focus here on DRI-EAF steelmaking as a viable green steelmaking technology. We assume full domestic production in Europe in terms of supply chain configuration; however, in the medium to long term, importing HBI could also prove to be an economically viable alternative (Lopez et al., 2023). In addition, technologies such as electrolysis-based iron and steelmaking could play an important role in the future; research looking at time horizons from 2030 and beyond may therefore include a more diversified technology portfolio of primary steelmakers.

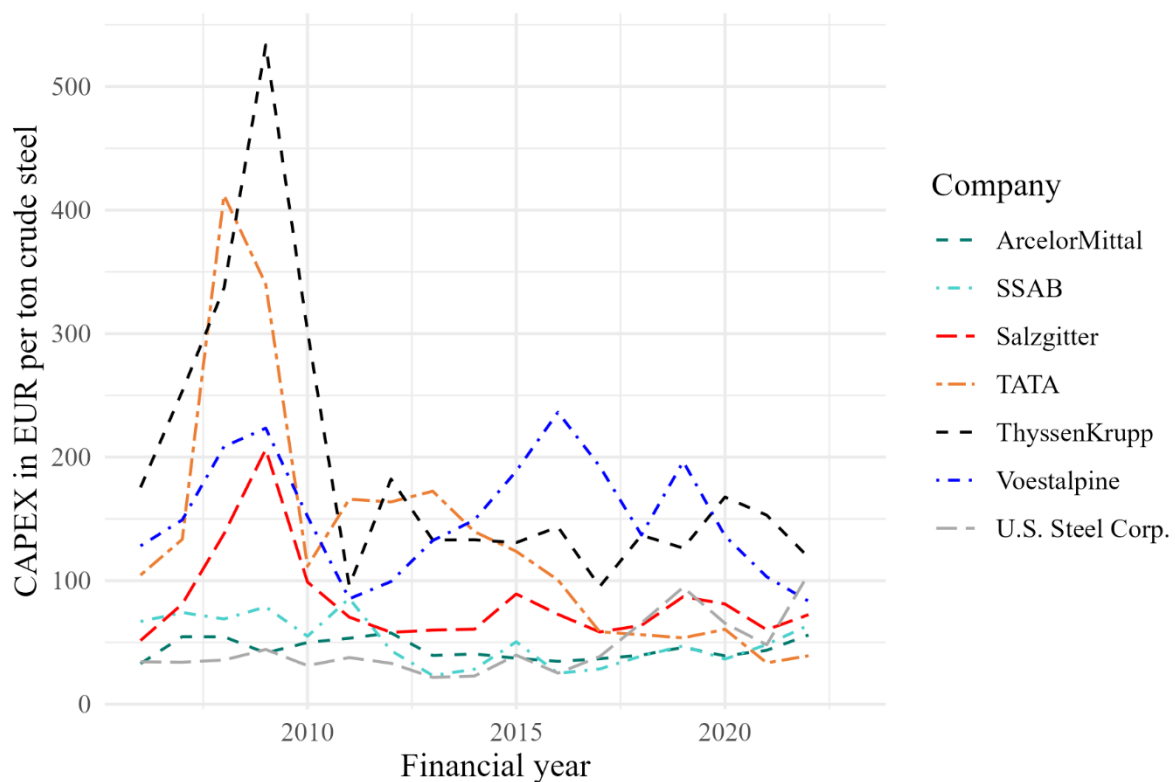
Appendix

Figure A1: EBITDA margins of listed steel producers operating in the EU-27 nations



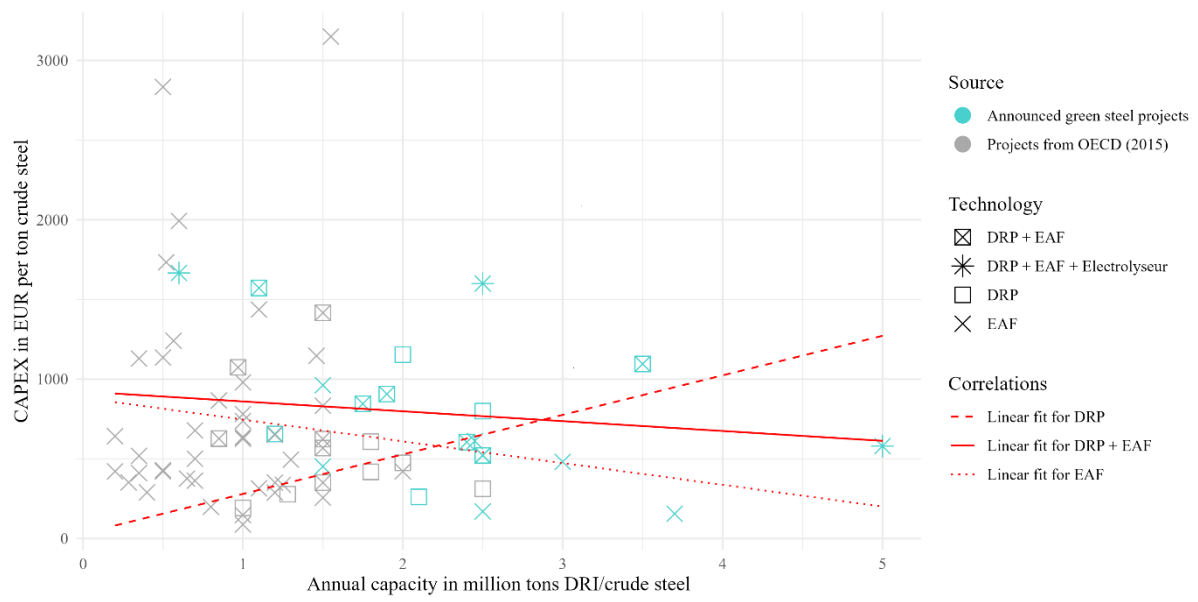
Note: Calculations based on Bloomberg data. Financial year periods may differ from calendar years and may vary between companies.

Figure A2: Historical CAPEX for listed steelmakers operating in the EU-27 countries



Notes: CAPEX are reported for the whole company, not only for the steel segment. Financial year periods may differ from calendar years and may vary between companies.

Figure A3: CAPEX for (H-)DRI-EAF route by annual steel capacity



Note: All values are adjusted for inflation (2022 producer prices). Projects with separate information for DRPs and EAFs appear under the respective technologies and the integrated pathway.

Table A2: CAPEX estimates for DRI-EAF steelmaking and electrolytic hydrogen production from the literature

Author (year)	CAPEX			Including electrolyser
	in € per ton DRI/steelmaking capacity per year			
	DRP	EAF	DRP and EAF	
Bosley et al. (1987)	97	74	171	
Lockwood Greene Technologies (2000)	165	92	257	
Daniëls (2002)	380	86	466	
van Wortswinkel and Nijs (2010)	109	61	170	
Wörtler et al. (2013)	230	184	414	
Allwood (2016)		209		
vanRujiven (2016)	170	275	337	
Mayer et al. (2018) ^a				1113
Xylia et al. (2018)	230	169	399	
International Energy Agency (2020) ^{a,b}			490-1258	
Santis et al. (2021) ^a	250	250	500	650
Facchini et al. (2021)		100		
Hornby (2021)			507	812
Haendel et al. (2022)	291			
McKinsey & Company (2023)	279	279	558	810

Notes: Currencies were transformed to euros based on the average exchange rates of the publication years or base years given for the CAPEX estimates. CAPEX for electrolyzers, expressed in kW, have been converted by multiplication with a factor of 0.271 according to Valentin Vogl et al. (2018). CAPEX were not adjusted for inflation.

^a Derived (in part) from annualized CAPEX values

^b 90% capacity utilization is assumed

Table A2: Announced full-scale green steel projects

Company	Country of project	Technology	Plant year online	Production capacity	CAPEX	
				in million tons steel per year	in million € ₂₀₂₃	in € ₂₀₂₃ per ton steel
Algoma Steel	Canada	EAF	2024	3.70	575.99	155.67
ArcelorMittal	Spain	DRI + EAF	2025	1.1	1729.11	1571.92
ArcelorMittal	Germany	DRI + EAF	2026	1.75	1480.40	845.94
ArcelorMittal	Canada	DRI + EAF	2028	2.4	1452.31	605.13
ArcelorMittal	Belgium	DRI + EAF	2030	2.5	1302.75	521.10
Blastr Green Steel	Finland	DRI + EAF + ELS	2026	2.50	4000.00	1600.00
British Steel	United Kingdom	EAF	2026	1.5	1443.38	962.25
Dillinger Saarstahl	Germany	DRI + EAF	2027	3.5	3835.00	1095.71
GravitHy	France	DRI	2027	2	2308.00	1154.00
H2 Green Steel	Sweden	DRI + EAF + ELS	2024	5.00	2901.58	580.32
H2 Green Steel	Spain	DRI + ELS	2025	2.00	2723.94	1361.97
Hydnum Steel	Spain	DRI + EAF + ELS + renewable energy	2026	0.60	1000.00	1666.67
Liberty Steel	Australia	DRI + EAF	2024	1.20	787.79	656.50
Liberty Steel	Romania	DRI + EAF	2024	2.50	1306.78	522.71
Metalloinvest	Russia	DRI	2024	2.10	549.53	261.68
POSCO	South Korea	EAF	2026	2.50	425.38	170.15
Salzgitter	Germany	DRI + EAF	2033	1.90	1723.00	906.84
SSAB	Sweden	EAF	2025	1.50	678.73	452.49
Tata Steel	United Kingdom	EAF	2027	3.00	1443.38	481.13
Thyssenkrupp	Germany	DRI	2026	2.50	2000.00	800.00
Voestalpine	Austria	EAF	2027	2.45	1500.00	612.24

Note: Data as stated for the planned projects are based on the authors' information search. Only projects for which information on production capacity and investment needs could be retrieved are included. CAPEX are adjusted for inflation based on the year in which the project information was published.

Table A3: TCI for 30% green steelmaking across listed steelmakers operating in the EU-27 nations and impact on their debt-equity ratios

Scenarios					TCI in Million €			Debt-to- equity		
#	30% DRI-EAF capacity in 2030 of current capacities	CAPEX for DRI-EAF in €/ton steel capacity/year	CAPEX for electrolyser in €/ton steel capacity/year		Mean ^a	Min/max ^a	Total	Average across companies in %	Average change in percentage points	Average change in %
A2		600	250		2,447	760/6,912	17,127	57.2	19.4	51.4
A3		750	-		2,159	671/6,098	15,112	54.9	17.1	45.3
A4		750	250		2,879	895/8,131	20,150	60.6	22.8	60.4
B1	Globally	600	-		5,081	1,313/10,620	24,722	69.2	29.7	175.3
B2		600	250		7,198	1,860/15,045	35,023	81.6	42.1	206.7
B3		750	-		6,351	1,641/13,275	30,903	76.6	37.2	194.2
B4		750	250		8,468	2,188/17,700	41,203	89.0	49.6	225.6

Notes: Based on the analysis of seven listed steel producers operating in the EU-27 nations (Arcelor Mittal, Salzgitter, SSAB, TATA Steel, ThyssenKrupp, U.S. Steel Corp, and Voestalpine). For the global scenarios B1 to B4, the mean and min/max TCI and the average (change in) debt-equity ratio are only analyzed across companies with crude steel production outside the EU-27 nations.

Supplementary materials

Description of the literature search methodology. Using Google Scholar and Web of Science, we collected articles related to green steel investment costs using the following search string¹: “steel AND (capital expenditure OR CAPEX OR investment cost) AND (green OR net zero OR decarboni* OR climate* OR fossil-free OR direct reduced iron OR DRI OR electric OR EAF OR hydrogen OR H2).” Approximately 143,000 and 50 search results, respectively, were returned. After screening the articles for relevance of title and abstract, we searched the articles for assumptions of installation-based CAPEX for DR plants, EAFs, and/or for hydrogen production via electrolysis. Whenever an article contained a CAPEX estimate that referenced another source, we consulted the respective sources and any further cross-references to obtain the original article related to the estimate. All articles that made original CAPEX assumptions were included in a final database, where we also collected all assumptions associated with the CAPEX estimates. We continued the literature search until further articles did not result in any new original assumptions on the projected CAPEX of the DRI-EAF route. In addition to CAPEX estimates for DR plants and EAFs, we also included frequently quoted CAPEX values or ranges for H₂ production via electrolysis in the database. In addition, we screened the most relevant grey literature on steel decarbonization (industry reports), as these often contain CAPEX assumptions. Conference proceedings were excluded from the analysis if they were not directly referenced for CAPEX assumptions. Only articles written in English were considered.

¹ The asterisk is used as a placeholder to include variations of the terms (beginning with the same letters) in the search.

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