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To cite this article: Lorenzo Rinaldi *et al* 2024 *Environ. Res. Lett.* **19** 074059

View the article online for updates and enhancements.

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
23 March 2024

REVISED
19 May 2024

ACCEPTED FOR PUBLICATION
26 June 2024

PUBLISHED
5 July 2024



LETTER

# Assessing environmental and market implications of steel decarbonisation strategies: a hybrid input-output model for the European union

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**Keywords:** steel decarbonisation, carbon footprint, price impact, hybrid input-output analysis, Exiobase, European union

Supplementary material for this article is available online

## Abstract

As a key material for manufacturing clean energy technologies, steel is crucial for energy transition, but its production causes 2.6 Gton of $CO_2$ emissions at global level each year. In 2020 the European Union (EU) set a net-zero emissions target by 2050, fostering innovation in the steel industry to reduce its environmental impact. However, a scenario-oriented and technologically comprehensive analysis assessing prospected environmental and market implications of steel decarbonisation strategies remains a gap, which is addressed in this paper. The analysis adopts a hybrid input-output-based life-cycle assessment model built in the MARIO framework, extending the Exiobase database to represent the supply chains of the most promising low-carbon steelmaking technologies in the EU, such as hydrogen- or charcoal-injected blast furnaces and natural gas- and hydrogen-based direct reduction routes. The penetration of these technologies is explored by formulating scenarios resembling European climate targets. The results show a reduction in the carbon footprint of steel across all scenarios, ranging up to −26% in 2030 and to −60% in 2050. However, the extent of footprint reduction is highly dependent on the share of clean electricity in the European supply mix, highlighting the relevance of holistic decarbonisation strategies. Economic implications affect steel prices, which rise up to 25% in 2030 and 56% in 2050, opening discussions on the need for suitable policies such as CBAM to avoid protectionism and encourage international technological progress.

## 1. Introduction

Steel is fundamental for the clean energy transition, nonetheless, its production is highly carbon-intensive, causing 2.6 Gton of CO2 emissions at global level [1]. The industry's heavy reliance on fossil fuels and the relatively young age of facilities pose challenges to reducing its environmental impact. Blast furnaces (BFs) globally average around 13 years old, far below their typical 40 year lifespan [1]. European facilities are even older, averaging 50 years, putting the European Union (EU) in a pioneering position to foster the transition of this sector [2].

In 2022, the EU produced 136 Mton of primary steel, with 57% from blast furnace-basic oxygen furnaces (BF-BOF) using coke and 43% from secondary steel made from iron scrap using electric arc furnaces [3]. While increasing coke-based facilities' efficiency seems challenging, modern BFs aim to replace it with cleaner fuels like hydrogen (H2-inj) and charcoal (CHL-inj), as further emissions reductions through existing methods are limited [4].

Hydrogen, predominantly produced via steam reforming (62% of global market in 2022 [5]), is set to see increased utilisation of electrolyzers due to emerging policies [6]. Charcoal, once the primary reductant in BFs, is gaining attention again as a renewable fuel [7]. An alternative to BF-BOF is the direct reduction (DR) route, in which the fuel adopted (natural gas, NG-DR) represents the main difference [8]. A variant, H2-DR, replaces natural gas with hydrogen, though it is in early development stages. Nonetheless, whichever decarbonisation pathway the steel industry will follow, a mix of all of these technologies is likely to be employed.

Many studies attempted to assess environmental impacts of new technologies and future decarbonisation strategies of the industry, mainly adopting life-cycle assessment (LCA) methodologies: Suer *et al* [9] and Nduagu *et al* [10] adopted comparative LCA to assess the carbon footprint of steel production via coal- and natural-gas-based DR technologies, however, focusing on the current technological state. Conte *et al* [11] employed environmentally-extended input-output analysis to provide economic and environmental insights of H2-DR in Italy. The same technology is compared to BF-BOF also by Mayer *et al* [12], underlining despite being promising from the environmental perspective, it is still not economically competitive. Other examples come from the EU-funded project *Green Steel for Europe*, which outlined multiple decarbonisation pathways to achieve the EU 2030–2050 climate targets [13]. While such pathways offer insights into the future trajectory of the industry, they are not supported by an economic assessment. This aspect has been addressed in the decarbonisation roadmap published by the EUROFER, providing an estimation of the effect of different transition scenarios on steel prices [14]. Nevertheless, these studies fail to link the economic burden of the proposed decarbonisation strategies with their environmental benefits, leaving a critical scenario-oriented and technologically comprehensive analysis on the topic as a substantial literature gap.

### 1.1. Objective and methodology justification

The paper aims to correlate the environmental and market implications of European steel decarbonisation strategies, by analysing the current and projected carbon footprint of major steelmaking routes and their impact on steel price. To achieve this, input-output analysis was identified as the most suitable approach for two main reasons: (i) it extends the traditional LCA approach, which often emphasizes the environmental footprint of individual products or processes from a cradle-to-grave perspective, whereas the supply-use input-output table (SUT) model enables a broader examination of the entire economic system and its interactions; (ii) it allows the introduction of desired supply chains as new industrial activities, built upon specifically tailored inventories [15]. Furthermore, this hybrid LCA approach seems to lead to more accurate results than traditional LCA [16].

Input-output tables are also vastly used for scenario analyses: by applying modifications to a baseline table, it is possible to calculate the impact of such changes by comparing the baseline and the modified tables. The approach is versatile to many fields of application and literature is rich in examples: a selection related to iron and steel sector includes [17–19]. The hybrid-units Exiobase database was adopted [20, 21]. The software implementation was based on the open-source MARIO framework [22]. Detailed instructions on the analytical and practical process to reproduce the methodology and the case study are provided in the supplementary material.

## 2. Materials and methods

### 2.1. The hybrid input-output model

The model adopted in this study is structured as a SUT, of which a schematic representation is provided in figure 1. SUT models distinguish among commodities supplied (**S** matrix) and consumed (**U** matrix) by industrial activities in each represented country.

Reiterating the classical Leontief approach [23], **S** and **U** matrices combined represent the so-called *intermediate transactions* matrix **Z** [24]. Final demand of commodities by households and other economic agents is accounted in matrix **Y**. By diagonalizing (^ operator) the total production vector **X** (defined as the sum of intermediate transactions and final consumption), it is possible to derive the intermediate technical coefficients matrix **z** by expressing **Z** per unit of total production (equation (1)) and to formulate the Leontief quantity model (equation (2)), where **I** is an identity matrix of appropriate dimensions and **w** is known as Leontief inverse matrix. It is worth noting that, as **Z** embeds both **U** and **S** (as shown in figure 1), **z** embeds **u** and **s**, which represent respectively the *technical coefficients* and the *market shares* matrices. The former collects, for each industrial activity, the inputs required to produce one single unit of the activity's output. The latter, on the other hand, describes how much of each unit of a certain commodity is supplied by each activity

$$\mathbf{z} = \mathbf{Z}\widehat{\mathbf{X}}^{-1} \tag{1}$$

$$\mathbf{X} = (\mathbf{I} - \mathbf{z})^{-1}\mathbf{Y} = \mathbf{w}\mathbf{Y}. \tag{2}$$

Input-output models, when applied for LCA analyses, are generally environmentally-extended and allow to evaluate the embedded environmental impact of industrial commodities and activities, on selected impact dimensions. For this study, the analysed dimension is the carbon footprint of steel, limited to the main GHGs (i.e. CO2, CH4, N2O). In particular, **E** matrix displays information about the environmental transactions that every industry is directly responsible for. Other factors of production related to the value added of each industry (e.g. compensation of employees, taxes…) are allocated into matrix **V**. Similarly to **z**, also **V** and **E** can be expressed

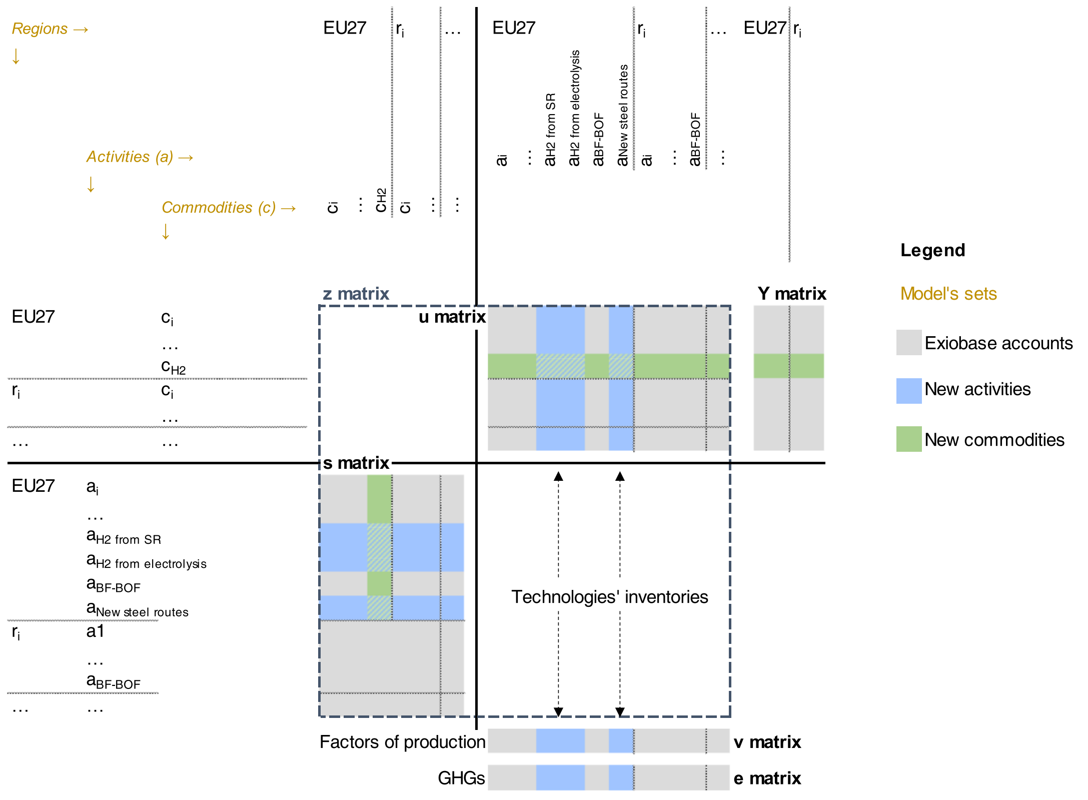


**Figure 1.** Supply-use input-output model structure.

per unit of total production $\mathbf{X}$, therefore matrices $\mathbf{v}$ and $\mathbf{e}$ can be calculated by equation (3) and (4) respectively

$$\mathbf{v} = \mathbf{V}\widehat{\mathbf{X}}^{-1} \tag{3}$$

$$\mathbf{e} = \mathbf{E}\widehat{\mathbf{X}}^{-1}. \tag{4}$$

To move from direct environmental impact accounting ($\mathbf{e}$) to an embedded (or consumption-based) accounting approach, it is necessary to multiply $\mathbf{e}$ by the Leontief inverse matrix (equation (5)), where $\mathbf{f}$ will be henceforth called specific footprint matrix. In the end, it is also possible to extend the calculation of $\mathbf{f}$ by exploding it into a squared matrix $\mathbf{f_{ex}}$ as described by Wiedmann [25]. Matrix $\mathbf{f_{ex}}$ allocates, for each industrial activity, the responsibility of its footprint to the upstream regions and activities (equation (6)), where $\widehat{\mathbf{e}}_k$ is the diagonal matrix obtained by the diagonalisation of each environmental extension ($k$) represented in $\mathbf{e}$

$$\mathbf{f} = \mathbf{ew} \tag{5}$$

$$\mathbf{f}_{\mathbf{ex}_k} = \widehat{\mathbf{e}}_k \mathbf{w}, \forall k. \tag{6}$$

The same concept can be applied to calculate commodity prices $\mathbf{p}$, which are nothing else than the embedded impact of factors of production equation (7)

$$\mathbf{p} = \mathbf{vw}. \tag{7}$$

As mentioned in the previous Section, the model's underlying database is the hybrid-units version of Exiobase. Such database covers 43 countries, including all EU member states which were aggregated into one region, 16 main trade partners and 5 rest-of-the-world (RoW) regions. No clustering was applied to the 163 industrial activities and 200 commodities represented in Exiobase, except for electricity, aggregated into '*Electricity from fossil fuels*', '*from nuclear*' and '*from renewables*'. Since the original database represents 2011, electricity production mixes have been nowcasted to 2022 based on Ember data [26].

### 2.2. Steelmaking supply chains models

The SUT model was extended to account for new supply chains resembling the manufacturing of steel via the innovative routes listed in section 1. With reference to figure 1, these were added as new industrial activities as new rows of $\mathbf{s}$ and new columns of $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{e}$, initially set as equal to the original Exiobase '*Manufacture of basic iron and steel and of ferro-alloys and first products thereof*' activity, assuming it produces steel only from BF-BOF.

Afterwards, each route was characterized with its specific life-cycle inventory as shown in table 1, which compares the main inputs required in each route expressed per $\text{ton}_{\text{steel}}$ supplied. Inventories are characterized in the columns of $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{e}$ matrices. For BF-BOF and CHL-inj, equivalent routes equipped with

**Table 1.** Main inputs required by innovative steelmaking routes to produce 1 $ton_{steel}$ (compared to BF-BOF described in Exiobase) and by the hydrogen production sectors to produce 1 $kg_{H2}$ in EU.

| | | | Steelmaking routes | | | | | Hydrogen production | |
|---|---|---|---|---|---|---|---|---|---|
| Type | Exiobase inputs | Unit | BF-BOF [20] | H2-inj [27] | CHL-inj [7] | NG-DR [9, 28] | H2-DR [9, 28] | By steam reformers [29, 30] | By electrolyzers [30, 31] |
| Commodity | Cement; lime and plaster | kg | 0.027 | 0.027 | 0.027 | 28.00 | 28.00 | — | — |
| | Charcoal | kg | — | — | 132.0 | — | — | — | — |
| | Chemicals | kg | 0.124 | 0.124 | 0.124 | 56.00 | 56.00 | — | — |
| | Coke oven coke | kg | 161.5 | 132.0 | 27.40 | 21.00 | 21.00 | — | — |
| | Electricity | GJ | 0.237 | 0.237 | 0.237 | 3.415 | 3.415 | 0.001 | 0.167 |
| | Hydrogen from electrolysis | kg | — | 7.250 | — | — | 89.86 | — | — |
| | Hydrogen from steam reforming | kg | — | 1.810 | — | 71.25 | — | — | — |
| | Iron ores | kg | 379.0 | 379.0 | 379.0 | 1500 | 1500 | — | — |
| | Natural gas and services | kg | 6.247 | 6.247 | 6.247 | 4.000 | 4.000 | 3.227 | — |
| | Steam and hot water supply services | kJ | — | — | — | — | — | 40.15 | 50.29 |
| Environmental extension | $CO_2$ | ton | 1.508 | 1.429 | 1.110 | 0.040 | 0.040 | 0.009 | — |

CCUS devices are considered, assumed having 80%-lower CO2 intensities.

Due to the multi-regional nature of the model, the total consumption of each commodity shown in table 1 was redistributed between domestic and imported inputs, assuming the same import rates consistent with those represented in Exiobase: for instance, the input of '*Cement; lime and plaster*' to H2-inj route has been split into a domestic input and an imported input for each foreign region, in accordance to how much cement is imported by the EU region in Exiobase.

Hydrogen is not represented in the Exiobase, therefore it was necessary to model it as a new commodity supplied by two additional activities responsible for its production via steam reforming and electrolysis. The main data adopted are reported in table 1.

The BF-BOF activity in Exiobase needed further modifications: producing, apart from steel, also '*blast furnace gas*' and '*oxygen steel furnace gas*', its emission intensity is affected by the ones of these by-products: consequently, these were disjointed and allocated to a new activity ('*Blast furnace gas production*'). As for secondary steel, Exiobase allocates its supply to the '*Re-processing of secondary steel into new steel*' activity. The model resulting from these arrangements is used as baseline for the case study and represents the 2022 situation.

Further information about the methodology employed can be found in the supplementary material.

### 2.3. Case study

#### *2.3.1. Scenarios formulation*

Decarbonisation scenarios are derived from those of the Green Steel project [13], designed to achieve 55% reduction of GHG emissions compared to 1990 by 2030 and carbon neutrality by 2050. These scenarios (henceforth labelled as GS) are modelled by changing the market share of each steel production route in the EU (figure 2).

In the baseline scenario, European steel production comprises 57% primary steel from BF-BOF and 43% secondary steel [3]. Three GS scenarios for 2030 are formulated: GS-Mix, GS-H2 and GS-Delayed. GS-Mix balances penetration among innovative technologies, while GS-H2 emphasizes increased availability of hydrogen, leading to larger shares of H2-inj and H2-DR GS-Delayed focuses on H2-inj without activating DR routes due to perceived limitations on transitioning from BF to DR (NG-DR covers only 5.9% against 10+% in the other two scenarios). Other technologies cover approximately 10% of the market, with varying emphasis on CCUS and charcoal injection. GS 2030 scenarios have been complemented with a REPowerEU scenario, reflecting the EU target of supplying 30% of primary steel with H2-DR [6]. For 2050, two GS scenarios are considered: the GS-Tech scenario prioritizes H2-DR (27%) and CHL-inj-CCUS (25%), while GS-Scrap assumes a larger share of secondary steel (50.1%). A more conservative forecast assumed by the STEPS scenario of the IEA [1] is also modelled for 2050, where BF-BOF is still the most adopted technology for primary steel

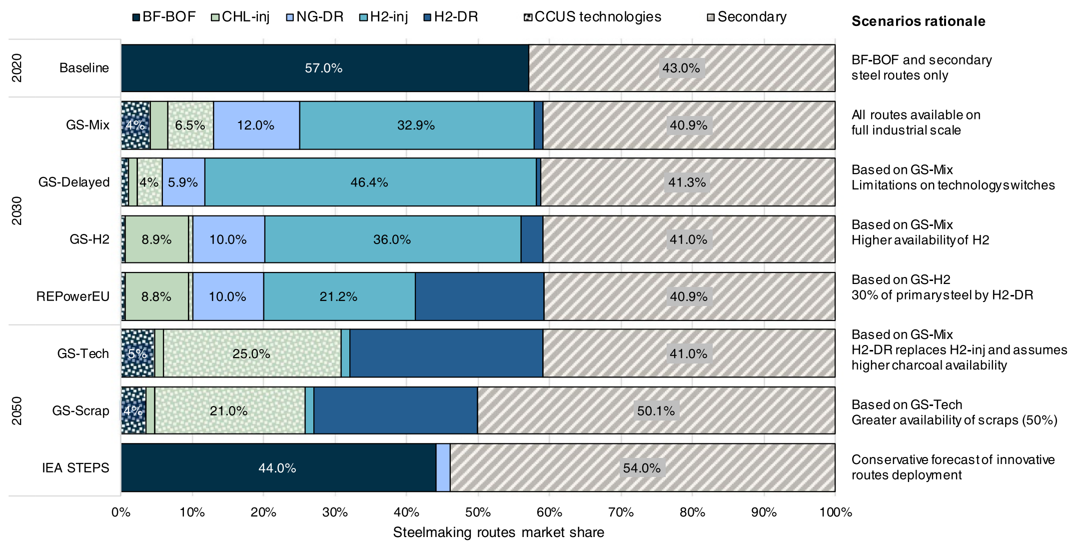


**Figure 2.** Scenarios' rationales and related steelmaking routes' market shares.

**Table 2.** Multipliers of capital expenditures assumed [32].

| Steelmaking routes | Multipliers |
|---|---|
| H2-inj | 0.150 |
| CHL-inj | 1.004 |
| BF-BOF + CCUS | 1.250 |
| CHL-inj + CCUS | 1.254 |
| NG-DR | 0.125 |
| H2-DR | 0.125 |

but most of the market share is supplied by secondary steel (54%).

It is important to note that steel demand remains constant across all scenarios. Additionally, the future European electricity mix is updated in accordance with REPowerEU and Fit-for-55 targets, with renewables supplying 69% and 81% of electricity in 2030 and 2050, respectively.

### 2.3.2. *Technologies price assumptions*

The projected steel supply mixes would lead to variations of its price, caused by the different costs characterizing each technology. Starting from the original Exiobase activity, technology-specific multipliers were applied to the '*Operating surplus: Consumption of fixed capital*' factor of production, in the value-added matrix **V**, to model different expenditure requirements. Although there may be other cost differences [12], it was assumed capital cost to be the primary discriminant across the analysed technologies. The multipliers adopted (table 2) refer to the findings of the *Green Steel* project [32].

The different steel production mixes implemented drive the penetration of more or less expensive technologies in each scenario: scenario-specific steel prices are calculated by applying equation (7).

### 2.3.3. *Sensitivity analysis*

Sensitivity analyses have been performed on key parameters.

- *Hydrogen colour:* hydrogen from steam reforming is always grey (i.e. from natural gas); hydrogen from electrolysis, by default, is yellow (i.e. input electricity coming from the grid), but also pink (electricity only from nuclear) and green (only from renewables) were considered.
- *Charcoal injection rates* were changed from 0.132 to a minimum value of 0.080 kg/ton$_{steel}$ ([7]) and a maximum of 0.16. This latter value models a configuration without coke consumption.
- For *hydrogen injection rate* in H2-inj route, besides the reference value of 9.06 kg/ton$_{steel}$ (reported in table 1), a lower value of 1.51 kg/ton$_{steel}$ was considered, as suggested by Tang *et al* [27].
- *CCUS rate of emission reduction* was varied across 60% (*CCUS min*) and 90% (*CCUS max*). The default value is 80%, as reported in table 1.
- In the H2-inj route, 100% H2 by steam reforming and by electrolysis extreme cases were investigated.
- In terms of the *electricity mix*, two cases were considered. The first, referred to as '*EE 2022*', assumes the same mix as the baseline both in 2030 and 2050; the second, referred to as '*EE clean*', assumes a 0%

share of fossil electricity in 2050 (not applied in 2030).

## 3. Results and discussions

### 3.1. Carbon footprints assessment

*3.1.1. Baseline steel footprints inside and outside of the EU*

The initial step in the investigation of the results is the calculation of the 2022 baseline carbon footprints, both of primary and secondary routes. This assessment helps to demonstrate model results are consistent with other literature values: EU primary steelmaking route results in 1.99 $ton_{CO2eq}/ton_{steel}$ (aligned to the reference value of 2.0 [33]), while that of secondary steel production is 0.27 $ton_{CO2eq}/ton_{steel}$ (reference values range from 0.3 to 0.4 $ton_{CO2eq}/ton_{steel}$ [1, 34]).

Furthermore, a comparison of the EU situation with other major steel-producing countries was conducted, as shown in figure 3. Regarding primary steel, the EU positions around the median global value, close to some competitors (China, India and Russia) and much better than others (Japan, USA and South Korea). Taking into account the current mix of primary and secondary steel production, from figure 5 it appears that in the baseline model the European steel already has a lower environmental impact than its other major competitors, even though its market is dominated by the obsolete BF-BOF technology. The implementation of advanced, cleaner steelmaking routes would further reduce the carbon footprint of European steel, thereby positioning the EU as a global leader in technological innovation. This is supported by the findings of the nextSections, which report the carbon footprints of each of the newly added steel technologies along with the resulting steel footprint in each of the formulated scenarios.

*3.1.2. Carbon footprint of innovative steel routes*

Starting from BF-BOF-based technologies, the adoption of charcoal (CHL-inj) would lower by 10% the carbon footprint of traditional coke-fired BFs. Coupling the use of charcoal with CCUS devices would lead to 0.92 $ton_{CO2eq}/ton_{steel}$, less than half of the baseline value.

The impact of employing hydrogen is much more uncertain since it depends on how the hydrogen itself is produced. Three values of carbon footprint are calculated according to the hydrogen colour (yellow by default). H2-inj, however, relies on coke as main fuel, therefore its footprint is roughly constant (in figure 4, pink and green H2 markers overlap). In contrast, H2-DR experiences much larger volatility: the case of yellow hydrogen yields 2.33 $ton_{CO2eq}/ton_{steel}$, the highest value compared to all other technologies, while green and pink lead to 0.86 and 0.81, making the technology a valid alternative to decarbonize the sector. NG-DR route yields a footprint value of 1.41 $ton_{CO2eq}/ton_{steel}$ (aligned with [33]), 40% less than BF-BOF.

As shown in equation (6), the adopted model allows splitting the environmental impacts by activity. Figure 4 highlights primary steel production (i.e. direct impact) represents the major contribution for all BF-based routes, due to its heavy dependence on coke. NG-DR sees, reasonably, hydrogen production as the main contributor, given natural gas is entirely used for on-site production of grey hydrogen. As foreseeable, again, the largest fraction of H2-DR impact is due to electricity production, since it only employs hydrogen from electrolysis.

In the proposed scenarios each technology covers a more or less high market share, but, as anticipated in figure 2, those covered by the most carbon-intensive technologies (BF-BOF and H2-DR) tend to be small, bringing to a reduction of the European steel footprint in 2030 and 2050.

*3.1.3. Scenarios projections*

Considering a mix of primary and secondary routes, the baseline GHG footprint of 1 ton of marketed steel in EU is around 1.25 $ton_{CO2eq}$ in the baseline 2022 model, significantly cleaner than that of other major steel producers. Figure 5 also reports a focus on EU steel footprint in 2030 and 2050 projected scenarios, including results of the performed sensitivity analyses.

As expected, all scenarios lead to a GHG footprint reduction. The lowest impacts in 2030 are reached by the REPowerEU scenario (median value of 0.93 $ton_{CO2eq}/ton_{steel}$, −26% from 2022), followed by GS-Mix (0.99, −20%), GS-H2 (1.08, −14%) and GS-Delayed (1.11, −11%). GS scenarios lead to a further reduction in 2050, with the GS-Tech (0.55 $ton_{CO2eq}/ton_{steel}$, −56% from 2022) and GS-Scrap (0.50, −60%). It should be noted that the latter two scenarios may be overly optimistic, assuming a complete renewal BF-BOF plants with clean fuels and widespread adoption of other innovative technologies that are still in development, all within the next 30 years. A more conservative projection is given by the IEA STEPS scenario which, on the contrary, keeps a high share of BF-BOF (see figure 2) and records a 0.97 $ton_{CO2eq}/ton_{steel}$ footprint, only −22% from 2022.

The replacement of old-fashioned BF-BOF plants with newer and cleaner ones would provide an opportunity for the EU to become a leading light in technological innovation and the fight against the decarbonisation of hard-to-abate sectors. However, results are subject to variations according to the performed sensitivities (figure 5). In particular, decarbonising the electricity mix (refer to 'EE 2022' and 'EE clean'

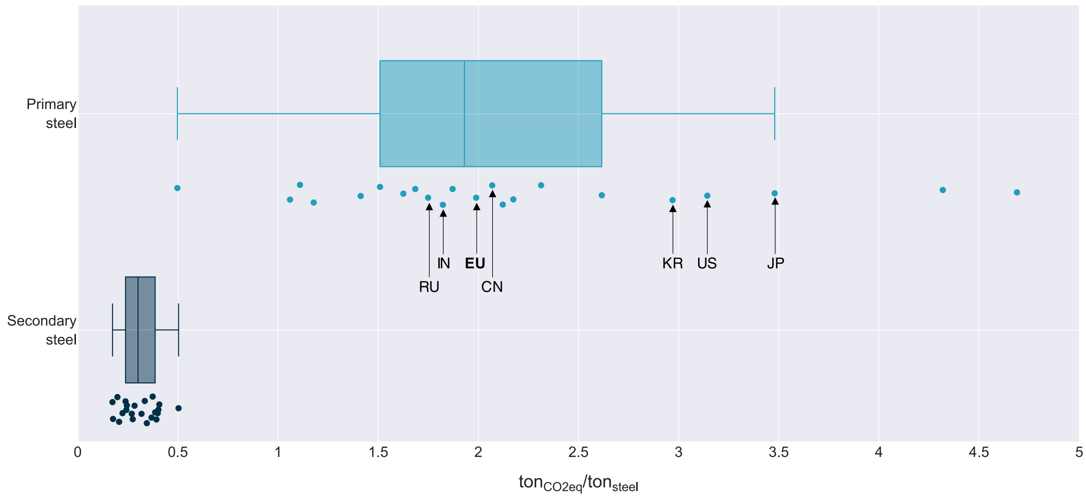


**Figure 3.** Baseline GHG footprint of primary and secondary steelmaking routes by region.

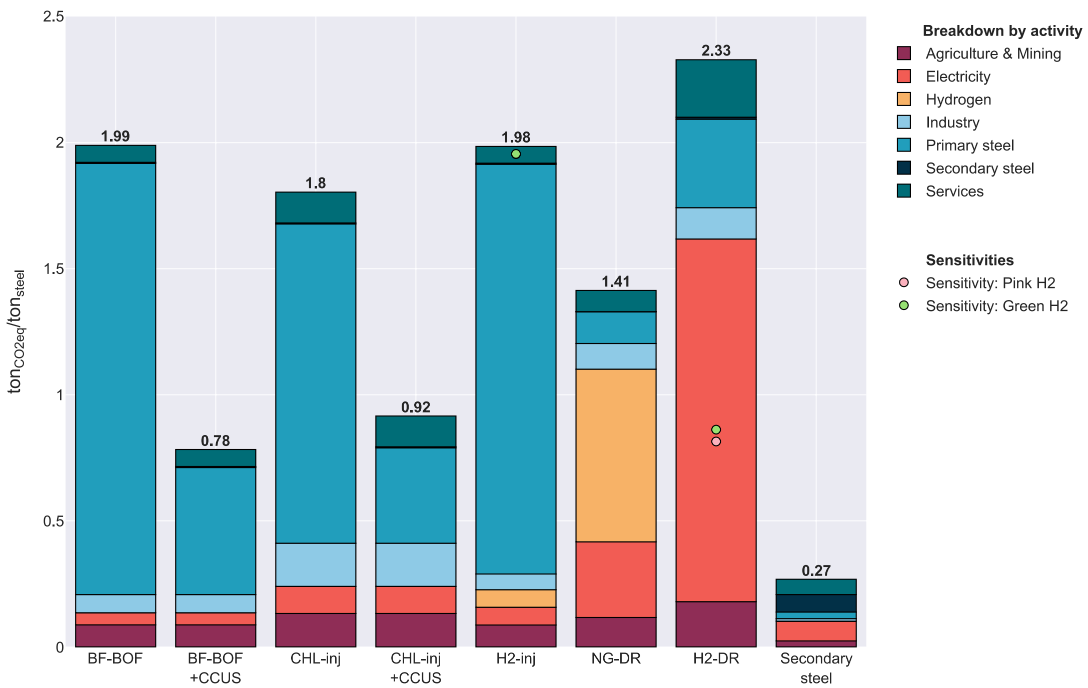


**Figure 4.** GHG footprint of steelmaking routes in the EU, split by origin activity. Sensitivities on hydrogen colours were performed for H2-inj and H2-DR.

arrows) seems fundamental to achieve a significant environmental impact reduction of the steel sector. The effectiveness of CCUS devices is the second most impactful sensitivity parameter, yet limited to 2050 scenarios, while others have a marginal effect.

Furthermore, it would be worth considering the possible implications of this decarbonisation for the market. Given that Europe already seems to be better positioned than its competitors in this regard, it is possible that large investments and more expensive technologies could have an impact on the continent's economic position.

### 3.2. Market implications: steel price

The price of European steel in the baseline model is 470 €/$ton_{steel}$, comparable with global market values [35] and in between the price of steel in the main producing countries (figure 6(a)).

EU steel price rises in all the scenarios. Regarding 2030, the highest increases are recorded in the REPowerEU scenario (590 €/$ton_{steel}$ and +25.5% in the average case), consistently with it yielding the lowest carbon footprint. In other scenarios, the increase is less pronounced, ranging from +5.1% in GS-Delayed and +11.6% in GS-H2. In 2050, the steel price raises

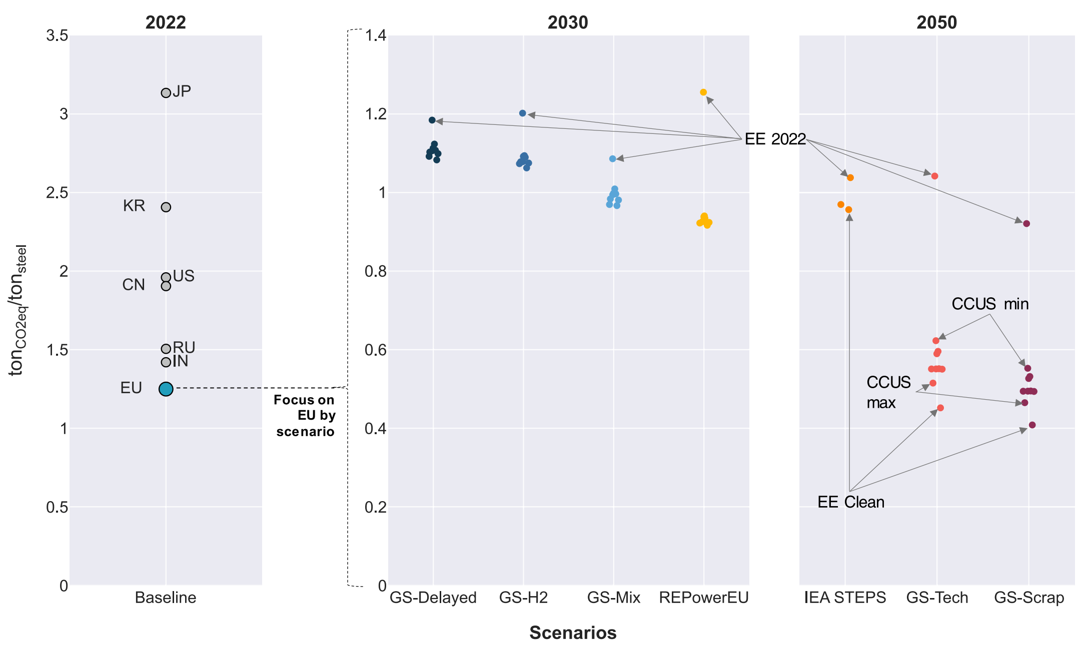


**Figure 5.** GHG footprint of steel commodity in main producing regions (2022). Future 2030–2050 projections in EU by scenario, including sensitivity.

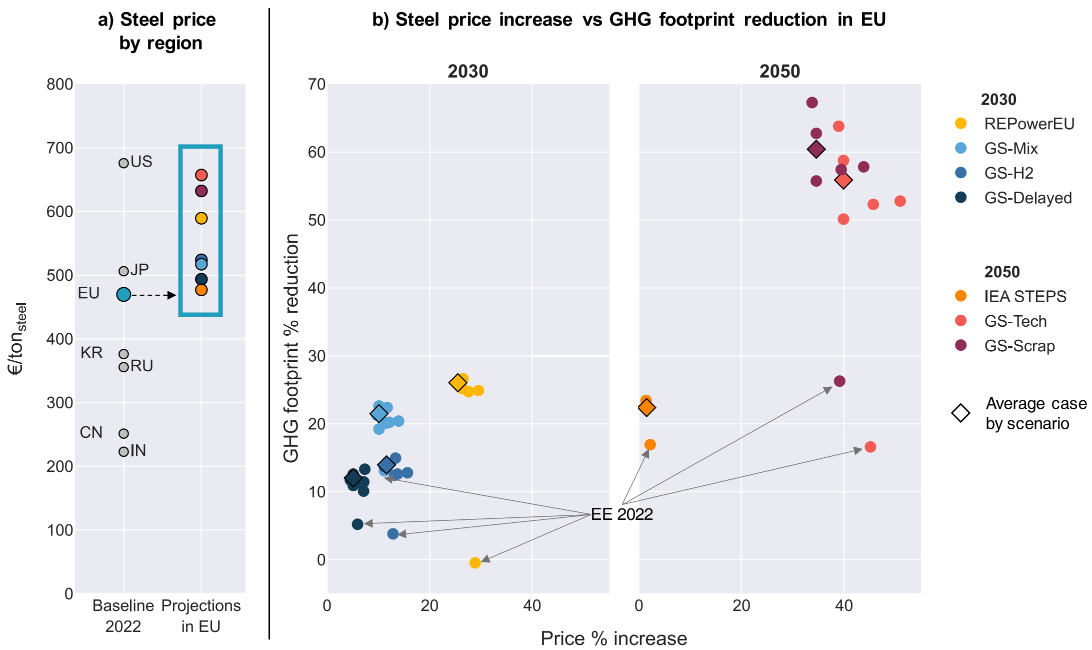


**Figure 6.** (a) Steel price by region; (b) relative steel price increase against GHG footprint % reduction by scenario in the EU with respect to baseline.

up to 657 €/ton$_{steel}$ in GS-Tech (+40%) while IEA STEPS, due to its conservative assumptions, show only a 1.5% increase from 2022.

Figure 6(b) also highlights the largest price increase does not correspond to the largest footprint reduction: in 2030, the GS-Mix reduces the footprint much more than GS-H2, at a slightly lower price. The same holds for 2050 scenarios, as GS-Scrap yields a lower environmental impact and a lower price than GS-Tech. This is attributable to the higher share of secondary steel in the former scenario, being less emissions-intensive and cheaper than primary steel routes.

Another notable result is that, in 2030, the difference in GHG footprint reduction between the REPowerEU and GS-Mix scenarios is only

0.06 $ton_{CO2eq}/ton_{steel}$. Still, the price difference is much more significant, amounting roughly to 72 €/$ton_{steel}$.

### 3.3. Policy recommendations

The penetration of new technologies in the European market leads to an increase in the price of steel in each scenario. While the EU is already well positioned with respect to the major steel-producing countries in terms of environmental impact standards (figure 5), this is not the case for the price of the steel it produces, which, when compared to, for example, South Korea, Russia, India and China, is not competitive.

While there is a clear need for decarbonisation-oriented policies in the EU steel sector, both for plant ageing and climate-related reasons, our results suggest that the scenario envisaged by the REPowerEU plan may not necessarily lead to the best economic-environmental compromise: the H2-DR technology seems not yet ready for large-scale deployment (finding in line with those of Mayer *et al* [12]) since it would be much more expensive than other routes bringing only marginal emissions reduction. Indeed, in the Green Steel scenarios, it only accounts for up to 4% of the market share, while other more mature technologies are preferred, such as H2-inj, CHL-inj + CCUS and NG-DR.

In order for the EU to establish itself as a leading light in the field of steelmaking technological innovation, it is of the utmost importance to implement policies to keep domestic production economically competitive, without introducing protectionist policies, like "foreign pollution fee" proposals in the US [36], but applying the indiscriminatory approach, such as the carbon border adjustment mechanism (CBAM), launched in late 2023 [37], coupled with the domestic emission trading system (ETS). This approach, in fact, pushes internal emissions cut, while encouraging adoption of similar measures by trade partners all over the world, thus contributing to global decarbonisation.

A final note on the importance of decarbonizing the power sector is warranted. As figure 5 illustrates, introducing innovation in the steel sector without addressing electricity production may not be effective. Also, acting upon power sector may reduce embedded emissions of many other industrial activities other than steel production, thereby enhancing the overall effectiveness of the intervention.

## 4. Conclusions

This paper shows that all innovative routes analysed have the potential to successfully reduce the environmental impact of steel production, but the extent of this reduction depends heavily on the intensity of concurrent decarbonisation of the electricity supply mix, which the EU is strongly committed to.

The economic implications may be severe: European steel price may raise up to 26% in 2030 and 40% in 2050. Moreover, large price increases do not necessarily correspond to equivalently significant decreases in carbon footprint, highlighting discrepancies between different steelmaking routes in achieving better environmental results and suggesting an optimal mix of technologies should be investigated. Despite cleaner hydrogen supply will be a factor, H2-DR technology, whose vast deployment is envisaged in the REPowerEU plan, may not yet be ready for large-scale penetration. In the short-term, H2-inj represents a more valid alternative, if complemented by the use of NG-DR, as shown by the result of GS-mix scenario which leads to almost the same carbon footprint reduction as REPowerEU but to much lower price raises.

An additional relevant topic regards international competition among major steel producers: European steel price is already higher than Indian, Chinese and Russian and is projected to approach other competitors', putting the EU in an insecure position on the global market; while new technologies may be adopted also by other countries, this will not probably be part of a short-term strategy, due to less ambitious climate mitigation plans and younger steel production facilities [2]. Informed and evidence-based political decision-making, which considers national interest, without undermining global development goals and climate pledges, is therefore crucial to properly regulate this evolving market.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10843374 [38].

## Acknowledgments

The authors acknowledge support from the Horizon Europe R&I programme project IAM COMPACT (Grant No. 101056306). The content of this paper does not necessarily reflect the opinions of the European Commission and the responsibility for it lies solely with its authors.

## Conflict of interest

The authors declare no competing financial or non-financial interests.

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