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Hydrogen-based steel production and global climate protection: An empirical analysis of the potential role of a European cross border adjustment mechanism

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ABSTRACT

The European Union's aim to become climate neutral by 2050 necessitates ambitious efforts to reduce carbon emissions. Large reductions can be attained particularly in energy intensive sectors like iron and steel. In order to prevent the relocation of such industries outside the EU in the course of tightening environmental regulations, the establishment of a climate club jointly with other large emitters and alternatively the unilateral implementation of an international cross-border carbon tax mechanism are proposed. This article focuses on the latter option choosing the steel sector as an example. In particular, we investigate the financial conditions under which a European cross border mechanism is capable to protect hydrogen-based steel production routes employed in Europe against more polluting competition from abroad. By using a floor price model, we assess the competitiveness of different steel production routes in selected countries. We evaluate the climate friendliness of steel production on the basis of specific GHG emissions. In addition, we utilize an input-output price model. It enables us to assess impacts of rising cost of steel production on commodities using steel as intermediates. Our results raise concerns that a cross-border tax mechanism will not suffice to bring about competitiveness of hydrogen-based steel production in Europe because the cost tends to remain higher than the cost of steel production in e.g. China. Steel is a classic example for a good used mainly as intermediate for other products. Therefore, a cross-border tax mechanism for steel will increase the price of products produced in the EU that require steel as an input. This can in turn adversely affect competitiveness of these sectors. Hence, the effects of higher steel costs on European exports should be borne in mind and could require the cross-border adjustment mechanism to also subsidize exports.

1. Introduction

The European Union aims to become climate neutral by 2050. The related efforts in Europe[1] to protect the climate could however be undermined by higher emission levels in other parts of the world, i.e. carbon leakage impends (Ecorys and Cambridge Econometris, 2013; European Parliament, 2021). Companies may relocate European production of goods elsewhere due to production cost advantages that arise from less strict climate protection regulations abroad. The relocation of production will imply a decline in profits, tax income and jobs within the EU.

The EU's "carbon leakage list" specifies European industrial sectors that are exposed to a significant risk of carbon leakage. In order to mitigate that risk, these sectors receive free greenhouse gas (GHG) emission allowances (European Commission, 2019). Other regions than the EU face the threat of carbon leakage as well; in particular countries with ambitious GHG targets and high carbon prices are confronted with this problem. In addition to the free allocation of CO_2 emission allowances, exceptions from carbon pricing and reductions of CO_2 tax rates for industries at risk represent further possible measures against carbon

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[1] In the following we use Europe and EU as synonyms for EU-27.

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leakage.

In our investigation we focus on a fourth option to counteract the risk of carbon leakage: imposing a CO_2 price on certain goods imported from outside the EU. The idea of such a carbon border adjustment mechanism (CBAM) has recently regained much prominence in Europe (European Parliament, 2021). The trigger for this renewed attention is the announcement of new EU climate protection targets: a 55% reduction in net GHG emissions relative to 1990 levels (European Commission, 2020). In the course of the EU's initiatives to reach this goal, plans have been advanced to establish a CBAM. According to a draft proposal an import tax will be levied on eligible imported goods (European Commission, 2021a). Importers of goods like steel, cement, electricity, fertilizer, and iron would be required to purchase emissions certificates from a new carbon border adjustment mechanism authority to cover the GHG emissions embedded in the goods. The core idea is to compensate the possible competitive advantage of importers into the EU due to lax climate protection laws in their non-EU home countries. The official adjustment proposal was released in July 2021. According to the Australian Climate Council "CBAMs are designed to ensure a level playing field for economies that have carbon pricing schemes" (Climate Council, 2022). Thus, beside the EU other actors are interested in introducing such a measure. Schemes that at least resemble a CBAM are adopted only in California's and Quebec's cap-and-trade systems yet (Böhringer et al., 2022), where electricity imports are taxed on the basis of emissions intensity. Therefore, the EU is one of the pioneers in CO_2-related cross border adjustments (Römer et al., 2021) and the implications of the EU's approach and its potential effects on carbon leakage have still to be better understood.

The risk of leakage in countries is usually analyzed with simulations or econometric studies. The leakage effects found in these studies differ strongly with a tendency of smaller rates found in econometric studies (Bierbrauer et al., 2021). Due to these differences, a comparison of the relevance of carbon leakage in individual regions differing e.g. with respect to industrial structure or environmental regulation, is subject to uncertainties.

According to the European Commission a CBAM " … will initially apply only to a selected number of goods at high risk of carbon leakage: iron and steel, cement, fertilizer, aluminum and electricity generation." (European Commission, 2022). A CBAM should ensure a reduction of GHG emissions, without pushing carbon-intensive production outside Europe (European Commission, 2021a, 2022). We take the iron and steel sector as an example to investigate the effects of a European CBAM. In doing so, we do not confine only to the question of whether a European CBAM could become an effective means to safeguard this sector's present production routes against international free-riders in climate protection (European Commission, 2021b). Instead, we consider new routes required to reach the European goal of becoming carbon free and examine whether a CBAM suffices to protect the greening of European industrial sectors against international carbon leakage (European Commission, 2021b).

Specifically, we investigate whether a CBAM based on emission certificate prices is sufficient to keep the application of green steel production technologies like hydrogen-based direct reduced iron technologies competitive on the European market. Such green steel production is a prerequisite for attaining the EU's goal to become carbon free.

We choose the iron and steel sector as example for the following reasons: 1) the European Commission proposed to tax imports of steel via a future CBAM, 2) the sector is included in the EU's leakage list (European Commission, 2018), 3) it causes high levels of emissions accounting for 5.7% of EU's total GHG emissions (European Commission, 2021b) and 4) EU imports of iron and steel are remarkably high, both in quantity and value. The imported 41 million tonnes of steel and iron from outside the EU value approx. 27,161 million € (Eurostat, 2021). In comparison, e.g. cement imports also being planned to be taxed, value 352 million € only (TrendEconomy, 2021). We consider German (green) steel production as a European example as Germany is presently the largest steel production site in the EU (EUROFER, 2021). Currently, about 27% of steel production in the EU-27 is located in Germany.

In our analysis, we proceed as follows: In Section 2 we first give an overview of recent research efforts and approaches concerning the decarbonization of the steel sector. We then outline the techno-economic fundamentals of this sector and in doing so, we address the prices of inputs required for alternative production routes. In Section 3, we present the design of our study and our approach for assessing floor-prices and the cost of crude steel production. In Section 4, we show our results including a sensitivity analysis and investigate the influence of rising steel prices on other economic sectors. We discuss our results and conclude on the introduction of a CBAM in Section 5.

2. State of research and technologies

Research on the role of the steel sector in decarbonizing economies focused mainly on comparisons of energy efficiencies of different countries (see e.g., Hasanbeigi et al., 2016; Oda et al., 2012), on potentials for improvements in efficiencies (see e.g., Long et al., 2020; Wu et al., 2016) and on possible reductions in specific emissions (da Costa et al., 2013; Li and Zhu, 2014). Studies on the future of the iron and steel production emphasizing technological aspects have been conducted by Zhang et al. (2018), Wang et al. (2007), Hasanbeigi et al. (2013), Moya and Pardo (2013), and IEA (2017). Using the example of the US, Bassi et al. (2009), for instance, analyse the impacts of climate policies on US energy-intensive industries on an aggregated level.

In the past, studies mainly focused on conventional steel production technologies (see e.g., Arens et al., 2017; Arens et al., 2012). Recently, the use of hydrogen for steel making gains more and more attention (see e.g., Flores-Granobles and Saeys, 2020; Toktarova et al., 2020). Hölling and Gellert (2018), for instance, provide a concept of the direct reduction process based on hydrogen. Among others, they calculate hydrogen demand and electricity consumption as well as costs for this process. Vogl et al. (2018), Karakaya et al. (2018) as well as Rechberger et al. (2020) evaluate a potential design of a hydrogen-based steel production via direct reduction and its performance for European steel producing countries. Rechberger et al. (2020) compare the direct reduction process via natural gas and via hydrogen. Both analyse energy use and CO_2-emission mitigation potential of the process, while Vogl et al. (2018) moreover assess the economic performance. Furthermore, Vogl et al. (2018) show under which conditions the hydrogen-based steel production via direct reduction becomes competitive with an integrated steel plant. They calculate input quantities, energy consumption, CO_2-emissions, and total costs of a hydrogen-based direct reduced iron (DRI) process and conclude that energy demand is comparable with conventional steel making technologies and that competitiveness of production costs is strongly dependent on electricity prices, prices for CO_2-emissions, as well as scrap input. The results of Rechberger et al. (2020) show that a hydrogen-based production route via direct reduction has a lot of potential for environmentally friendly steel making depending on the electricity mix. Keys et al. (2019) compare different technologies for producing steel with less CO_2-emissions including hydrogen-based direct reduction. They consider potential energy and material savings, emission mitigation, investment costs, and infrastructure requirements to evaluate the actual feasibility of those technologies. Weigel et al. (2016) apply a multi-criteria analysis on the German steel production to evaluate technological, social and political, economic, safety and vulnerability, as well as ecological factors of alternative steel making production routes. They find that a hydrogen-based direct reduction process has the highest average score and thus is the most promising future option. In a previous paper, Fischedick et al. (2014) evaluate technical, economical, and ecological parameters of those alternative steel making production routes and compare them with conventional steel producing processes. Special attention is paid to the CO_2-emission mitigation potential. Fischedick et al. (2014) examine hydrogen-based direct reduction and conclude that it is the most promising alternative steel production route concerning economic and environmental factors. Furthermore, Otto et al. (2017) analyse the integration of renewable energy and hydrogen into the German steel production process. Thereby they examine different steel producing technologies, among others, a hydrogen-based production route via direct reduction. Otto et al. (2017) compare technologies of steel production. They point out that those innovative production technologies could lead to less dependence on coal. Moreover, they show that using alternative steel producing technologies with integrated renewable energy allows a reduction of CO_2-emissions. The potential of a reduction of CO_2-emissions and fuel demand is especially high in the hydrogen-based process via direct reduction. In their paper, Kushnir et al. (2020) analyse barriers of a transition of the Swedish steel industry towards a hydrogen-based direct reduction process by applying a technological innovation system study. They conclude that the framework of the technological innovation system performs well for such a transition although further improvements are necessary. Moreover, Patisson and Mirgaux (2020) focus on a hydrogen-based direct reduction process and compare it with a carbon monoxide based reduction. The authors focus on physicochemical aspects and apply a specific structural kinetic pellet model. Bhaskar et al. (2020) investigate how to reduce the CO_2-emissions of steel production and therefore introduce a new system linking hydrogen-based direct reduction and methane pyrolysis. They find that this coupling leads to higher specific energy demand as well as lower capital and operational costs. Hence, they conclude that a hydrogen-based direct reduction in combination with methane pyrolysis is a promising steel production process. Though, a detailed techno-economic analysis is still necessary. Later on, Bhaskar et al. (2020) analyse mass and energy flows of hydrogen-based direct reduction in combination with an electric arc furnace to assess its feasibility. Thereby, they focus on energy consumption and CO_2-emissions. Moreover, they are conducting sensitivity analyses to indicate the main influencing factors of energy consumption.

Since the steel industry is an important part of the European economy, and should remain in the future, it must be included in strategies for CO_2-reduction (European Commission, 2021b). Branger et al. (2016) and Kuik and Hofkes (2010) address competition aspects of the European steel industry by investigating carbon leakage within the EU ETS. In this context Kuik and Hofkes (2010) stress the need for border adjustments by using an aggregated computable general equilibrium (CGE).

The new technologies (like a hydrogen-based direct reduction process) being currently on the agenda are linked with many uncertainties (i.e. with respect to costs and technological characteristics). In addition, the overall economic and political context remain uncertain (see e.g., Muslemani et al., 2021; Wang et al., 2021). Hence, there is still a gap in analysing the future of the European steel industry taking the broad range of uncertainties into consideration.

3. Method

3.1. Study design

Our study aims to analyse the requirements of a carbon border adjustment mechanism (CBAM) to keep the application of hydrogen-based direct reduced iron technologies competitive on the European market as it is a prerequisite for attaining the EU's goal to become carbon free.

Currently, two production routes dominate steel production globally (World Steel Association, 2020): the blast furnace/basic oxygen furnace (BF/BOF) route and the scrap/electric arc furnace (EAF) route. The EAF route is less energy and CO_2 emission intensive than the BF/BOF route (see e.g., Arens et al., 2017; World Steel Association, 2016). As a new, third route hydrogen-based direct reduced iron technologies combined with EAF (H_2-DRI/EAF) offers high potential to reduce GHG emissions, in particular if green hydrogen is used, i.e. hydrogen produced with the help of renewable energy.

The three steel production routes differ in the inputs required and therefore in their levels of production cost and GHG emissions (see e.g., Remus et al., 2013; Wu et al., 2016). The BF/BOF production route largely bases on using iron ore and coking coal. For EAF, scrap and electricity and for H_2-DRI/EAF, iron ore, electricity and hydrogen are necessary (Bhaskar et al., 2020).

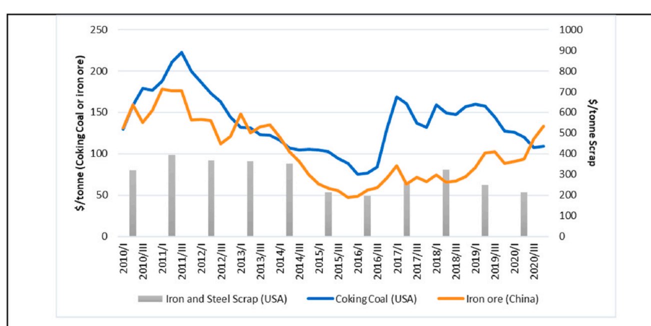
Iron ore, coking coal and iron scrap are important input factors. Considering their prices in the 2010–2020 period reveals that prices for coking coal and iron ore have been very volatile (Fig. 1), and prices for coking coal fluctuated between \$75 and \$222 per tonne (Steelonthenet.com, 2014; Steelonthenet.com, 2021).

Transport costs changed considerably in the past: A great share of the inputs needed for steel production as well as steel products themselves are transported on ships. Thus, transport cost strongly depends on the charter rates for bulk carriers which fluctuated significantly: In the period from 2015 to 2020, the charter rates for Capesize vessels ranged between \$6250/day and \$22,250/day (UNCTAD, 2020). The examples presented above show that key cost factors fluctuated enormously in the past. Based on that historical development, we consider any prognosis for key cost factors associated with significant uncertainty. The future price of green H_2 is uncertain as well (see., e.g. Glenk and Reichelstein, 2019; Vogl et al., 2018).

Due to the uncertain costs for input factors, future costs for producing steel are subject to significant uncertainty. Focusing on one selected pathway for cost can therefore result in misjudging challenges and options. In our study, we account for this by employing a systematic sensitivity analysis with respect to the price of raw materials, transport costs, energy efficiency in the BF/BOF route and the price of green hydrogen. For the former two, we start with the minimum prices observed between 2010 and 2020 (we refer to these as "default conditions" in what follows) and increase prices continuously. As default value for the energy efficiency of BF/BOF, we take today's level. For green hydrogen, we consider a price ranging from \$1.96/kg to \$3.96/kg (current price level (2020)).

3.2. Calculation of cost and emissions

We examine to which extent the H_2-DRI/EAF production route - as key technology for greening primary steel production - needs to be protected via a CBAM to become viable (Wang et al., 2021). In particular, we analyse under which conditions H_2-DRI/EAF in Germany is competitive to steel produced using the BF/BOF route in selected non-European countries. For H_2-DRI/EAF, we always assume the use of green hydrogen in our study. We use a floor price model to assess the competitiveness of the different production routes in different countries via the floor price difference (Vögele et al., 2020). While we are aware



$ per tonne	Min	Max	Average	2020
Scrap*	196	393	296	213
Coking Coal*	75	222	140	109
Iron ore**	47	179	102	133

Fig. 1. Historical development of prices for scrap, coking coal, and iron ore.

that competitiveness cannot be measured in terms of floor price alone (Germany is currently the second most expensive supplier of crude steel produced via BF/BOF and remains at least to some extent competitive by e.g. emphasizing product quality), we consider the floor price difference a key indicator. Moreover, we employ specific GHG emissions as indicator for the climate friendliness of production routes. As a key characteristic, our model explicitly considers transportation cost, i.e. cost of transporting inputs by vessel from exporting countries to the production sites and the transport of crude steel to the markets (Sundal and With, 2010). In order to assess impacts of rising cost of steel production on goods that use steel as intermediate product, we utilize an input-output price model. To put these results into context, we examine the effects of rising steel prices on other sectors of the economy.

We employ the information on input prices presented in Section 2 for assessing cost of producing crude steel. We evaluate floor price differences in order to obtain a suitable representation of the input parameter space and the global development of cost gaps.

For doing so, we employ a floor price model (Vögele et al., 2020). As a key characteristic, it explicitly includes cost of transporting inputs by vessel from exporting countries to the production sites, the production cost in the corresponding steel plant, and the transport of crude steel to the markets. The transportation routes depend on the vessel types. We distinguish between Capesize and Panamax vessels. Our model can be reduced to two equations. Eq. (1) reflects the cost of crude steel produced in country n by using production route a and sold at the steel market l, whereas equation (2) refers to the calculation of transport cost.

$$p_a^{n,l} = \sum_{i=1}^{k} x_{a,i}^{n} \cdot \left(\sum_{m=1}^{r} \left[\alpha_i^{m,n} \cdot \left(c_i^m + tr_i^{m,n} \right) \right] + env_a^n \right) \cdot \left(1 + prof_a^n\right) + tr_{steel}^{n,l} \tag{1}$$

with

n index for steel producing country

l index for steel market

a index for production route

i index for input factor

m index for foreign producing country

$x_{a,i}^n$ production coefficient i reflecting the demand for e.g. raw materials, electricity, gases, or labour used for production of one tonne of crude steel using production route a [tonne/tonne], [GJ/tonne], [m^3/tonne] or [working hour/tonne]

$\alpha_i^{m,n}$ share of imported raw material input i from the foreign producer m to the overall demand for i in country n

c_i^m: free on board (FOB) price of the raw material i in country m [\$/tonne]

$tr_i^{m,n}$ cost for transporting raw material i from country m to n [\$/tonne]

env_a^n additional cost resulting from environmental regulations [\$/tonne]

$prof_a^n$ envisaged profit rate for the producer in country n by route a [%]

$tr_{Steel}^{n,l}$ cost for transporting steel from country n to l [\$/tonne]

In eq. (1), the floor price of crude steel produced in the country n by using production a and sold on the market l is determined by technological aspects represented by production coefficients $x_{a,i}^n$ combined with the cost for the needed input factors (which results from FOB prices and transport cost), envisaged profit rates and the cost for transporting the steel to the sales market. We calculate the transport costs as follows:

$$tr_i^{m,n} = \min_v \left(d_{i,v}^{m,n} \cdot r_v + \left[\left(d_{i,v}^{m,n} - b_{i,v}^{m,n} \right) \cdot o_v^{sea} + b_{i,v}^{m,n} \cdot o_v^{cong} \right] \cdot p_{oil} + c_v^{harb} + e_v^{m,n} \right) + tm_i^{m,n} \tag{2}$$

with

v index of vessel type

$d_{i,v}^{m,n}$ days needed for transporting input i from country m to country n using a vessel of type v [day]

r_v charter rates [\$/day]

$b_{i,v}^{m,n}$ days accounted for congestion and bunkering [day]

o_v^{sea} fuel consumption of a vessel of type v during its trip on sea [tonne/day]

o_v^{cong} fuel consumption of a vessel of type v during congestion time [tonne/day]

p_{oil} average price for fuels used for the vessels [\$/tonnes]

c_v^{harb} harbour specific cost [\$/tonne]

$e_v^{m,n}$ other costs (e.g. fees for using Suez Canal) [\$/tonne]

$tm_i^{m,n}$ cost for transportation of inputs i by other transportation means [\$/tonne]

In the past, the cost of the input factors needed for steel production as well as the transportation cost fluctuated significantly. Since we expect this to continue in the future, we conduct a systematic sensitivity analysis. For modelling the range of change in the prices for raw materials, we consider an increase for the price of iron ore from 0% up to 400%, for the price of coking coal from 0 up to 280%, and for the price of scrap up to 134% compared to 2016's level. We choose the 2016 prices as starting point as prices of raw materials and charter rates for bulk carriers were the lowest at that time.

The input-output price model employed for assessing impacts of increases in cost on goods where steel is used as intermediate product is based on the assumptions that each industry produces only one homogeneous product and that the inputs remain in constant proportion to the level of output. This implies that there is no substitution between different materials and no technological progress. Hence, we assume fixed input coefficients of production. In principle, the price of product i corresponds to a) the sum of cost for intermediates plus b) value added directly linked to activities of sector i:

$$p_i = \sum_{j=1}^{n} a_{ji} \cdot p_j + v_i \tag{3}$$

with

p_i: price of product i

n: number of products

a_{ji}: production coefficient reflecting amount of good j needed for producing good i

v_i: value added generated in sector i

In matrix notation, we obtain

$$P = A^T P + V \tag{4}$$

and, activating the equation towards P,

$$P = \left(I - A^T\right)^{-1} \cdot V \tag{5}$$

which allows for assessing impacts of changes in cost for one product on the prices of other products:

$$\widehat{P} = \left(I - A^T\right)^{-1} \cdot \Delta V \tag{6}$$

Here, ΔV denotes the vector with assumed direct changes in price components of individual goods (e.g. changes in wages, taxes and other cost components).

The scenarios we consider in our analysis are based on historical development of cost and prices parameters. In particular, we use cost and prices observed in the period from 2010 to 2020 for exports of coking coal, iron ore and scrap, on domestic prices for e.g. electricity in steel producing countries as well as transportation cost. In our analysis, we consider Germany, China, India, Japan, Korea, Russia and the USA. All data used for the calculations of cost and emissions are presented in Vögele et al. (2022).

3.3. Data analysis

In a first step the results of the calculations will be analysed graphically by examining how cost gaps will change if input parameters differ. In the graphical analyses we will focus on specific countries. By employing a meta-model approach, we assess dependencies mathematically. This analysis explores how floor prices will vary if cost for input factors increases. Again, the analyses will be conducted for individual countries. In a third step, we will link the cost figures with the information on the calculated country and production route specific CO_2 emissions. Based on this data we will be able to draw conclusions on specific CO_2 avoidance cost and thus to specification of CBAM being needed to avoid carbon leakage.

4. Results

4.1. Differences in floor prices

We find that crude steel produced via BF/BOF in selected competing countries (China, India, Japan, Korea, Russia, USA) is cheaper than steel produced via H_2-DRI/EAF in Germany. For some scenarios, costs of hydrogen-based crude steel produced in Germany are even significantly higher. The current floor price difference of German steel compared to the competing countries ranges from $6/tonne (USA) to $48/tonne (China). For some favourable yet reasonable scenarios, Germany can offer hydrogen-based crude steel at similar prices as Japan and the USA and even maintain today's difference of floor prices for India and South Korea. However, this is not the case for China.

We find that even if green H_2 was for free, Germany's steel industry could not maintain the current floor price difference with respect to China under otherwise default conditions, as it would still face a cost disadvantage of $93 per tonne when using H_2-DRI/EAF (Fig. 2). For the most favourable scenario (transport costs and prices of raw materials are high, no efficiency improvements in the BF/BOF route), cost parity is reachable if the price of H_2 reduces to approx. $1.65 per kg. However, if the Chinese industry improves the efficiency of its BF/BOF production route by 20%, the maximal increase we consider, then a H_2-price of only approx. $0.67 per kg would lead to cost parity if we stick to the most favourable scenario otherwise.

We visualise in Figs. 2–5 the floor price difference Δp [$/tonne] for steel offered on the EU market for selected competing countries, different production routes depending on the increase of prices for raw materials r, the increase of transport cost t and the price for green H_2 p_{H2}. We furthermore visualise the cost difference depending on the efficiency gain e_{BOF} in the BF/BOF production route. For modelling the range of r, we consider an increase for the price of iron ore from 0 up to 400%, for the price of coking coal from 0 up to 280%, and for the price of scrap up to 134% compared to 2016's level, respectively, and thus end up with a generic variable $0\% \leq r \leq 400\%$. We choose the 2016 prices as starting point aka "default scenario" as prices of raw materials and charter rates for bulk carriers were the lowest at that time. As ranges, we set $\$1,960/tonne \leq p_{H2} \leq \$3,960/tonne$, $0\% \leq e_{BOF} \leq 20\%$ and $0\% \leq t \leq 400\%$.

In every country considered, crude steel via BF/BOF is the cheapest alternative, while H_2-DRI/EAF is the most expensive one. Regardless of the production route, Germany is always among the most expensive three providers of crude steel and therefore is exposed to strong competitive pressure.

Predominantly, the floor price difference is positive, meaning that crude steel produced via BF/BOF in the competing countries is cheaper than steel produced via H_2-DRI/EAF in Germany. However, for South Korea and the USA, negative Δp is achievable for sufficiently large r and t and low p_{H2} (Figs. 4 and 5). For India, today's floor price difference of $22/tonne can be maintained in some scenarios (Fig. 3). Therefore, in some scenarios, steel produced via H_2-DRI/EAF can at least compete from a cost perspective. Nevertheless, even for those countries positive floor price differences prevail. Depending on the scenario, Δp varies between -$55/tonne (Japan) and $360/tonne (China).

4.2. Sensitivity analysis and a meta-model of the floor price difference

Prices for significant input factors have proven to be volatile in the past and the precise development of p_{H2} is difficult to forecast for the longer future. Moreover, the amount of possible efficiency gains e_{BOF} in the BF/BOF production route in competing countries in the future is unknown. We consider Δp a key indicator for competitiveness. Therefore, it seems worthwhile to analyse Δp for a competing country using the BOF production route and Germany using H_2-DRI/EAF from a global point of view. Using the General Algebraic Modeling System (GAMS, 2021), r, p_{H2}, e_{BOF}, and t are systematically varied in the ranges provided in section 4.1 using 20 equidistant steps for each input factor. The output variable created is the average cost of steel production without accounting for transportation to the steel market with envisaged profit rates. Evaluating the cost difference in the 194,481 ($= 21^4$) combinations of r, p_{H2}, e_{BOF} and t created this way yields a suitable representation of the input parameter space and the global behaviour of Δp.

We now consider r, p_{H2}, e_{BOF} and t variables and Δp a mathematical function of them:

$$\Delta p(r, H_2, e_{BOF}, t) = p_{BOF}^{country,Germany}(r, H_2, e_{BOF}, t) - p_{\mathrm{H2-DRI}}^{Germany,Germany}(r, H_2, e_{BOF}, t), \quad (7)$$

where the production costs are computed according to (1). To take a global view of Δp means to find a simple description of Δp aka a meta-model. However, even if our floor price model (1) is mathematically rather simple being merely a weighted sum of products of input factors,

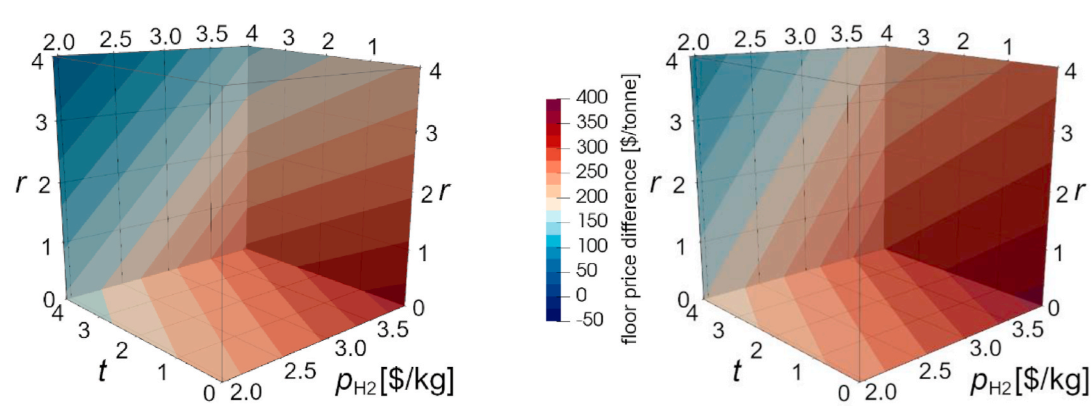


Fig. 2. Floor price difference with respect to China for the current level of efficiency of the BF/BOF production route (left) and increased level of efficiency by 20% (right). It depends on the price of raw material r, transport cost t ($r, t = 0$: default scenario, $r, t = 4$: increase by 400%) and price for green hydrogen p_{H2}.

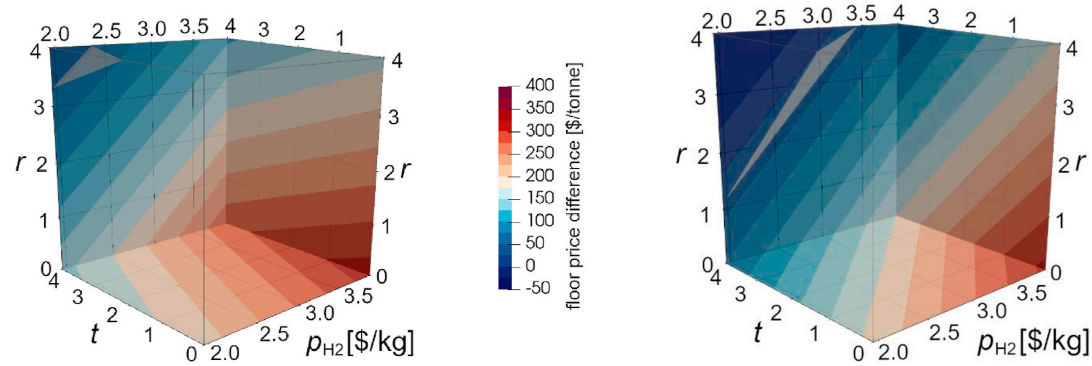


Fig. 3. Δp for India, $e_{BOF} = 0\%$ (left) and Japan, $e_{BOF} = 0\%$ (right). The translucent grey surface indicates today's difference of floor prices.

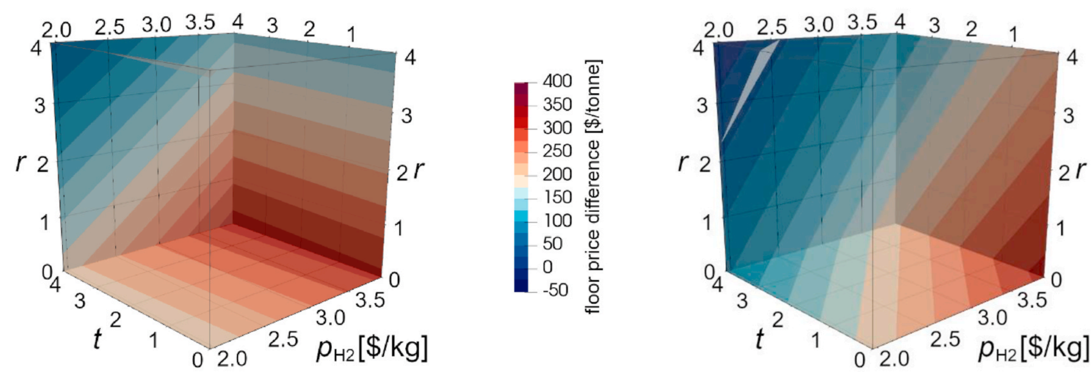


Fig. 4. Δp for Russia, $e_{BOF} = 0\%$ (left) and South Korea, $e_{BOF} = 0\%$ (right). The translucent grey surface indicates today's difference of floor prices.

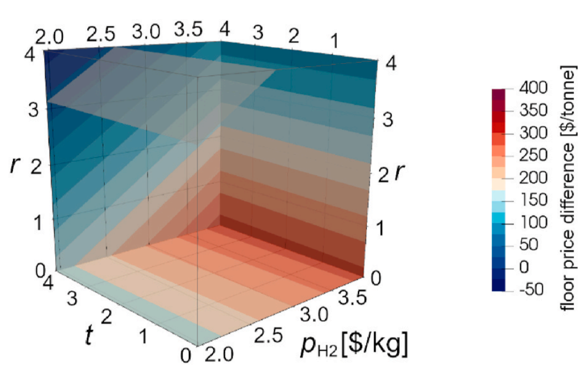


Fig. 5. Δp for the USA, $e_{BOF} = 0\%$. The translucent grey surface indicates today's difference of floor prices.

its sophistication is in the sheer number of parameters and summands. Therefore, we build a meta-model by least-squares-fitting

$$\Delta p^{'}(r, p_{\mathrm{H2}}, e_{BOF}, t) = \alpha + \beta r + \gamma p_{\mathrm{H2}} + \delta e_{BOF} + \theta t + \mu\, r \cdot e_{BOF} \quad (8)$$

to the data points created above. Then, $\max|\Delta p - \Delta p^{'}| \leq \$1.47/tonne$ for all these data points and all competing countries (Table 1). This justifies neglecting other products of input factors in our approach and replacing Δp by Δp' in further analysis. For the values of the coefficients of Δp', we refer to Table 1. However, excluding the term $r \cdot e_{BOF}$ altogether and therefore fitting a purely linear meta-model to the data leads to a maximal deviation of about \$20/t with respect to Δp, which is why we consider such a meta-model too imprecise for further analysis.

We employ Δp' for a sensitivity analysis. The gradient of $\Delta p^{'}$ and taking the absolute value of its components yields upper bounds

$$\nabla(\Delta \mathrm{p}) = \begin{pmatrix} \beta + \mu\, e_{BOF} \\ \gamma \\ \delta + \mu\, r \\ \theta \end{pmatrix} \leq \begin{pmatrix} \max\{|\beta|, |\beta + 0.2\mu|\}, \\ |\gamma| \\ \max\{|\delta|, |\delta + 4\mu|\} \\ |\theta| \end{pmatrix} := \begin{pmatrix} \widetilde{\sigma}_r \\ \widetilde{\sigma}_{H2} \\ \widetilde{\sigma}_{eBOF} \\ \widetilde{\sigma}_t \end{pmatrix} \quad (9)$$

for the changes in the cost difference with respect to changing input factors; the inequality is meant component-wise. However, the ranges of the input factors differ such that we scale the sensitivity factors $\widetilde{\sigma}_i$ with respect to the range of the i-th input factor to make them comparable. The resulting coefficients σ_i (Table 2) provide upper bounds for the change of the floor price difference in \$/tonne if the according input variable changes by 1% of its considered range.

The sensitivity factors exhibit that for Δp, r is the most influential input factor for all competing countries but Korea and Japan, as σ_r has the largest absolute value. However, the influence of p_{H2} comes close to that, whereas increasing the efficiency of the BOF production route in the competing country has a smaller effect. Depending on the geographical location, t plays an important (e.g. Japan or Korea) or insignificant (e.g. Russia or the USA) role, but never exceeds the other influence factors by a wide margin. For all competing countries, Δp decreases for increasing r and e_{BOF} and for decreasing p_{H2}.

4.3. *Implications for carbon border adjustment mechanisms*

We assess the emissions of crude steel produced in China using BF/BOF and supplied in Europe with 2.5 t CO_2 per tonne of crude steel, whereas crude steel production using H_2-DRI/EAF and green hydrogen is nearly CO_2 free.

A CBAM in the form of add-on taxes on import prices (being related to the CO_2 content of the corresponding import good) could mitigate the

Table 1
Coefficients for the meta-model $\Delta p'$ according to eq. (2).

Competing country	α	β	γ	δ	θ	μ	$\max\lvert\Delta p - \Delta p'\rvert$
China	93.39	−33.81	0.06200	104.86	−15.03	49.32	0.18 $/t
India	67.22	−36.26	0.06200	131.86	−11.50	44.55	0.54 $/t
Japan	60.33	−32.00	0.06200	134.98	−32.20	50.71	1.47 $/t
Korea	63.65	−22.71	0.06200	115.43	−28.14	45.41	1.23 $/t
Russia	61.28	−42.68	0.06200	120.62	1.531	65.91	0.15 $/t
USA	38.98	−50.34	0.06200	86.98	0.8014	41.48	0.17 $/t

Table 2
Sensitivity factors for selected competing countries.

Competing country	σ_r	σ_{H2}	σ_{eBOF}	σ_t
China	1.35	1.24	0.604	0.601
India	1.45	1.24	0.620	0.460
Japan	1.28	1.24	0.676	1.288
Korea	0.908	1.24	0.594	1.126
Russia	1.707	1.24	0.769	0.0612
USA	2.01	1.24	0.506	0.032

cost advantage of the climate unfriendly production route. We now search for the necessary level of such import taxes in order to protect the infant hydrogen-based steel sector. Therefore, we relate the differences in induced CO_2 emissions to the observed cost differences. Fig. 6 displays our results for BF/BOF in China vs. H_2-DRI/EAF (Germany). According to our calculations, at the current cost level, a cross-border tax of about \$110/tonne CO_2 is necessary for avoiding that imports of steel produced in China using BF/BOF are cheaper than green steel in Germany. The results show that with decreasing prices for hydrogen and increasing cost for raw materials, a significantly lower cross-border tax suffices. Taking the historical development of the prices for raw material, transportation cost and expectations regarding future prices for green hydrogen into consideration we expect a cross-border tax range sufficient to protect green steel production in Europe to be between \$50 and \$150 per tonne of CO_2.

The cost of producing crude steel using the H_2-DRI/EAF route in Europe is higher than using the BF/BOF route in China. Although the competitive disadvantage of European H_2-DRI/EAF steel relative to imports from China could be addressed by a cross border levy, this does not guarantee competitiveness of the H_2-DRI/EAF route. Adjustments

BF/BOF (China) vs. H2- DRI (Germany) — H2 Price $/t

Increase on prices for raw materials	Incr. in transport. cost	3960	3860	3760	3660	3560	3460	3360	3260	3160	3060	2960	2860	2760	2660	2560	2460	2360	2260	2160	2060	1960
Increase on prices for raw materials 0%	0%	133	130	128	126	123	121	118	116	113	111	109	106	104	101	99	96	94	92	89	87	84
	40%	131	128	126	123	121	118	116	113	111	109	106	104	101	99	96	94	92	89	87	84	82
	80%	128	126	123	121	118	116	114	111	109	106	104	101	99	97	94	92	89	87	84	82	80
	120%	126	123	121	119	116	114	111	109	106	104	101	99	97	94	92	89	87	84	82	80	77
	160%	123	121	119	116	114	111	109	106	104	102	99	97	94	92	89	87	85	82	80	77	75
	200%	121	119	116	114	111	109	106	104	102	99	97	94	92	89	87	84	82	80	77	75	72
	240%	119	116	114	111	109	107	104	102	99	97	94	92	90	87	85	82	80	77	75	73	70
	280%	116	114	112	109	107	104	102	99	97	94	92	90	87	85	82	80	77	75	73	70	68
	320%	114	112	109	107	104	102	99	97	95	92	90	87	85	82	80	78	75	73	70	68	65
	360%	112	109	107	104	102	99	97	95	92	90	87	85	82	80	78	75	73	70	68	65	63
	400%	109	107	104	102	99	97	95	92	90	87	85	82	80	78	75	73	70	68	65	63	61
Increase on prices for raw materials 100%	0%	120	117	115	112	110	107	105	103	100	98	95	93	90	88	86	83	81	78	76	73	71
	40%	117	115	112	110	108	105	103	100	98	95	93	91	88	86	83	81	78	76	74	71	69
	80%	115	112	110	108	105	103	100	98	95	93	91	88	86	83	81	78	76	74	71	69	66
	120%	113	110	108	105	103	100	98	96	93	91	88	86	83	81	79	76	74	71	69	66	64
	160%	110	108	105	103	100	98	96	93	91	88	86	83	81	79	76	74	71	69	66	64	62
	200%	108	105	103	101	98	96	93	91	88	86	84	81	79	76	74	71	69	67	64	62	59
	240%	105	103	101	98	96	93	91	88	86	84	81	79	76	74	71	69	67	64	62	59	57
	280%	103	101	98	96	93	91	89	86	84	81	79	76	74	72	69	67	64	62	59	57	55
	320%	**101**	98	96	93	91	89	86	84	81	79	76	74	72	69	67	64	62	59	57	55	52
	360%	98	96	94	91	89	86	84	81	79	77	74	72	69	67	64	62	59	57	55	52	50
	400%	96	94	91	89	86	84	81	79	77	74	72	69	67	64	62	60	57	55	52	50	47
Increase on prices for raw materials 200%	0%	106	104	101	99	97	94	92	89	87	84	82	80	77	75	72	70	67	65	63	60	58
	40%	104	102	99	97	94	92	89	87	85	82	80	77	75	72	70	68	65	63	60	58	55
	80%	102	99	97	94	92	89	87	85	82	80	77	75	72	70	68	65	63	60	58	55	53
	120%	99	97	94	92	90	87	85	82	80	77	75	73	70	68	65	63	60	58	56	53	51
	160%	97	95	92	90	87	85	82	80	77	75	73	70	68	65	63	60	58	56	53	51	48
	200%	95	92	90	87	85	82	80	78	75	73	70	68	65	63	61	58	56	53	51	48	46
	240%	92	90	87	85	82	80	78	75	73	70	68	65	63	61	58	56	53	51	48	46	44
	280%	90	87	85	83	80	78	75	73	70	68	66	63	61	58	56	53	51	49	46	44	41
	320%	88	85	83	80	78	75	73	70	68	66	63	61	58	56	53	51	49	46	44	41	39
	360%	85	83	80	78	75	73	71	68	66	63	61	58	56	54	51	49	46	44	41	39	37
	400%	83	80	78	75	73	71	68	66	63	61	58	56	54	51	49	46	44	41	39	37	34
Increase on prices for raw materials 300%	0%	93	91	88	86	83	81	78	76	74	71	69	66	64	61	59	57	54	52	49	47	44
	40%	91	88	86	83	81	79	76	74	71	69	66	64	62	59	57	54	52	49	47	45	42
	80%	88	86	84	81	79	76	74	71	69	67	64	62	59	57	54	52	50	47	45	42	40
	120%	86	84	81	79	76	74	71	69	67	64	62	59	57	54	52	50	47	45	42	40	37
	160%	84	81	79	76	74	72	69	67	64	62	59	57	55	52	50	47	45	42	40	38	35
	200%	81	79	76	74	72	69	67	64	62	59	57	55	52	50	47	45	42	40	38	35	33
	240%	79	77	74	72	69	67	64	62	60	57	55	52	50	47	45	43	40	38	35	33	30
	280%	77	74	72	69	67	64	62	60	57	55	52	50	47	45	43	40	38	35	33	30	28
	320%	74	72	69	67	65	62	60	57	55	52	50	48	45	43	40	38	35	33	31	28	26
	360%	72	69	67	65	62	60	57	55	52	50	48	45	43	40	38	35	33	31	28	26	23
	400%	69	67	65	62	60	57	55	52	50	48	45	43	40	38	35	33	31	28	26	23	21
Increase on prices for raw materials 400%	0%	80	77	75	73	70	68	65	63	60	58	56	53	51	48	46	43	41	39	36	34	31
	40%	77	75	73	70	68	65	63	60	58	56	53	51	48	46	43	41	39	36	34	31	29
	80%	75	73	70	68	65	63	61	58	56	53	51	48	46	44	41	39	36	34	31	29	27
	120%	73	70	68	65	63	61	58	56	53	51	48	46	44	41	39	36	34	31	29	27	24
	160%	70	68	66	63	61	58	56	53	51	49	46	44	41	39	36	34	32	29	27	24	22
	200%	68	66	63	61	58	56	53	51	49	46	44	41	39	36	34	32	29	27	24	22	19
	240%	66	63	61	58	56	54	51	49	46	44	41	39	37	34	32	29	27	24	22	20	17
	280%	63	61	58	56	54	51	49	46	44	41	39	37	34	32	29	27	24	22	20	17	15
	320%	61	59	56	54	51	49	46	44	42	39	37	34	32	29	27	25	22	20	17	15	12
	360%	59	56	54	51	49	46	44	42	39	37	34	32	29	27	25	22	20	17	15	12	10
	400%	56	54	51	49	46	44	42	39	37	34	32	29	27	25	22	20	17	15	12	10	8

BF/BOF (Germany) vs. H2- DRI (Germany) — H2 Price $/t

Increase on prices for raw materials	Incr. in transport. cost	3960	3860	3760	3660	3560	3460	3360	3260	3160	3060	2960	2860	2760	2660	2560	2460	2360	2260	2160	2060	1960
Increase on prices for raw materials 0%	0%	124	121	119	116	113	111	108	105	103	100	97	95	92	90	87	84	82	79	76	74	71
	40%	123	121	118	115	113	110	107	105	102	99	97	94	92	89	86	84	81	78	76	73	70
	80%	123	120	117	115	112	109	107	104	101	99	96	94	91	88	86	83	80	78	75	72	70
	120%	122	119	117	114	111	109	106	104	101	98	96	93	90	88	85	82	80	77	74	72	69
	160%	121	119	116	113	111	108	106	103	100	98	95	92	90	87	84	82	79	76	74	71	69
	200%	121	118	115	113	110	108	105	102	100	97	94	92	89	86	84	81	78	76	73	71	68
	240%	120	117	115	112	110	107	104	102	99	96	94	91	88	86	83	80	78	75	73	70	67
	280%	119	117	114	112	109	106	104	101	98	96	93	90	88	85	82	80	77	75	72	69	67
	320%	119	116	114	111	108	106	103	100	98	95	92	90	87	84	82	79	77	74	71	69	66
	360%	118	116	113	110	108	105	102	100	97	94	92	89	86	84	81	79	76	73	71	68	65
	400%	118	115	112	110	107	104	102	99	96	94	91	89	86	83	81	78	75	73	70	67	65
Increase on prices for raw materials 100%	0%	103	100	97	95	92	90	87	84	82	79	76	74	71	68	66	63	60	58	55	53	50
	40%	102	99	97	94	92	89	86	84	81	78	76	73	70	68	65	62	60	57	55	52	49
	80%	101	99	96	94	91	88	86	83	80	78	75	72	70	67	64	62	59	57	54	51	49
	120%	101	98	96	93	90	88	85	82	80	77	74	72	69	66	64	61	59	56	53	51	48
	160%	100	98	95	92	90	87	84	82	79	76	74	71	68	66	63	61	58	55	53	50	47
	200%	100	97	94	92	89	86	84	81	78	76	73	70	68	65	63	60	57	55	52	49	47
	240%	99	96	94	91	88	86	83	80	78	75	73	70	67	65	62	59	57	54	51	49	46
	280%	98	96	93	90	88	85	82	80	77	75	72	69	67	64	61	59	56	53	51	48	45
	320%	98	95	92	90	87	84	82	79	77	74	71	69	66	63	61	58	55	53	50	47	45
	360%	97	94	92	89	86	84	81	79	76	73	71	68	65	63	60	57	55	52	49	47	44
	400%	96	94	91	88	86	83	81	78	75	73	70	67	65	62	59	57	54	51	49	46	44
Increase on prices for raw materials 200%	0%	82	79	76	74	71	68	66	63	60	58	55	53	50	47	45	42	39	37	34	31	29
	40%	81	78	76	73	70	68	65	62	60	57	55	52	49	47	44	41	39	36	33	31	28
	80%	80	78	75	72	70	67	64	62	59	57	54	51	49	46	43	41	38	35	33	30	27
	120%	80	77	74	72	69	66	64	61	59	56	53	51	48	45	43	40	37	35	32	29	27
	160%	79	76	74	71	68	66	63	61	58	55	53	50	47	45	42	39	37	34	31	29	26
	200%	78	76	73	70	68	65	63	60	57	55	52	49	47	44	41	39	36	33	31	28	26
	240%	78	75	72	70	67	65	62	59	57	54	51	49	46	43	41	38	35	33	30	28	25
	280%	77	74	72	69	67	64	61	59	56	53	51	48	45	43	40	38	35	32	30	27	24
	320%	77	74	71	69	66	63	61	58	55	53	50	47	45	42	40	37	34	32	29	26	24
	360%	76	73	71	68	65	63	60	57	55	52	49	47	44	42	39	36	34	31	28	26	23
	400%	75	73	70	67	65	62	59	57	54	51	49	46	44	41	38	36	33	30	28	25	22
Increase on prices for raw materials 300%	0%	60	58	55	52	50	47	45	42	39	37	34	31	29	26	23	21	18	16	13	10	8
	40%	60	57	55	52	49	47	44	41	39	36	33	31	28	25	23	20	18	15	12	10	7
	80%	59	57	54	51	49	46	43	41	38	35	33	30	27	25	22	20	17	14	12	9	6
	120%	59	56	53	51	48	45	43	40	37	35	32	29	27	24	22	19	16	14	11	8	6
	160%	58	55	53	50	47	45	42	39	37	34	31	29	26	24	21	18	16	13	10	8	5
	200%	57	55	52	49	47	44	41	39	36	33	31	28	26	23	20	18	15	12	10	7	4
	240%	57	54	51	49	46	43	41	38	35	33	30	28	25	22	20	17	14	12	9	6	4
	280%	56	53	51	48	45	43	40	37	35	32	30	27	24	22	19	16	14	11	8	6	3
	320%	55	53	50	47	45	42	39	37	34	32	29	26	24	21	18	16	13	10	8	5	2
	360%	55	52	49	47	44	41	39	36	34	31	28	26	23	20	18	15	12	10	7	5	2
	400%	54	51	49	46	44	41	38	36	33	30	28	25	22	20	17	14	12	9	7	4	1
Increase on prices for raw materials 400%	0%	39	37	34	31	29	26	23	21	18	15	13	10	8	5	2	0	-3	-6	-8	-11	-14
	40%	39	36	33	31	28	25	23	20	17	15	12	10	7	4	2	-1	-4	-6	-9	-12	-14
	80%	38	35	33	30	27	25	22	19	17	14	12	9	6	4	1	-2	-4	-7	-10	-12	-15
	120%	37	35	32	29	27	24	21	19	16	14	11	8	6	3	0	-2	-5	-8	-10	-13	-16
	160%	37	34	31	29	26	23	21	18	16	13	10	8	5	2	0	-3	-6	-8	-11	-13	-16
	200%	36	33	31	28	25	23	20	18	15	12	10	7	4	2	-1	-4	-6	-9	-11	-14	-17
	240%	35	33	30	28	25	22	20	17	14	12	9	6	4	1	-2	-4	-7	-9	-12	-15	-17
	280%	35	32	30	27	24	22	19	16	14	11	8	6	3	0	-2	-5	-7	-10	-13	-15	-18
	320%	34	32	29	26	24	21	18	16	13	10	8	5	2	0	-3	-5	-8	-11	-13	-16	-19
	360%	34	31	28	26	23	20	18	15	12	10	7	4	2	-1	-3	-6	-9	-11	-14	-17	-19
	400%	33	30	28	25	22	20	17	14	12	9	6	4	1	-1	-4	-7	-9	-12	-15	-17	-20

Remarks: Light blue: Cost level of 2020

Fig. 6. Level of carbon levy (\$/tonne CO_2) for avoiding import of embedded CO_2 emissions (left) and additional cost (\$/tonne CO_2) needed as incentive for using H_2-DRI/EAF in Germany (right). Green indicates combinations of cost that favour H_2-DRI/EAF, yellow situations that are unfavourable at a \$/CO_2 level which corresponds to the price for CO_2 allowance in Europe and red combinations that are extremely disadvantageous for H_2-DRI/EAF.

within the EU are also required as the BF/BOF steel production in the EU remains cheaper than H_2-DRI/EAF production. Abandoning the free allocation of emission permits to the steel sector could contribute to such an EU internal adjustment. Then, a price for CO_2 allowances of at least $67/tonne could induce H_2-DRI/EAF to become a competitive option in Europe.

As steel is a classic example for a good used mainly as intermediate for other products, an increase in the prices for steel due to a more climate-friendly production in Europe and the implementation of a cross-border adjustment mechanism will result in increasing cost for other products. Using the input-output table of Eurostat for Europe as basis and employing our price model (Vögele et al., 2022), we assess the price sensitivity of goods on changes in prices of steel. In order to identify the impacts of higher cost for steel (resulting from higher production cost and the introduction of a cross-border tax that equal current cost advantages of H_2-DRI/EAF) we assume an increase in the price of steel by 50%.[2] If this increase in the steel price is completely passed, the prices for fabricated metal products produced in Europe will increase by 5%, the cost of "casting of metals" by 4.1%, the prices for machinery by 1.8% and the prices of motor vehicles by 1.8% (Fig. 7).

The observed influence of prices for steel on prices in other production sectors in the EU will in turn adversely affect competitiveness of these sectors. Hence, the effects of higher steel costs on European exports should be borne in mind and could require the cross-border adjustment mechanism to also subsidize exports. Consequently, such subsidization would go beyond the support of iron and steel exports.

The required high level of the proposed levy most likely exceeding a higher price plainly derived via the ETS might be seen as a major obstacle as it may conflict with international trade regulations. There may be also political opposition from sectors exporting goods (e.g. from companies producing fabricated metal products). The iron and steel sector itself may fear the loss of privileges like the receipt of emission allowances free of charge while the benefits of the cross-border adjustments may appear more uncertain. Retaliation of major steel exporting countries like India and China impend as they could also invent new trade restrictions (both affecting imports and exports). Albeit for other reasons, such activities raising uncertainties for international trade could be observed in the very recent past. Russia recently imposed export duties on sales of several sorts of Russian wood, for example, and China might consider its recent anti-foreign sanctions legislation as a tool to exert influence on foreign companies.

5. Conclusions and policy implications

Implementing a cross border adjustment mechanism (CBAM) in the EU has some appeal. Free allocation of emission permits on emitters listed in the carbon leakage list will decline as the total amount of available permits will shrink in the coming years. Therefore, an alternative way for protecting energy intensive sectors threatened by competitive disadvantages induced by ambitious European climate policy is urgently sought.

In our analysis we examine the impact of a CBAM on the cost of steel production and on prices of downstream outputs using steel as an input. In contrast to other studies (e.g., Medarac et al., 2020; Pardo et al., 2012), we assess cost gaps by conducting intensive sensitivity analyses that include modifications in efficiencies, in prices of key input factors and in transportation cost. In our study we do not only emphasize costs but also differences in emissions resulting from using different production and transportation routes. Since we modify cost factors as well as efficiencies our approach provides information on the sensitivity of this cost gap/emission reduction ratio. Hereby, our approach goes beyond studies that usually dispense with intensive analyses of modifications in cost and emission figures (see e.g. Arens et al., 2017; Wu et al., 2016).

Our study focuses on Hydrogen-DRI as green steel production route. It is straightforward to employ our approach to the assessment of cost gaps of other green steel production routes (see e.g. McKinsey & Company, 2020; Toktarova et al., 2020). It is moreover possible to investigate the sensitivity of the results wrt. key input factors we assume to be fixed in our work. Our approach can be transferred to other industrial sectors like cement, electricity and fertilizers that are scheduled to be included in the carbon border adjustment mechanism (Ecorys, 2013). Since our method is traceable and transparent and since all input data are publicly available, it can easily be employed and extended by other researchers.

Our results raise the concern that the proposed CBAM will not suffice to bring about competitiveness of European green steel production employing the relatively clean H2-DRI/EAF route. This concern holds both within the EU and globally. Globally, because cost of crude steel produced via the H2-DRI/EAF route in Europe tends to remain higher than steel produced via the BOF route and imported from China (despite CBAMs). Therefore, the CBAM does not necessarily eliminate the risk of carbon leakage. The results are in line with findings of e.g. McKinsey & Company (2020). The question remains what the alternative to a CBAM could be that both ensures that external carbon costs are better reflected by steel prices and prevents the exodus of the European steel industry.

A combination of carbon border adjustment measures with the concept of climate clubs is discussed in the literature (see e.g. Tagliapietra and Wolff, 2021), as it will help to price carbon and therefore to 'correct' prices. However, whether it can improve international competitiveness of the European steel production is quite uncertain as – albeit the club limits the scope for carbon leakage and the CBAM helps to 'correct' steel import prices –, European cost disadvantages remain that accrue from other aspects, like higher labour and green hydrogen costs.

Public support of and investments in research on technological improvements (e.g. reducing labour costs) and development of less expensive green hydrogen supply routes should therefore complement CBAM policies in order to reduce the risk of leakage. The EU already seeks to reduce green (and blue) hydrogen prices by exploring (also) other world regions' potentials for cheaper supply (see e.g. Bhandari, 2022) and by developing new funding mechanisms like the H2Global instrument (see e.g., H2Global, 2022).

Within the EU, there prevails a cost advantage of BF/BOF steel production relative to the less polluting H2-DRI/EAF route and this advantage is not directly affected by the adjustment mechanism. Indirectly, however, it tends to support green steel production in Europe: as the free allocation of emission permits tends to fade away if the CBAM is implemented, green steel production within the EU will become more competitive relative to the more polluting steel production routes in the EU. The results support statements of the European Commission (European Parliament, 2021) as well as findings of Römer et al. (2021).

According to the carbon leakage list of the European Commission (2018, 2019), besides the iron and steel industry, energy intensive sectors like "manufacture of pulp", "manufacture of paper and paperboard", "manufacture of cement" and "aluminium production" are exposed to international competition. Like for iron and steel production these sectors require inputs with strongly fluctuating prices (e.g. because they have to be transported costly over longer distances) (see e.g., European IPPC Bureau, 2022; World Bank, 2019). Tools like ours should help to identify the cost of substitution possibilities.

There has to be some caution as e.g. substitution possibilities for dirty production routes may be quite heterogeneous in the different sectors. Therefore, future research should seek to closely inspect these individual sectors and general conclusions should not hastily been drawn from the findings in the steel sector. CBAM aims to reduce the threat of carbon leakage resulting from cost disadvantages. In the short-term measures like promotion of R&D on hydrogen technologies in Europe, support of using black, grey or blue hydrogen that are currently

[2] This assumption is in line with our calculations for 2020 and with results of other studies (e.g. Vogl et al., 2018; Mayer et al., 2019) which expect that the use of H_2-DRI will be linked with 30%–50% higher cost.

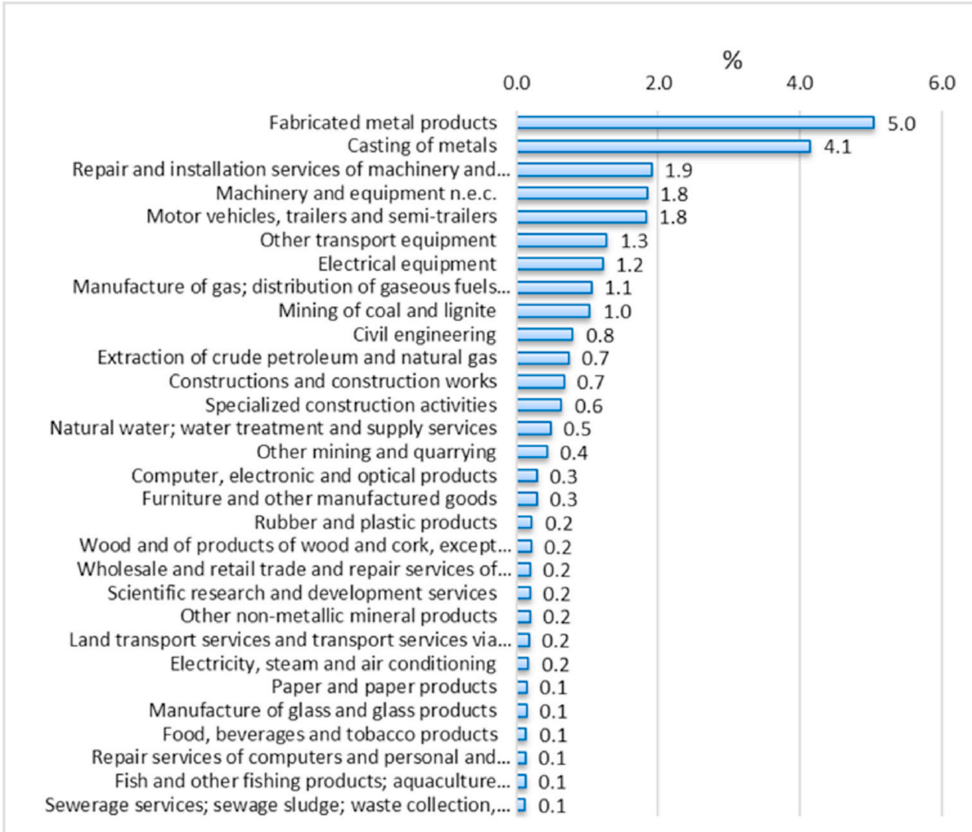


Fig. 7. Changes in prices for goods if an assumed increase in the cost of steel by 50% is completely passed. The numbers are calculated by using the Input-Output table for Germany (Statistisches Bundesamt, 2021). In contrast to the tables of the EU, the sector "Basic metals" is disaggregated. Hence, it is possible to assess impacts of changes in the cost of the production of basic iron and steel.

less costly than green hydrogen can help to reduce domestic production cost and thus, to reduce cost disadvantages and the requirement of high cross-border adjustment.

CRediT authorship contribution statement

Dirk Rübbelke: Conceptualization, Supervision, Writing – review & editing. **Stefan Vögele:** Methodology, Software, Writing, Writing – original draft. **Matthias Grajewski:** Investigation, Methodology, Writing – review & editing. **Luzy Zobel:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Vögele et al. (2022).

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