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RESEARCH ARTICLE

Climate true-cost analysis of industrial goods and its regulatory implications on value chains and global competition

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Abstract

Climate change and its damaging consequences for ecology and humanity is advancing. Industry and its metals sector are responsible for most greenhouse gas emissions. Current costs of industrial goods do not reflect the true costs caused by the externalized climate damages of its production and thus offer no competitive incentive to decarbonize. Additionally, regional climate regulation can lead to competitive distortion. We therefore aim to investigate the impact of climate cost internalization on the metals industry. Using true-cost analysis for an exemplary and widely used metal product, the effects of climate true costs depending on production region, technology, and energy mix, CO_2e taxation and value chain are examined. Based hereon, the impact of internalizing climate true costs together with the introduction of a carbon-border tax on the carbon leakage problem, climate protection, and the cost situation for companies in global competition are investigated. The results of the study show that steel and wire production is responsible for most CO_2e emissions showing significant decarbonization effects by steel recycling whereas production location and logistics play a minor role. On a competitive level, cost internalization has hardly any effect on the product costs because of the currently low CO_2e-taxation rates. Thus, almost no incentive to produce or consume in a climate-protective way is generated, incentivizing production in pollution havens versus highly climate regulated regions. Instead, to realize emission efficiency gains and innovations leading to a competitive advantage of decarbonized products and value chains, a significant increase of CO_2e-taxation rates together with a carbon-border tax is necessary.

KEYWORDS
climate true costs, industrial ecology, industrial goods, industrial sustainability, metal industry, true-cost accounting

1 | INTRODUCTION

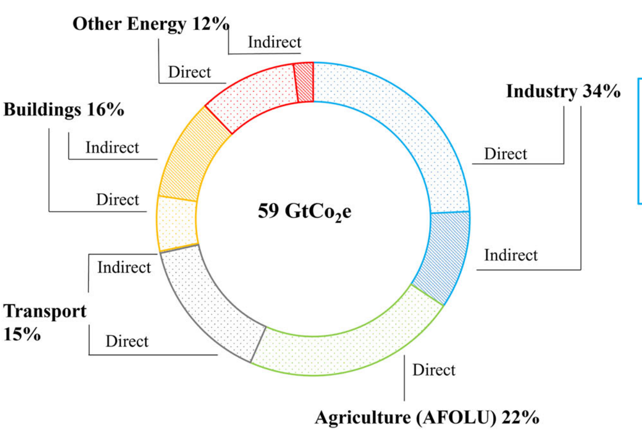
Global rise in temperature present humanity and ecology with a challenge of existential magnitude. Effective climate mitigation demands a focus on those economic sectors responsible for the most of greenhouse gas (GHG) emissions—industry (34%) and agriculture (22%) (Figure 1, left).

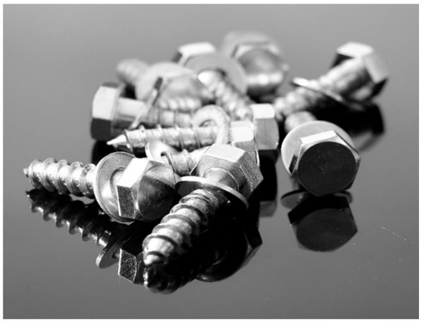
Comprehensive research results for the agriculture sector associated with food production (Mehrens-Raizner & Gaugler, 2022; Pretty et al., 2000; Tegtmeier & Duffy, 2004) have made clear that a differentiated and measurable view of the respective sector is required (Poore & Nemecek, 2018). Pieper et al. (2020), highlight through life cycle assessment (LCA) methods that significantly less emissions arise in the production of plant-based products compared to animal-based products. Based on these stark emission differences of agricultural products, Michalke et al. (2022) and Seubelt et al. (2022) argue that true-cost accounting can play an important role in political measures that aim to fix the currently observed market failure in the agriculture sector and thus create an incentive to significantly reduce GHG emissions.

Industry is responsible for an even higher share of GHG emissions than agriculture. However, it remains an open question if a similar leverage for emission reductions can be uncovered in the industry sector. To answer this question and thereby identify efficient reduction pathways, both policymakers and the concerned industrial companies need greater transparency on product-specific emissions, true costs, and their drivers within the value chain. The metals sector is the largest emitter within industry with 7.8% of global GHG emissions (IPCC, 2022). One of the largest contributors to GHG emissions is steel production because of its use of the blast furnace process which generates large amounts of CO_2e (Hasanbeigi & Price, 2013).

To quantify the environmental impact of the production of goods, LCA plays a central role (Beltran et al., 2020; Hellweg & i Canals, 2014; Kühnen & Hahn, 2017). Assessing environmental impacts, LCA focuses on specific products and services, utilizing life cycle inventory (LCI) databases to describe representative production processes (Steubing et al., 2022). Not free from weaknesses (Klöpffer, 2012), ISO 14040 and ISO 14044 (Finkbeiner et al., 2006) offer a suitable approach for carrying out an LCA (Kühnen & Hahn, 2017; Nuss, 2012). With the aim of harmonizing existing approaches in line with ISO 14040 and ISO 14044, the International Life Cycle Data System compiles “good practice approaches” (European Commission, 2010). Following this approach, Olmez et al. (2016) compare the environmental impacts of different processes and final products in iron and steel production in Turkey, by utilizing SimaPro software and the IMPACT 2002+ impact assessment method finding that steel making has the highest total environmental impact. A more recent study was performed by Chisalita et al. in 2019 also applying LCA methodology. They focused on reducing CO_2 emissions in the iron and steel industry and analyzed the environmental impact of an integrated steel mill with and without carbon capture and storage (CCS) technologies. The results indicate that integrating CCS technologies can significantly reduce global warming potential (GWP), but it may also lead to increased emissions in other categories (Chisalita et al., 2019). Equally applying LCA for the same research field, Suer et al. (2022) examine the environmental impact of primary and secondary steel production. To decarbonize the steel industry, they emphasize the role of breakthrough technologies to achieve environmentally friendly steel production, with a focus on recycling methods for metals and steel.

This study similarly draws from LCA methods. These are solely applied to CO_2e. Because of the focus on CO_2e, we are technically not conducting a full LCA (which would include an assessment of all drivers). Our methodology builds on the true-cost accounting methodology of Hentschl et al.





Exemplary and widely used metal screw product

FIGURE 1 Left: Total global anthropogenic direct and indirect GHG emissions for the year 2019 (in Gt Co_2e) by sector and subsector. Direct emissions estimates assign emissions to the sector in which they arise (scope 1 reporting). Indirect emissions—as used here—refer to the reallocation of emissions from electricity and heat to the sector of final use (scope 2 reporting). Emissions are converted into CO_2 equivalents based on global warming potentials with a 100-year time horizon (GWP_{100}). Percentages may not add up to 100 across categories due to rounding at the second significant digit. AFOLU, Agriculture, forestry and other land use (IPCC, 2022, p. 66); Right: Exemplary products of the metal industry: galvanized and hardened self-drilling hexagon head screws. Underlying data for Figure 5 are available in the Supporting Information (sheet S7).

(2023) and Michalke et al. (2023). However, because our results do not target balancing and controlling practices of businesses, we employ the term "True Cost Analysis" (TCA) to describe our methodology. As this study focuses on the metal industry as the largest industry emitter of GHG, a screw made from carbon steel is selected as an exemplary test object for a widely used metal product (Figure 1, right) and a respective industrial producer of such screws was identified. This study concerns itself with the question which climate costs can be determined for this product and to what extent these costs can be differentiated—according to the production region, technology and energy mix, and CO_2e-taxation rates—across the value chain. Varying these production parameters is necessary as they can have a significant impact on a product's carbon footprint. Emissions from the carbon intense blast furnace process can, for example, be reduced through the use of scrap steel in the electric arc furnace process (Fleiter, 2013). But also, the production region with differences in energy mix plays a role. The German energy mix, for example, has a higher percentage of renewable energies and therefore has a significantly lower emission intensity than the Chinese energy mix (Federal Statistical Office of Germany, 2022; International Energy Agency, 2022; Our World in Data, 2022). Of course, long transportation distances of offshoring also produce additional emissions.

Subsequently, the impact of internalizing climate true costs together with the introduction of a carbon border adjustment mechanism (CBAM) on the carbon leakage problem, climate protection, and the cost situation for companies in global competition will be investigated. More specifically, we are interested in the implications of the ambitious climate goals set by influential economic players like the EU, for example, the Non-Financial Reporting Directive (European Commission, 2014) or the European Green Deal (European Commission, 2022). Does cost internalization lead to a situation in which climate-damaging production in countries with less strict environmental legislation is incentivized (Levinson & Taylor, 2008)? This is the scenario assumed by the "Pollution Haven hypothesis." Or does the contrary "Porter hypothesis" apply, according to which strict and efficient environmental legislation—like that of the EU—leads to efficiency gains as well as more innovation and thus a competitive advantage of more strictly regulated markets (Porter, 1991)? To evaluate these two hypotheses, we have modeled three production scenarios. Hereby, our goal is not to argue for the general validity of either of the two hypotheses. Instead, we compare the three production scenarios to examine how three different CO_2e price levels would determine whether the cost situation in the screw/metal product market is best described by the Porter or the Pollution Haven hypothesis.

The paper is structured as follows: In the subsequent *Methods* section, the methodological TCA approach, its data and the scenarios are presented. The results from the calculation of the scenarios are presented in the consecutive *Result* section. In the *Discussion* section, these results as well as their implications for the—CO_2e price dependent—validity of the Pollution Haven and Porter hypothesis are analyzed. The paper closes with concluding remarks regarding the efficiency of CO_2e taxation and the main sources of emission during the manufacturing process.

2 | METHODS

2.1 | Overall approach

The applied methodology comprises four overall steps (see Figure 2). In the first step, the product system of the object of investigation is developed with an industry partner who also provided real production parameters (= step 1). In a second step, an LCA of the exemplary product system is carried out, distinguishing between three different production scenarios. The aim of the LCA is to determine the GWP_{100}, which forms the basis

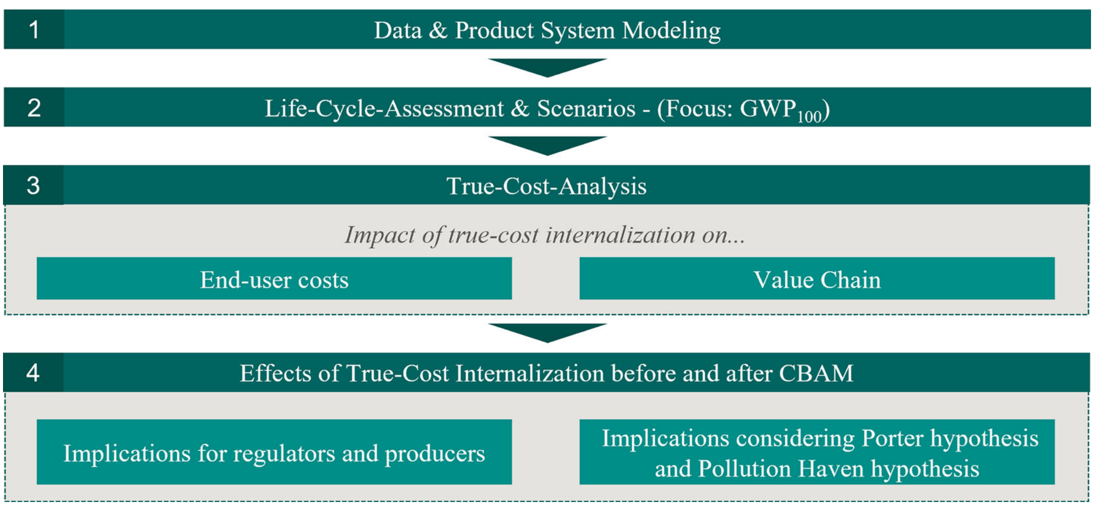


FIGURE 2 Four-step methodology of climate true-cost analysis of industrial goods.

for the subsequent TCA (= step 3). In this way, for the three production scenarios, the actual climate true costs are calculated, which arise from the manufacturing and delivery of the screw product cradle-to-gate. From this, the implications of an internalization of the true costs on the end-user costs and the actors along the value chain are determined. In the fourth step, based on the true-cost results of the three manufacturing scenarios, the implications on the cost structure of screw producers based on the Pollution Haven hypothesis and the Porter hypothesis are analyzed, whereby conclusions are drawn about the global competitive situation of the three exemplary manufacturers before and after the introduction of a CBAM as well as possible implications on climate regulation through internalization.

2.2 | Data and product system modeling

The empirical data for the modeling of the screw production process (see Figure 3) was collected by an industrial partner company at its production facility in Asia. Further scenarios (see Section 2.3) were derived from this real production process and thus represent a derivation of the real production processes. The Supporting Information (sheet S1) provides a description of the LCA modeling parameters, S2 provides the GaBi datasets used for each scenario including reference year of dataset, and S3 provides logistics data and details for each scenario.

The industry partner is a leading tool and solution provider for the construction industry headquartered in the EU and offers products such as power tools, measuring equipment, as well as system solutions and, software with worldwide facilities. As reference product, a galvanized and hardened self-drilling hexagon head screw made from carbon steel with a sales price of 9.93 €/kg of screws was chosen.

2.3 | Life cycle assessment and scenarios

The goal of the LCA is to determine the GWP_{100} in CO_2e in order to calculate the true cost of the screws caused by the externalized climate damages while comparing different production scenarios. It is important to point out that we are not conducting a common LCA, as this would require all potential drivers of environmental impacts to be included. However, this study solely deals with CO_2e. In the following, this part of the study will be called "LCA," but with its exclusive focus on CO_2e, it only reflects a small part of a conventional, fully comprehensive LCA. The functional unit is defined as the production and delivery of 1 kg of the above-mentioned screws for use in the German construction industry (see product system in Figure 3).

The LCA is conducted using the LCA Software GaBi-ts from Sphera with the respective databases "Education" and "Professional" accessed through an Academy license agreement (Sphera Solutions, 2020a, 2020b). and is performed according to DIN ISO 14044 (DIN e.V, 2006), which includes modeling the product system as well as calculating the LCI and derive the required impact category GWP_{100}. To assess the impact category, the method CML 2001 in the latest version from 2016 is applied, which also includes the necessary category GWP_{100}. (CML—Department of Industrial Ecology, 2016).

The amount of GHG emitted by the product system cradle-to-gate can differ significantly. Depending on the variables production location, transportation distances, and technology mix as well as energy mix, the functional unit will have a higher or lower impact on the environment. To evaluate the impact of a variation of these factors on the $GWP_{100,}$ three LCA scenarios have been developed in consultation with the industry partner for which detailed information is provided in Table 1. The three scenarios are defined as follows:

Scenario I: Screw production in a country with rather lax climate regulation using conventional production systems and materials, like blast furnace steel and the regional electricity mix. Following the manufacturing, the product is shipped to the end customer in the EU (Germany).

Scenario II: Regional screw production in a highly regulated region in the EU (Germany) using conventional production systems and materials, like blast furnace steel and regional electricity mix (Burck, 2022). Transportation distances are comparatively short due to regional production.

Scenario III: Regional production of the screw in the EU with a focus on decarbonization achieved using recycled electric arc furnace steel, wind power, and biobased gas. Transportation distances are identical to Scenario II.

The energy and material flows remain identical for all three scenarios as depicted in Figure 3. The product system variation for each scenario was achieved by exchanging the input processes in GaBi, as described in Table 1 as well as by varying the transportation distance.

2.4 | True-cost analysis

In order to quantify the impact of carbon emissions caused by the three manufacturing scenarios in such a way that it is measurable for consumers, suppliers, and regulators the carbon emissions have to be internalized into the product price using TCA (Hentschl et al., 2023; Michalke et al., 2023). In order to calculate these climate true costs, the method convention 3.1 for calculating environmental costs published by the German Federal Environment Agency (GFEA) is used (Bünger & Matthey, 2020). For the base year of 2020, GFEA calculates with two different true-cost rates depending on whether a discount rate of 1% according to the present preference of classical environmental economics is applied (Siebert, 1978, p. 150) or if the true costs are not discounted reflecting intergenerational fairness which is consistent with a discount rate of 0%. As a third true-cost

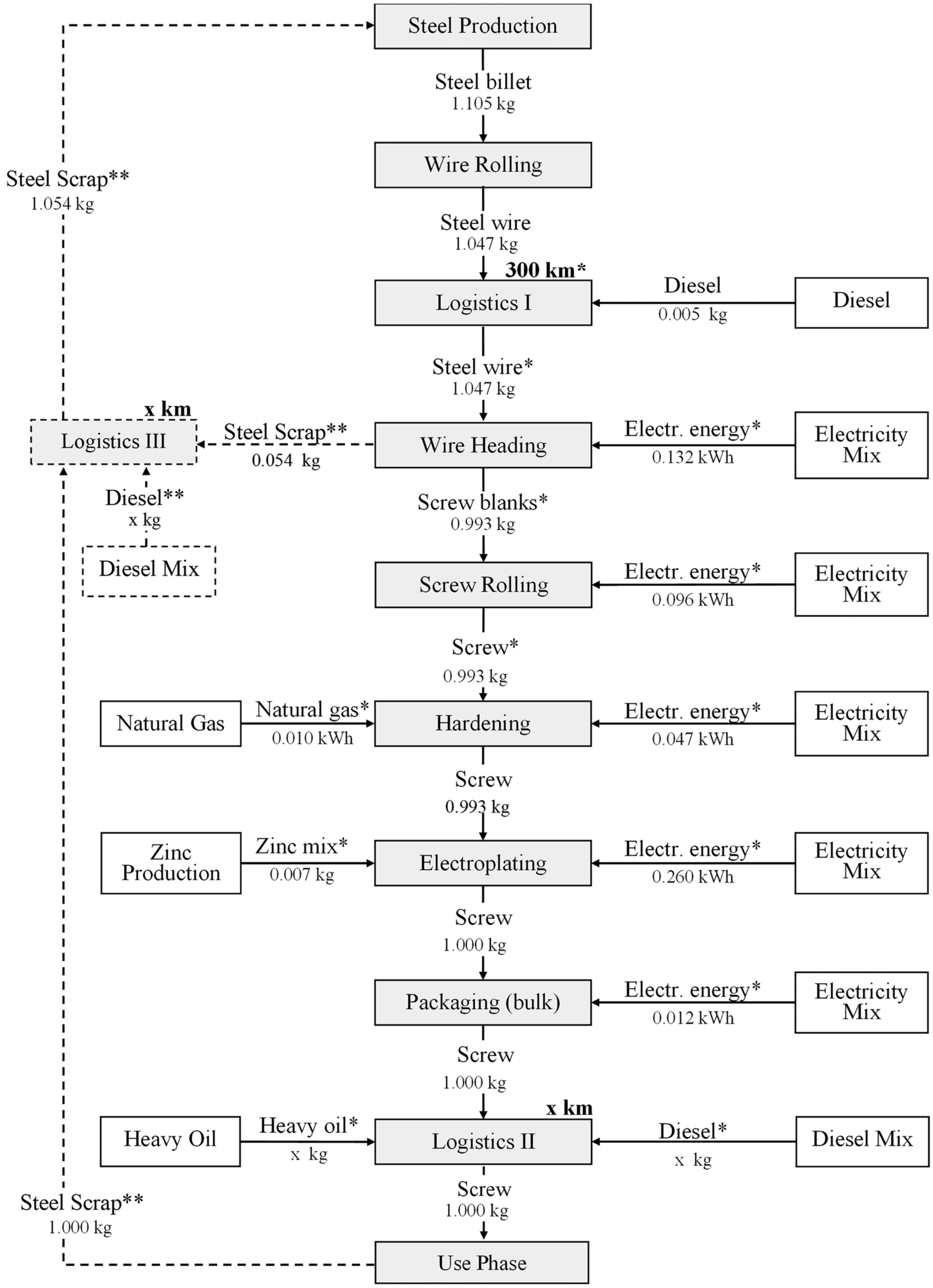


FIGURE 3 Product system for the described functional unit. Actual production parameters, which were collected by the industry partner, are marked with "*." These parameters are not varied during the scenario analysis. All sub-processes and flows that are not marked with "*" will be changed during the scenario analysis in GaBi based on the methodology as described in Sections 2.3 and 2.4. Production parameters marked with "**" represent the transportation process of the simplified re-introduction of steel scrap generated during production or at the end of the screw's lifespan back to the steel mill. This sub-process was only applied in Scenario III, hence the dashed lines. The sub-processes and transportation distances modeled in GaBi can be viewed in the Supporting Information (sheets S2 and S3).

value, the current climate costs that EU-based producers must realistically pay within the current EU emission trading system (ETS) are used as a benchmark of the current situation. For the true-cost calculation the following three cost rates are defined.

Cost Case A amounts to 0.043€/kg CO_2e and reflects the average price an EU-based company currently must pay for the effective emission of 1 kg of GHGs due to the EU-ETS. Throughout the year 2022 the price of one EU-ETS emissions allowance averaged out at around 0.075€/kg CO_2e

TABLE 1 Description of the varying production parameters of the three scenarios. Corresponding processes were used for modeling the scenarios derived from the product system depicted in Figure 3.

	Scenario I	Scenario II	Scenario III
Scenario description	Conventional production in a pollution haven (rather lax climate regulation) and export to EU-based customer (Germany)	Conventional, regional production in a country with high environmental regulation	Regional manufacturing in a country with high environmental regulation and a focus on decarbonized production using recycled steel
Production location	Asia Pacific (China)	EU (Germany)	EU (Germany)
Customer location	EU (Germany)	EU (Germany)	EU (Germany)
Steel production	Blast furnace in China with low percentage of steel scrap added (2%) (Sphera Solutions, 2020c)	Blast furnace in Germany with high percentage of steel scrap added (20%) (Sphera Solutions, 2020d)	Electrical arc furnace in Germany with 96% steel scrap used
Electricity mix	Electricity Mix China	Electricity Mix Germany	100% Windpower Germany (except electric arc furnace process)
Gas type	Natural gas China Mix	Natural gas Germany Mix	100% biobased gas Germany
Length of supply chain	Truck diesel China from producer to harbor (30 km)	Truck diesel Germany from producer to customer (300 km)	Truck diesel Germany from producer to customer (300 km)
	Container ship China from China to Germany (20.000 km)	-	Truck diesel Germany from scrapyard to steel mill (300 km)
	Lorry diesel Germany from harbor to customer (300 km)	-	-

(ember-climate.org, 2021). Taking into account the share of free ETS certificates allocated in 2020, which is exemplary derived from the emissions report of the German Emissions Trading Agency, a realistic 0.043€/kg CO_2e results (Deutsche Emissionshandelsstelle, 2021).

Cost Case B amounts to 0.195€/kg CO_2e and reflects the climate true costs in the base year 2020 calculated by the GFEA when presence preference is applied and future true costs are discounted at a rate of 1% (Bünger & Matthey, 2020, p. 8) which is in line with the climate true cost of 209$/t CO_2e the IPCC calculated in its fifth assessment report (IPCC, 2014, p. 691).

Cost Case C amounts to 0.680€/kg CO_2e and reflects the climate true costs in the base year 2020 calculated by the GFEA when intergenerational fairness is preferred which means that future costs are not discounted (Bünger & Matthey, 2020, p. 8).

After all necessary data has been collected, the true cost, true price after internalization as well as the resulting true-cost surcharge compared to the initial price of the screw were calculated for each cost-case and scenario along the value chain using the calculations as laid out in Table 2.

3 | RESULTS

3.1 | Impact on global warming potential

The GWP_{100} of the three scenarios GWP_s is shown in Figure 4. Here, the product system from Scenario I at 3.25 kg CO_2e/kg screws causes the most CO_2e emissions of the three manufacturing alternatives. The screw from Scenario I produced in Asia (China) causes 17.3% more GHGs in a cradle-to-gate consideration than would be the case in a technically identical production in mid-Europe in Scenario II. Compared to Scenario III, Scenario I cause more than three times the amount of GHG emissions.

3.1.1 | Scenario I—Production in pollution haven and export

A detailed examination of the GWP from Scenario I reveals that the production of the steel wire cradle-to-gate, that is, from the mining of the iron ore to the rolling of the wire in the steel mill, is responsible for 78.7% of the total CO_2e emissions of the screw. The production of the screw at the industrial partner gate-to-gate causes 15.1% of the total GHG emissions. The transport of the screws from the manufacturer's plant in China to the end user in Germany accounts for only 6.2% of the emissions of the entire product system, and is thus relatively low despite the long transport distance of 20,330 km.

TABLE 2 Description of calculations performed during the true-cost analysis.

Calculation of the true-cost $c_{s,f}$	
Description	The calculation of the true cost of the three LCA scenarios for each cost case.
Calculation	$c_{s,f} = GWP_s \cdot k_f$ (1)
Variables	$c_{s,f}$ = True cost of scenario s when applying the CO_2e true-cost rate of case f GWP_s = Global warming potential (100 years) cradle-to-gate in scenario s k_f = Climate true-cost rate in cost-case f
Calculation of the true-price $p_{s,f}$ **after internalization**	
Description	The true-cost adjusted product-price of the screw after internalization is calculated.
Calculation	$p_{s,f} = P + c_{s,f}$ (2)
Variables	$p_{s,f}$ = True price of the screw in scenario s when applying the CO_2 true-cost rate of case f P = Offer price of the screw in case of direct sale by the partner in practice
Calculation of the true-cost surcharge $z_{s,f}$ **after internalization**	
Description	To make the true-cost impact comparable, the true cost of each scenario are set into relation to the selling price of the screw.
Calculation	$Z_{s,f} = C_{s,f} \div P \cdot 100$ (3)
Variables	$z_{s,f}$ = CO_2e true-cost surcharge on the offer price of the screw in scenario s when applying the true-cost rate of case f
Calculation of true-cost $c_{y,f}$ **and respective surcharge** $z_{y,f}$ **along the value chain**	
Description	To analyze the carbon true-cost impacts on the value-chain product system is simplified into three major steps. The steel and wire production, the screw production including all necessary transportation steps to the gate of the screw producers distribution based in Germany and the delivery to the end customer.
Calculation	$c_{y,f} = GWP_y \cdot k_f$ (4) $z_{y,f} = \frac{c_{y,f}}{q_y} \cdot 100\,\%$ (5)
Variables	$c_{y,f}$ = Caused climate true cost of process step y when applying the CO_2e true-cost rate of case f GWP_y = Global warming potential (100 years) cradle-to-gate in process step y $z_{y,f}$ = CO_2e true-cost surcharge on the offer price of the product from process step y when applying cost case f q_y = Sales price of (intermediate) product from process step y

3.1.2 | Scenario II—Regional production with current EU environmental regulations

The production of the steel wire, based on blast furnace steel from mid-Europe, emits cradle-to-gate with 2.41 kg CO_2e slightly less GHG than in Scenario I. In terms of the total climate footprint of Scenario II, the process step of steel and steel wire production, at 87.0%, takes up an even larger share than is the case in Scenario I (also due to lower logistic effort with 1.4% of the emissions due to short distance between producer and user). The process step of the screw production causes 11.9% of the emissions. From a climatic point of view, the sub-process step of screw production is thus 32.7% more efficient in mid-Europe than in China, which is mainly due to the higher share of renewable energy in the German electricity mix.

3.1.3 | Scenario III—Regional production with low-carbon steel

Scenario III reflects a production with low-carbon recycled steel as described in Table 1. Here, the steel wires were produced using recycled steel from the electric arc furnace process. In Scenario III, 0.77 kg CO_2e are emitted, which is a significant reduction (over 70%) compared to the first two scenarios.

3.2 | Impact on climate true costing

Based on the GWP_{100}–result of the Scenarios I, II, and III, the three cost rates k_f from Section 2 are applied. The result is a new true product price $p_{s,}$ for each scenario (see Figure 5) which indicates how much the screw should cost the end user in total if the climate externalities caused by its production and transportation are priced in. The true-cost surcharge z_s provides information on the relative rate of cost increase due to internalization. For better comparability, it is assumed that manufacturers in low-regulated pollution havens (e.g., Scenario I), are also obliged to internalize climate costs through a CBAM.

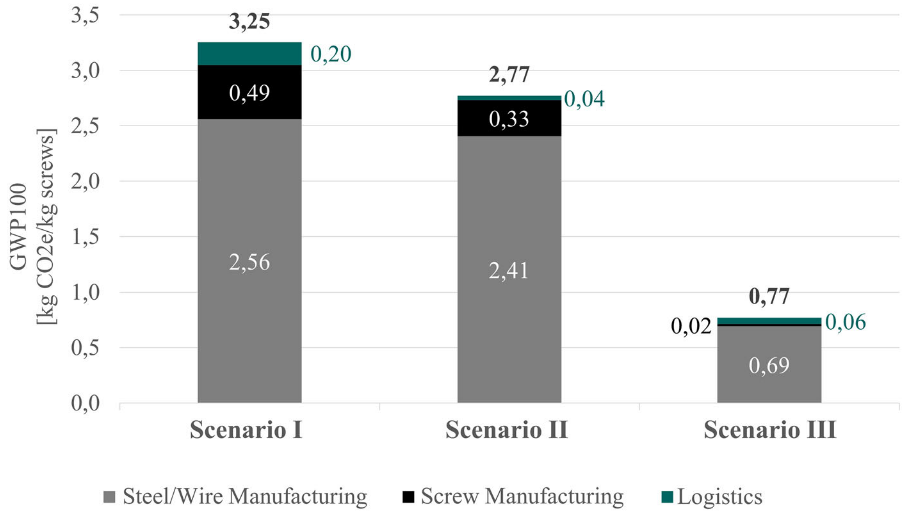


FIGURE 4 GWP_{100} results of the three LCA Scenarios I, II, and III subdivided into shares along the value chain. The results for each scenario have been aggregated into three clusters the steel and steel wire manufacturing, the actual screw production and all logistics or transportation processes in the production system combined. Underlying data for Figure 5 are available in the Supporting Information (sheet S7).

3.2.1 | Case A: Cost rate of average EU-ETS costs

As can be seen in Figure 5, a true-cost internalization in the amount of the average EU-ETS price of 0.043 €/kg CO_2e increases the true prices only slightly in all three manufacturing scenarios. The price of the screws produced in Asia, China and exported to mid-Europe increases by only €0.14/kg (1.4%) in Scenario I, by €0.12/kg in Scenario II, and by €0.03/kg (0.3%) in Scenario III being even less significant. Although regional manufacturing from Scenario II emits 14.8% less CO_2e than it does in Scenario I, the true-cost surcharge of Scenario II is just 0.2 basis points lower than that of Scenario I.

3.2.2 | Case B: Cost rate of presence-preferred true cost

If the case of the Federal Environment Agency's (Bünger & Matthey, 2020) present-preferred true climate impact costs of 0.195 €/kg CO_2e is applied, this leads to an increase in the end-user prices of the screw from 1.5% in the low-carbon Scenario III, over 5.4% in regional production Scenario II to 6.4% in Pollution Haven Scenario I.

3.2.3 | Case C: Cost rate of generation-appropriate true cost

With an internalization in the amount of the generation-appropriate true cost, 1 kg of screws produced in Scenario I becomes 22.3% more expensive. In the case of regional production in mid-Europe, the price surcharge of 19.0% is slightly lower than in Scenario I, but here, too, a significant increase in end-user costs and thus a heavy burden on end users or contractors is to be expected. In comparison, manufacturing in the low-carbon Scenario III results in a price increase of only 5.3%, which is less than one third of the increase from Scenarios I and II. The screws from Scenario III can be offered at a selling price of 10.45 €/kg, which is 13.9% cheaper than the selling price from Scenario I of 12.14 €/kg, if all costs of the climate impact are included. Thus, only for generation-appropriate cost case C, a significant effect between the low-carbon Scenario III and the current status quo in industry can be assumed.

3.3 | Impact on value chain

The internalization of climate true costs leads to additional costs for the manufacturing industry. For example, in the current EU ETS, the costs of GHG emissions have to be paid by the emitters themselves, that is, the manufacturing operators of industrial plants, on a polluter-pays basis (Deutsche Emissionshandelsstelle, 2021). Consequently, when examining the impact of internalizing the climate true cost, it is necessary to consider

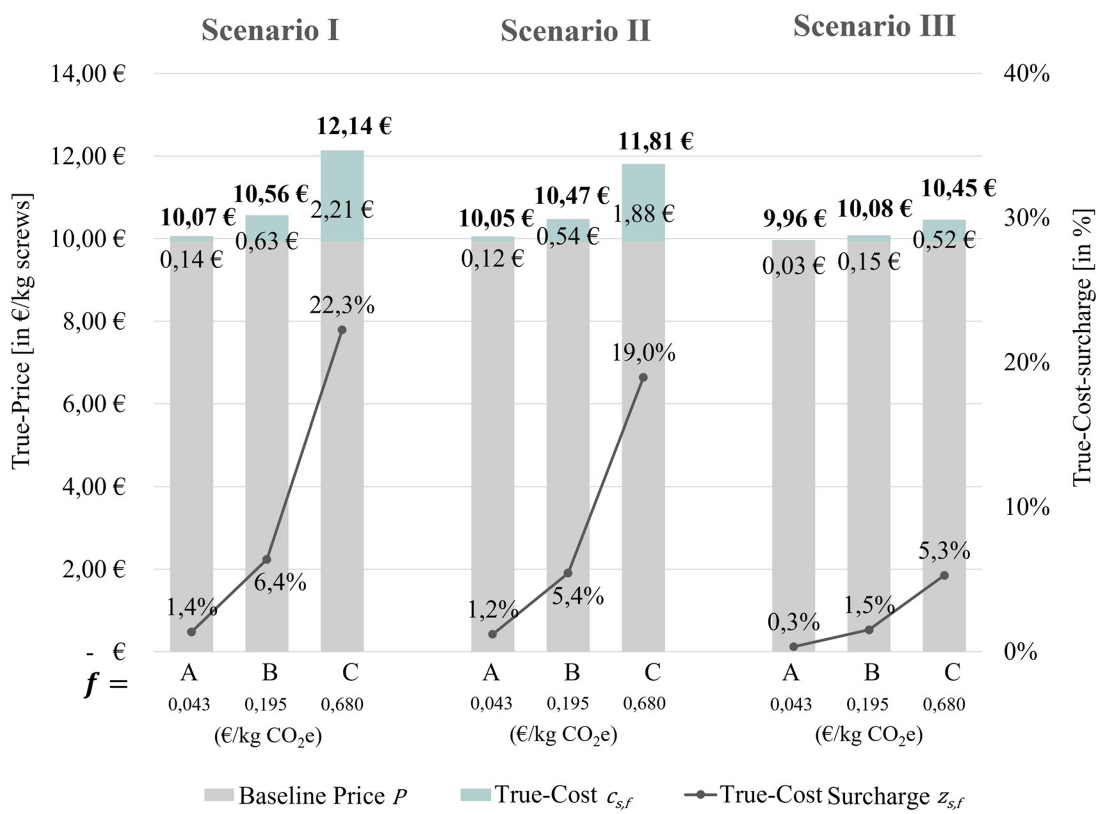


FIGURE 5 True-cost consideration in the three Scenarios I, II, and III plotting the climate true cost $c_{s,}$ of the respective cost case f = A, B, and C, the original price P of the product and the respective true-cost surcharge $z_{s,f}$. Underlying data for Figure 5 are available in the Supporting Information (sheet S7).

not only the consequences for end users, but also those for all producers and steps along the value chain. Therefore, the TCA has been carried out for an aggregated version of the value chains of all three scenarios (see Table 3).

The value chain of the screw in the cradle-to-gate production system comprises three basic intermediate products and actors (steel wire production, screw production, and logistics to end user). Of these, each producer must individually pay the true cost for the internalization of GHG emissions in the amount of the three cost cases f. When evaluating the impact on intermediate suppliers, the most relevant factor is how much true cost they must pay in relation to the selling price of their intermediate product. In this way, the exposure of each producer to climate regulation along the value chain can be well assessed.

It can be observed that the producer from sub-step $y = 1$, that is, the production of the steel and wire, has to bear by far the largest true-cost surcharge. This is especially true for Scenarios I and II due to the carbon intense blast furnace process. Already in cost case f = A, the steel and wire producer of Scenario I must pay a cost premium of 18.3% (11.5% in Scenario II) on its selling price leading to significant economic losses on his part. For cost case B, a price premium of 83.2% for Scenario I (52.1% for Scenario II) would be at hand. In cost case C, the steel and wire producer would be responsible for compensating climate costs in the amount of 2.9 times of his sales price leading almost to price parity of Scenarios I and II. The producer of steel and wire in low-carbon Scenario III instead must bear significantly lower price surcharges in all cost cases due to significantly lower GHG emissions in the order of 3.5–3.7 versus Scenarios I and II.

Moving forward along the value chain, the screw producer is hardly affected by the internalization of climate costs in all three cost cases. The same applies to the final step, where a logistics service provider delivers the product to the end customer.

4 | DISCUSSION

4.1 | GHG emissions and value chain

In all scenarios, the production of steel and wire is responsible for more than three quarters of the total GHG emissions. The main driver of emissions in Scenarios I and II is the energy-intensive blast furnace process. By using recycled steel in the electric arc furnace process in Scenario III, the GHG

TABLE 3 Results of the true-cost analysis for three aggregated steps of each scenario for the three cost rates A, B, and C each including the producers along the value chain and its respective subproducts.

		Unit	Steel and wire production			Screw production			Transport to end customer		
Process step y		-	1	1	1	2	2	2	3	3	3
Scenario		-	I	II	III	I	II	III	I	II	III
GHG emissions GWP_y		kg CO_2e/kg product	2.56	2.41	0.69	0.51	0.34	0.06	0.19	0.02	0.02
Product price q_y		€/kg product	0.60€	0.90€	0.90€	9.93€	9.93€	9.93€	13.82€	13.82€	13.82€
Source			(Made-in-China.com, 2023)	(Deutscher Schraubenverband E.V., 2021)		(data from industrial partner company)			(Cargoboard GmbH, 2022)		
Case $f = A$ (0.043€/kg CO_2e)	True cost $c_{y,A}$	€/kg product	0.11€	0.10€	0.03€	0.02€	0.02€	0.00€	0.01€	0.00€	0.00€
	Surcharge $z_{y,A}$	%	18.3%	11.5%	3.3%	0.2%	0.1%	0.0%	0.1%	0.0%	0.0%
Case $f = B$ (0.195€/kg CO_2e)	True cost $c_{y,B}$	€/kg product	0.50€	0.47€	0.14€	0.10€	0.07€	0.01€	0.04€	0.00€	0.00€
	Surcharge $z_{y,B}$	%	83.2%	52.1%	15.0%	1.0%	0.7%	0.1%	0.3%	0.0%	0.0%
Case $f = C$ (0.680€/kg CO_2e)	True cost $c_{y,C}$	€/kg product	1.74€	1.64€	0.47€	0.35€	0.23€	0.04€	0.13€	0.01€	0.01€
	Surcharge $z_{y,C}$	%	290.0%	181.8%	52.4%	3.5%	2.3%	0.4%	0.9%	0.1%	0.1%

emissions of steel wire production can be reduced by over 70%. Thus, taking the screw product as reference for the metal industry, the greatest lever in changing the GWP and CO_2e footprint lies in the raw material production process, which is often placed in regions with low climate regulations (World Steel Association, 2022, p. 9).

The production of the screw itself causes relatively low GHG emissions in all scenarios, with a maximum of 0.49 kg CO_2e (Scenario I) per kilogram of screws produced. By using renewable energies as assumed in Scenario III, the screw manufacturing process can almost completely decarbonized. Despite the long transport distance from China to Germany in Scenario I, the logistics process is responsible for only 6.2% of the total emissions. In Scenarios II and III, emissions caused by transport are negligible.

In summary, a comparison of the scenarios shows that it is the steel used and its manufacturing process that has the greatest influence on the climate footprint of the end product at the customer's site. The use of recycled steel from the electric arc furnace represents the largest decarbonization lever. The choice of steel manufacturing technology is thus the highest priority when evaluating potential decarbonization measures for metal products such as screws.

4.2 | Climate true costing

Based on the LCA, a TCA for three different cost cases was carried out, with the aim of determining how much more expensive a metal product would be if all external consequential CO_2e climate damages were internalized by climate regulation.

The evaluation of the consequences for end-user costs shows that true-cost internalization in cost case A, where the cost rate of 0.043 €/kg CO_2e represents the averaged prices in the current EU ETS, leads to only a very small price increase in all scenarios. End users will hardly notice and consequently not adapt a more sustainable consumer behavior. The incentive for producers to take decarbonization measures in the context of cost competition is low.

Applying cost case B, the internalization of true costs leads to an increase in both conventional manufacturing Scenarios I and II. Still, this increase is relatively low, for example, compared to (and well below) the expected inflation rate of the EU in 2022 (Lang & Ionescu, 2022). Furthermore, it is noticeable that the selling price of the screw produced regionally within the EU (Scenario II) is only 1.0% below that of the imported product from Scenario I. Taken in consideration that, for example, labor costs are significantly lower in Scenario I than in the other scenarios (Grömling et al., 2019), it is unlikely that the minor price difference based on the internalization of carbon costs would result in a competitive advantage for producers in the EU.

Only when applying the generational true-cost rate from cost case C, end-user prices could rise noticeable, imposing a significant burden on producers and users. Here, if the true cost are directly forwarded to the customer, the lower carbon footprint of the screw from Scenario III represents an incentive to buy, since its price after internalization can be up to 16.2% (1.69€/kg) lower than that from Scenario I (and 13.0% lower than Scenario II). Decarbonization through recycling hence represents a quick win, since the price of recycled steel is currently lower than that of new produced steel (Taroni Metal Recycling, 2020; U.S. Bridge, 2022). However, in reality the low availability of recycled steel represents a bottleneck to this approach, as the volume of new produced steel is significantly higher than available recycled steel (ArcelorMittal, 2023). But according to McKinsey (Hydrogen Council, 2021) already at a cost rate of 0.045€/kg CO_2e, there is cost parity between steel produced using green hydrogen and conventional blast furnace steel. On the other hand, Scenario I offers cost advantages in terms of labor, process, and material costs. However, even when taken into consideration those lower manufacturing costs of about 30%—according to the industry partner—of Scenario I versus the other scenarios, there is still a cost advantage of Scenario III. Assuming a share of manufacturing costs of 50% (= 4.97€/kg) on the original unit price—again according to the industry partner—the cost savings of Scenario I are thus 15% (1.49€/kg) in relation to the unit price. Hence, the true-cost advantage of Scenario III (1.69€/kg) is still at hand and will be even increased when adding the additional shipping costs from China to Germany (0.25 €/kg) of Scenario I.

In summary, despite the high GHG savings of Scenario III compared to Scenario II and especially Scenario I, no changes in the production system and thus GHG reductions are to be expected at the current CO_2e cost rates (A and B). The savings due to the lower CO_2e footprint of Scenario III are too small. As already mentioned in the previous subsection, the producers of steel and wire being responsible for the largest share of the GWP and thus carrying over 80% of the CO_2e-costs (and receiving relative low sales revenues) are fostered to migrate (or stay) in a pollution haven region. Only in cost case C combined with the implementation of a cross-border tax a CO_2e cost advantage based on the additional carbon true costs could be recognizable as an incentive for a change in the production system by the industry.

4.3 | Global competition and regulations

After the effects on the GWP and the true-cost internalization along the value chain have been examined, the consequences of climate regulatory measures on international cost-competitiveness for the metal (screw) industry is analyzed.

4.3.1 | Pollution haven

Without a CBAM—which represents the current competitive situation when comparing an EU-based manufacturer with one from a pollution haven—the producers from Scenarios II and III, which manufacture within the EU, would have to fully internalize their emitted GHG emissions in the amount of the respective cost cases, which partly results in significant additional costs. The producer from the Pollution Haven (Scenario I) does not face any climate-related additional costs.

A regionally limited, unilateral internalization, as represented by the EU-ETS, has the consequence that the producer from Scenario II is burdened with true-cost surcharges in the amount of up to 18.6% in cost case C, from which its profitability or price competitiveness suffers. Compared with Scenario I, both Scenario II and low-carbon Scenario III have significant competitive disadvantages. These are further reinforced by rising prices for emission certificates hence increasing internalization of climate costs. Taken into consideration the lower conventional manufacturing costs in a pollution haven versus Scenarios II and III, their competitive disadvantage will be even enlarged. For manufacturers from Scenarios II and III, migration to a pollution haven could therefore be a strategy for cost minimization from a rational economic point of view. This situation is widely known as carbon leakage (European Union, 2017). Of course, the costs for migrating to a new production location itself must also be taken into consideration.

According to the Pollution Haven hypothesis or the carbon leakage problem, a situation in highly regulated region results, where climate regulation, like the EU-ETS, create (additional) cost disadvantages for regional producers which incentivize migration to pollution havens instead of investing into decarbonization. Since emissions in these low regulated havens are with lower or even no surcharge, in many cases producers in pollution havens emit higher carbon emissions than their peers in high regulation countries, like in the EU. The validity of the Pollution Haven hypothesis is therefore strengthened by our research when comparing LCA results from Section 3.2, where conventional screw manufacturing in Germany (Scenario II) produces 14.8% lower CO_2e emissions compared to that in China from Scenario I (Levinson & Taylor, 2008).

4.3.2 | Porter hypothesis

To eliminate these competitive disadvantages and to restore the climate protection effect many regions and countries plan to introduce a CBAM. As a result, manufacturers from pollution havens will also have to pay for the climate damage they cause if they want to sell their products within a region with high emission regulations. In the context of Porter's hypothesis, strict but efficient regulation can lead to competitive advantage instead of industrial extinction and migration, it is worthwhile to analyze whether CBAM potentially is a feasible regulatory measure to achieve such a beneficial situation strictly focusing on cost-competitiveness at the example of the screw production.

For the producer from the pollution haven (Scenario I), this means that it now has to bear the highest carbon true cost in all three cost cases due to its high GHG emissions (Figure 5). This means that solely in relation to the add-on climate true costs the conventional manufacturer in Scenario II has a slight true-cost advantage. However, as outlined in the previous Section 4.2, this true-cost advantage is still lower than the advantage of up to 30% lower manufacturing costs of Scenario I. This means that a CBAM based on climate true cost of case A or B will not be a strict enough mechanism to efficiently incentivize a prioritizing of decarbonization over offshoring.

The low-carbon Scenario III, on the other hand, can minimize the negative consequences of rising CO_2e prices due to the significantly reduced GHG footprint and realizes a climate cost saving of 76.5% in comparison with Scenarios I and II. However, for cost cases A and B, the savings in manufacturing costs of Scenario I are still higher than the financial burden or the increased true climate carbon costs. As outlined in Section 4.2, from a cost-competitive perspective only for cost case C, manufacturers in Scenario II are incentivized to continue regional operations while optimizing their processes in terms of GHG efficiency through environmental innovations instead of migrating to a pollution haven.

Thus, the instruments of the ETS (e.g., of the EU) in combination with an effective carbon-border tax potentially represent an effective, that is, efficient, regulatory mechanism that is strict enough, that is, causes high enough carbon costs, that it creates an environment where decarbonization becomes an actual lever to minimize emissions in order to gain competitive advantages. The stricter the system is set, the more effective the incentive to decarbonize, as cost case C shows. Consequently, through a comprehensive carbon-border tax and rising ETS prices, the regulatory mechanism would promote the requirements of Porter's hypothesis which postulates that environmental regulation must be both efficient and stringent to drive climate innovation, leading to competitive advantages for regional producers and subsequential industrial decarbonization (Porter & van der Linde, 1995).

4.4 | Conclusion, limitations, and further research

The results of the study show that for screw manufacturing, steel and wire production is responsible for most CO_2e emissions showing significant decarbonization effects by steel recycling whereas production location and logistics play a minor role. On a competitive level, climate cost internalization has hardly any effect on the product costs because of the currently low CO_2e-taxation rates. Hence, almost no incentive to produce or consume in a climate-protective way is generated incentivizing production in pollution havens versus highly climate regulated regions. Instead, to realize emission efficiency gains and innovations leading to a competitive advantage of decarbonized products and value chains a more than a 10-fold increase in CO_2e-taxation rates together with a carbon-border tax is necessary.

In the analysis of the climate true-cost internalization in combination with a CBAM on competition in the screw industry, a uniform sales price is assumed. Since the focus of the present analysis is on the impact of climate regulation, the competitive analysis includes only those costs that manufacturers incur because of emitting GHG. Other factors that can lead to a cost advantage and thus influence the choice of location, such as regional raw material, wage, or investment costs have only been approximated. In practice, however, they must be considered in detail from a holistic corporate perspective.

To gain further insights into the challenges facing the metals industry because of increasing climate protection measures, the procedure described could be enlarged by integrating the mentioned different cost structures for different scenarios. Furthermore, the study can be applied to other exemplary products than the screw and compared with its results. It is also conceivable to apply the methodology to other industries, such as the minerals or chemical industry. In this way, it can be compared whether most emissions also occur in these industries, particularly at the beginning of the value chain, as is the case in the metal industry. Thus, the effects of stricter climate regulation along the different value-chain steps and possible distinctions in climate taxation can be analyzed to ensure a balanced triple-bottom line.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The GaBi modeling data that support the findings of this study are available in the supporting information (sheet S2) of this article. The logistics data that support the findings of this study are available in the supporting information (sheet S3) of this article. The empirical production data that support the findings of this study are available from the authors with the permission of the third party industrial partner upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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