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Multilayered assessment of a product's greenness in the context of greenshoring strategies and carbon border taxation systems: an application to the iron and steel industry in the EU

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ABSTRACT

Climate change represents one of the most urgent challenges of our time, requiring a profound transformation of economies and production methods. Major economies are setting climate neutrality targets and introducing carbon pricing policies to internalize environmental externalities. The European Union (EU) aims to achieve climate neutrality by 2050. To support this, the EU launched its first Emissions Trading Scheme (ETS) in 2005. However, the ETS has been linked to carbon leakage, a phenomenon where industrial production relocates outside the EU to countries with less stringent environmental laws. To mitigate this and promote global decarbonization, the EU is operationalizing the Carbon Border Adjustment Mechanism (CBAM), which applies a carbon price to imports equivalent to that imposed on domestic products. This mechanism is expected to generate financial impacts on imports and incentivize a recent industrial relocation strategy known as greenshoring.

This paper reviews existing industrial relocation strategies and develops a definition of greenshoring based on literature. Within this framework, a green product is defined and a multilayer framework to assess the greenness of a product is presented. The methodology is applied to the iron and steel sector to evaluate the environmental performance of both the overall industry and three specific products across the EU and its main exporting partners. The calculated CO_2 emissions per ton of product are then used to estimate the potential financial impact of CBAM, providing insights for evaluating greenshoring strategies and assessing the EU iron and steel sector performance among its major competitors.

1. Introduction

The transformation of global economies and production methods is essential to address the climate change [1]. For this purpose, major economies are setting climate neutrality targets and carbon pricing policies are becoming increasingly diffused instruments to address market externalities, now covering 24 % of global GHG emissions [2]. To meet the targets set by the Paris Agreement and limiting the increase of global temperature to well below 2 °C above pre-industrial levels by the end of the century [3], both the average price and coverage of carbon pricing systems must increase [4].

The European Union (EU) has set the goal to achieve climate neutrality by 2050, with an intermediate target of reducing emissions by 55 % by 2030 compared to 1990 levels [5]. To achieve these goals, emissions from key sectors must be significantly reduced. In 2022, energy supply, transport, and industry represented 71.5 % of the EU's GHG emissions [6]. The need to accelerate decarbonization in these sectors has led to the introduction of two Emissions Trading Systems. The first, the European Union Emission Trading System (EU ETS), became operational in 2005 and currently covers 38 % of the EU's emissions. It includes sectors such as electricity and heat generation, industrial manufacturing, aviation, and maritime transport [2]. The second system (EU ETS2) will become fully operational in 2027 and will extend carbon pricing coverage to fuel combustion in buildings, road transport, and additional sectors (small industry, manufactory and construction not included in the current ETS system) [7,8]. ETS 2 will work in parallel to

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the current ETS regulating fuel suppliers to the market in the mentioned end-use sectors for combustion purposes.

As of the most recent data available from the World Bank Dashboard (April 1, 2024), the EU ETS had a carbon price of €57.03 (US$61.30) [2]. Since its implementation, the EU ETS has contributed to a 47 % reduction in emissions from the power and industrial sectors compared to 2005 [9]. However, part of this reduction can be attributed to the relocation of production outside the EU to countries with less stringent environmental laws, a phenomenon known as carbon leakage [10,11]. To reduce the carbon leakage and encourage cleaner industrial production in non-EU countries, the EU has introduced the Carbon Border Adjustment Mechanism (CBAM) [12]. This policy instrument aims to apply a carbon price to imported products equivalent to that imposed on domestic production under the EU ETS. Initially, CBAM will cover sectors that are both carbon-intensive and at high risk of carbon leakage: cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen [12]. CBAM is currently in a transitional phase (2023–2025) and will become operational in 2026.

Starting from 2026, EU importers of goods covered by CBAM will be required to declare the CO_2 embedded emissions generated in the production of their products and purchase the corresponding number of CBAM certificates. The certificates price will be based on the weekly average auction price of the EU ETS (in €/tCO_2), deducting carbon costs already paid in the origin country [12]. This mechanism is expected to have direct financial implications on the price of imported products. Consequently, greenshoring strategies could be applied to mitigate these financial repercussions. While greenshoring is a nascent concept without a formal definition in literature, this paper provides an analysis of established shoring strategies (offshoring, reshoring, nearshoring, and friendshoring) to properly contextualize it. The definition of greenshoring is provided as the relocation of industrial activities aiming to reduce the carbon footprint of supply chains. To effectively guide greenshoring strategies in response to the introduction of CBAM it is essential to evaluate a definition of a green product within this context and to identify a methodology able to assess the greenest option. This paper addresses this gap by proposing a clear and quantitative definition of a green product and by developing a multilayered integrated framework for its assessment. The framework is first presented methodologically and then applied to the iron and steel sector as a case study. The sector's emissions are hard-to-abate, due to the high heat requirements, the use of carbon as input, low profit margins, high capital intensity, long asset life, and trade challenges [13]. The EU is one of the world's largest producers of iron and steel, having produced 126 Mt/y of steel in 2023 [14]. In the same year, the member states imported a total of 47.3 Mt/y of iron and steel products, with a total value of 42 G€/y [15]. The sector is subject to both the ETS and CBAM. The framework is applied to assess the greenness of iron and steel products (HS72, accordingly to the Harmonised System [16,17]), produced in the EU and in its main exporters in 2023, representing 70 % of total import value: China, South Korea, India, United Kingdom, Russia, Turkey, Taiwan, Vietnam, Brazil and Japan (Ukraine is excluded due to the ongoing geopolitical conflict) [15]. The framework is then applied to three of the most imported iron and steel products to the EU and its main exporter countries, representing 30 % of the sector's total import financial value: HS7208 "Flat-rolled products of iron or non-alloy steel, of a width ≥ 600 mm, hot-rolled, not clad, plated or coated", HS7210 "Flat-rolled products of iron or non-alloy steel, of a width ≥ 600 mm, hot-rolled or cold-rolled cold-reduced, clad, plated or coated" and HS7207 "Semi-finished products of iron or non-alloy steel". The result is an estimation of the average CO_2 emissions generated to produce one ton of finished product in each of the analyzed countries. To demonstrate the framework's relevance for informing greenshoring strategies and assessing European performance, the calculated CO_2 emissions per ton of products are used to evaluate the financial implications of CBAM's full operation on imported products' prices. The results are compared to the average European CO_2 emissions and production prices, providing insights into the EU's environmental and financial position relative to its main trading partners.

2. Background and literature review

2.1. The establishing carbon pricing regime

Climate policies implemented by governments could be broadly classified into pricing and non-pricing measures [18]. Pricing policies create an economic incentive that is not otherwise included in the market price, reflecting the social cost (or benefits) of a product. In contrast, non-pricing policies include all climate policies that do not involve the application of an economic incentive.

Climate pricing policies can be further categorized based on the type of market failure they aim to address. Market failure is defined as the inefficient allocation of goods and services in a free market [19]. Climate change is often indicated as one of the most significant market failures [20]. Such failures may originate from unpriced externalities or barriers to climate action related to information, behavior, technology or financial factors [18].

When climate pricing policies specifically target price externalities, they are known as carbon pricing. The goal of carbon pricing is to internalize the externalities associated with climate change into the market, resulting in the reduction of the demand for carbon-intensive goods, the acceleration of green innovation, the promotion of carbon capture and sequestration, and the discouragement of fossil fuel extraction [21]. Ideally, the applied carbon price should reflect the social cost of carbon, which is the discounted value of all future damages resulting from emitting one ton of carbon today [22,23].

Carbon pricing mechanisms are generally classified as direct or indirect. Direct carbon pricing instruments provide explicit price signals to reduce GHG emissions [24], including.

- Emission Trading Schemes (ETSs), which cap emissions from covered entities by issuing tradable emission units that entities can use to meet their obligations.
- Carbon taxes, which impose a fee on emitted GHGs or on the carbon content of fuels.

As of the most recent data (April 1, 2024), 24 % of global GHG emissions were covered by ETSs or carbon taxes [2]. 36 ETSs and 39 carbon taxes were in operation, with varying prices and shares of emission covered (Fig. 1).

The price of carbon taxes in 2024 ranged from $0.34/$tCO_2$ (2023 data) to $167.17/$tCO_2$, with an average value of $39.18/$tCO_2$. Emissions coverage varied between 1.9 % and 82.0 %, with an average of 43.4 % (Fig. 2).

For ETSs, prices ranged from $0.61/$tCO_2$ in Indonesia (excluding Mexico, for which no data was available) to a maximum of $61.3/$tCO_2$ for the EU ETS, with an average of $29.46/$tCO_2$. The lowest emissions coverage was observed in Canada (1.0 %), while the highest was in South Korea (89.0 %), with an average of 38.7 %.

Although carbon pricing systems have expanded over time - both regarding prices and coverages [25]- further increases are necessary to align with the Paris Agreement target and keep temperature increase at the end of the century well below 2 °C [3]. To do so, carbon prices should be higher than the average global marginal abatement cost, which represents the cost of mitigating one ton of CO_2 [26], estimated at $119.5/$tCO_2$ in 2030 for the 2 °C target and $305.5/$tCO_2$ for the 1.5 °C target [2,4]. If carbon pricing would fully reflect the social cost of carbon, estimates would vary depending on the methodology and discount rate applied. Typical values range from $40/$tCO_2$ to $525/$tCO_2$ in 2010 USD [27]. Individual studies may find different results based on their assumptions (e.g., Refs. [28,29]).

By internalizing the cost of carbon emissions, carbon pricing systems have direct financial repercussions on the price of products. Currently,

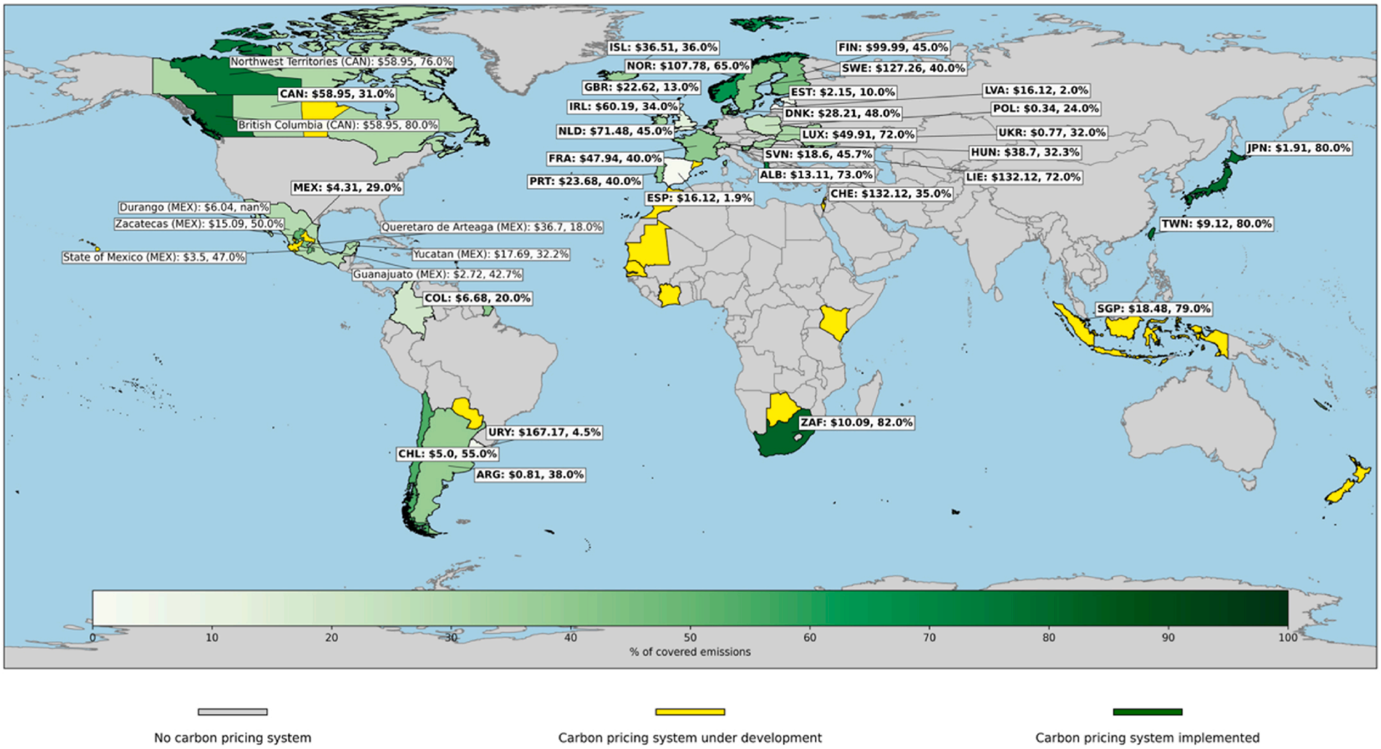

Fig. 1. Overview of carbon taxes under development and in force, indicating associated carbon costs and share of GHG emissions covered (as of April 1, 2024) [2].

83 % of carbon pricing systems already cover the industrial sector [2]. Achieving global climate targets necessitates an increase in both the coverage and the price of these systems [2,4], which would further affect product prices, supply and value chains [30–32]. Consequently, greenshoring is emerging as a new industrial strategy to mitigate these financial repercussions.

2.2. *The concept of greenshoring*

The concept of shoring emerged with globalization – particularly

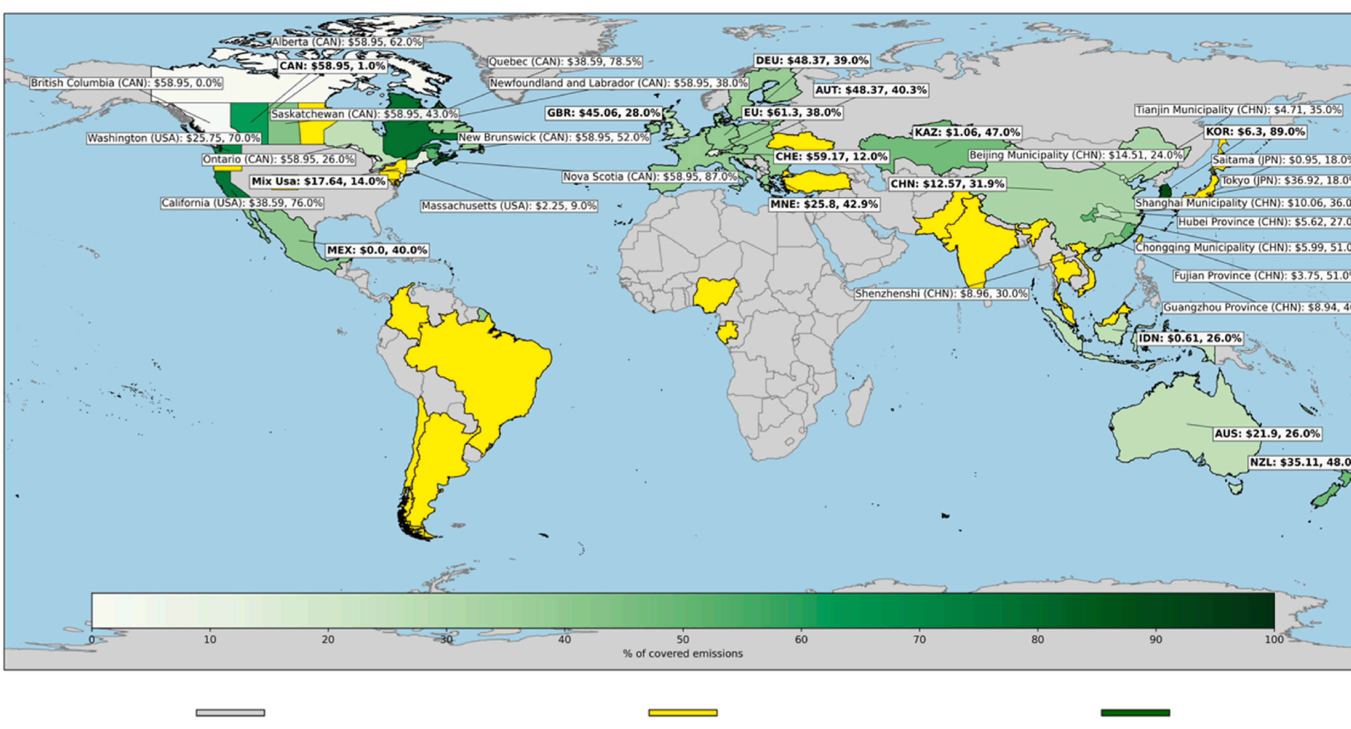

Fig. 2. Overview of Emission Trading Schemes (ETSs) under development and in force, indicating associated carbon costs and share of GHG emissions covered (as of April 1, 2024) – Mix USA: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont [2].

after 90s and the 2001 inclusion of China in WTO - and then was shaped by the series of international crisis (Russia-Ukraine war, Middle East crisis). If at first, relocation was driven by lowest cost considerations, recent crisis brought those industrial processes back to the countries of origin mainly for security reasons.

Several shoring strategies have emerged; even if a unique standardized classification is not commonly identified, the following main typologies can be listed.

- *Offshoring* refers to relocating activities in another country, commonly on the basis of lower production costs, thus increasing the profitability and enhancing the competitiveness of the products in the market. The offshoring process has widely characterised the globalisation of the economy, especially in the last thirty years.
- *Reshoring*, also known as *onshoring*, *inshoring* or *backshoring*, consists in the return of the industrial activities back to the original home country from where they have been relocated – being so the opposite to offshoring. This trend has been spreading due to the geopolitical and economic tensions at the global level that are leading towards the regionalization of economic systems. Reshoring offers advantages such as access to highly qualified personnel, improved logistics, proximity to the final customers, better compliance with new regulations, supply security and enhanced environmental sustainability.
- *Nearshoring* involves relocating production to geographically or economically nearby countries, benefiting from proximity in time zones, culture, and reduced transport and tariff costs.
- *Friendshoring*, also known as *alliedshoring*, is a form of shoring in which the relocation goes to "friend" countries, i.e. counties that share similar values, economic systems, and political orientations. Friendshoring has a strong geopolitical nature, and it is mainly driven by geopolitical tensions that are leading to the need for reducing the dependency from unfriendly countries and for increasing the supply security. An example is the increased supply of U.S. liquefied natural gas to EU as a substitute for Russian energy [33].

The categories of shoring are not compartmentalised but rather can overlap. The academic literature reflects this complexity. Van Hassel et al. [34] proposed an overview of the different definitions of shoring types, referring to the concepts highlighted by Ellram et al. [35] and Autesserre [36], which defined offshoring as "the locating of a manufacturing facility outside of the company's headquarters region", nearshoring as "sourcing work to a foreign, lower-wage country that is relatively close in distance and/or in time zone", and onshoring as "manufacturers returning part or all of their foreign production to domestic facilities". El-Sahli et al. [37] focused on reshoring, developing an approach for quantitatively assessing main drivers of reshoring at a single firm level, finding that technological changes within the firm significantly impact on this process, while, increasing costs in offshoring countries do not seem to affect it. The authors further highlight that there is a large literature on offshoring, the literature on reshoring is smaller but increasing, mentioning - among the others - the work of Bolter et al. [38], which provides a distinction in the definition of onshoring and reshoring (often used as synonyms). The authors defined, in fact, onshoring as the localization of the production close to market demand: in this perspective, onshoring can be a type of reshoring but also a type of offshoring. Reshoring, instead, was defined as the relocation of productive processes previously offshored back to the home country of the company (thus making reshoring always a type of onshoring that, differently from onshoring, is in any case a change of a previous offshoring decision). Barbieri et al. [39] performed a qualitative analysis of the research on reshoring by considering 57 papers on this topic published on international journals. Pedroletti et al. [40] carried out a more extensive analysis on the reshoring research activities, based on 135 papers, developing a conceptual framework characterized by 5 themes (antecedents, contingencies, decision, implementation, and outcome), and proposing a possible future research agenda. Only few studies, instead, try to investigate the relationship between environmental sustainability and reshoring; among them, those performed by Fratocchi et al. [41] and by Orzes et al. [42] can be mentioned.

The concept of "greenshoring" emerged in the last years, in the framework of a sequence of significant events occurring at the global level: the COVID-19 pandemic, the crisis between Russia and Ukraine, the conflicts in the Middle-East area, the energy transition towards decarbonization, the emergence of new technologies (e.g. artificial intelligence, robotics, new materials, etc.), and the international geopolitical tensions leading to a progressive shift from globalisation to regionalization. These circumstances are already widely impacting the world economic and productive systems, backing a transition from the well-established offshoring approach to new forms of shoring.

Despite the absence of a formalized definition, greenshoring is referred as "placing manufacturing content in low carbon regions of the world" [43] or as "the replacement of suppliers with high emissions or less sustainable resource use by suppliers with lower emissions and better environmental performance" [44]. The concept is closely related to a company's broader effort to reduce emissions and achieve climate targets, often in response to or to anticipate the introduction of carbon pricing systems [43,45–47]. For the purpose of this paper, greenshoring is defined as the relocation of industrial activities aiming to reduce the carbon footprint of the supply chains. This often involves relocating to countries that offer access to renewable energy, environmentally sustainable raw material processing, and technological solutions to help meet zero-emission goals. The selected country could be the home country [46,48,49], a near country, a friend country, or any other country.

The different form of shoring can be classified according to the dominant geographical area where they are implemented, and to the main driver that leads to their implementation, as showed in Fig. 3. From a geographical perspective, relocation can take place in home country (i.e. where a company manufacturing a given product is legally registered and has its legal residence, or the country whose government has jurisdiction over the company on legal matters), in close countries or in own economic-political area (i.e. neighboring countries with respect to the home country, belonging to a similar economic and political area), in allied countries (countries having a political/strategical alliance with the home country), or in any other countries. At the same time, the decision to relocate can be driven by financial (i.e. presence of low labor/material/logistics costs and/or of policies and regulations leading to an economic advantage to the productive company), by security-geopolitical (i.e. possibility of enhancing the security of the production, avoiding its relocation in areas characterized by ongoing or potential geopolitical crises) or environmental reasons (i.e. possibility/need for increasing the greenness of a given product/production process).

According to this scheme and to the previously provided definitions of the various forms of shoring, it clearly emerges that.

- the *reshoring* is uniquely related to the *home country.* With reference to its *drivers*, instead, it is often motivated by the *security-geopolitical* reasons, such as a reaction to the several geopolitical tensions, especially in a world affected by growing instability and fragmentation. However, reshoring can also be driven by financial considerations – e.g. possible costs savings on manufacturing, shipping, import tariffs, and currency risks - and by *environmental* aspects – e.g. need for reducing carbon footprint of the products for satisfying sustainability standards, avoiding taxations, and/or for enhancing their competitiveness-.
- the *nearshoring* involves relocating to a *close country/own economic-political area* and *allied countries.* Similarly to the reshoring, the main driver for the nearshoring is *security-geopolitical* one, but it can be also influenced by both *financial* and *environmental* aspects.

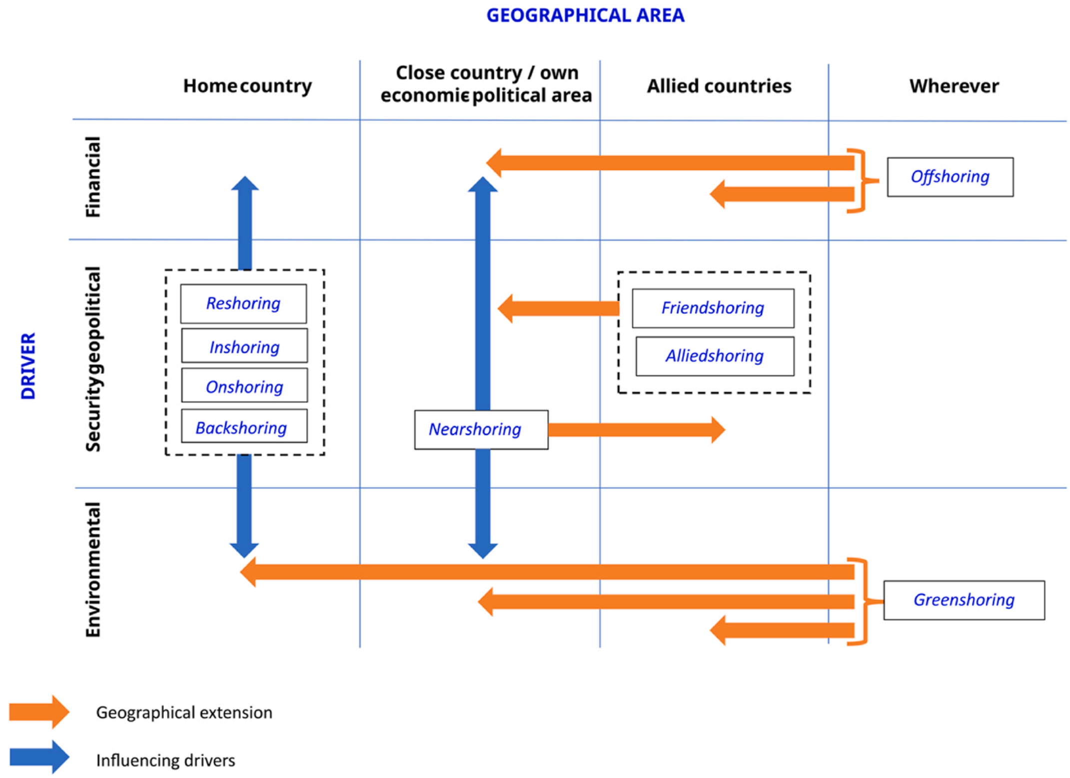

Fig. 3. Interplay of the different types of shoring.

- the *friendshoring* focuses on relocating to *allied countries*, which can be *close countries/countries belonging to the own economic-political area* or not. The friendshoring, due to its strong political nature, is influenced by the *security-geopolitical* drivers.
- the *offshoring* is the relocation to *any other country* (that could, in theory, include also *near* and/or *allied countries*) based on economic convenience. Therefore, the *driver* is *financial.*
- the *greenshoring* is a relocation that can be theoretically performed wherever the productive conditions allow a reduction of the carbon footprint of the product/production process. The relocation is driven by *environmental* reasons.

From this perspective, nearshoring and friendshoring can be considered as particular forms of offshoring, distinguished by their primary driver - security rather than cost. Greenshoring, instead, can be seen as a form of offshoring or of reshoring, depending on whether the enhancement of the greenness can be found in the home country or in another country.

2.3. The definition of a green product

To determine where greenshoring strategies should be implemented and if it would be beneficial, it is essential to define a green product in the context of greenshoring and to develop a quantitative method for greenness assessment.

Numerous attempts have been made to define a green product in literature, yet no universally accepted definition has been established [50,51]. A review of 43 academic papers (Table 1) [50–93] reveals that the definition of green product is often contextual to the case of analysis and varies in terms of both the impact dimensions and the product lifecycle phases that are included. The most frequent dimension in the definition of a green product is the environmental one, since 95 % of the studies explicitly mention it. Some definitions include also other dimensions e.g., social or economic (e.g., Refs. [57,69,80]).

Related to its impact, a green product could be defined either as one that has minimal or no impact in absolute terms (e.g., Refs. [60,76,85]), or as one that has a lower impact relative to similar products (e.g., Refs. [57,63,89]).

Other specific aspects in defining a green product could be.

- **Decreased pollution** (considered in 60 % of the papers), defined as toxic substances (40 %), harmful substances (7 %), emissions (12 %), or general pollution reduction (23 %).
- **Reduction in resource consumption** (63 % of the papers), linked to energy (49 %), materials (53 %), or water (2 %).
- **Reduction in waste generation** (33 % of the papers), defined by the reduction in packaging use (19 %), the enhancement of reparability and reusability (12 %), the extension of product lifespan (16 %), and/or the utilization of a product design that considers the entire lifecycle (23 %).
- **Material composition** defined by the presence of recycled (26 %), recyclable (28 %), renewable (12 %), and/or natural/biodegradable materials (5 %).

Regarding the stages considered, 40 % of the authors indicate the necessity to include the full life cycle, while 19 % focus on specific phases such as production, use, and disposal; the remaining studies do not specify which phase should be considered.

Human health is explicitly mentioned in 14 % of the studies, while animal welfare - defined as the absence of impact on protected species and/or the absence of animal testing - is included in 5 %.

The absence of a universally accepted definition for a green product and the variability in how it's defined across the analyzed literature, in terms of both impact dimensions and lifecycle phases, underscores the need for a specific definition within the context of greenshoring. This paper defines greenshoring as a strategy for relocating industrial activities with the goal of reducing the carbon footprint of the supply chains and frames it in the context of carbon pricing systems and border carbon taxation systems (i.e., CBAM). Based on this framework, a green product is defined as the variant of a product that shows the lowest CO_2

Table 1
Dimensions of the definitions of "green product" accordingly to the literature review.

	STAGES				REDUCED/ELIMINATED ENVIRONMENTAL IMPACTS					INCREASE IN EFFICIENCY			CIRCULAR ECONOMY								
	Production	Usage	Disposal	Whole Life-cycle	Toxic substances	Harmful substances	Emissions	Pollution	In general	Energy	Water	Materials	Reduced waste	Less packaging	Contain high recycled content	Recyclable	Reusable	Renewable materials	Natural/ biodegradable materials	Long useful life	Design aligned
Elkington and Hailes (1988) [52]	X	X	X						X	X			X	X						X	
Simon (1992) [53]	X	X	X		X			X		X		X	X	X	X		X			X	
Schmidheiny (1992) [54]						X						X	X	X			X			X	X
Peattie (1995) [55]	X	X	X				X		X	X		X	X			X					
Robert (1995) [56]					X							X						X			
Shrivastava and Hart (1995) [57]		X	X						X							X	X				
Roy et al. (1996) [58]								X	X	X		X	X	X	X	X	X	X		X	X
F.L. Reinhardt (1998) [59]									X												
Ottman (1998) [60]				X	X				X					X	X					X	
Commission of the European Communities (2001) [61]									X	X		X									
Janssen and Jager (2002) [62]				X					X			X									X
Soo-Wee and Quazi (2005) [63]				X			X		X	X			X			X					X
Ottman et al. (2006) [64]					X			X	X	X		X	X								
Luttropp and Lagerstedt (2006) [65]				X	X					X		X				X				X	
Ljungberg (2007) [66]	X	X			X		X		X	X		X				X		X		X	
Nimse et al. (2007) [67]					X				X	X	X		X	X	X						
D'Souza et al. (2007) [68]					X				X				X	X	X	X					
Albino et al. (2009) [69]				X	X				X			X						X			X
U.S. Department of Commerce, Economics and Statistics Administration (2010) [70]								X		X		X									
Panjaitan and Sutapa (2010) [71]				X					X												
Gao et al. (2010) [72]				X					X	X		X									
Durif et al. (2010) [73]				X	X				X						X			X	X		X

(*continued on next page*)

Table 1 (*continued*)

	STAGES				REDUCED/ELIMINATED ENVIRONMENTAL IMPACTS					INCREASE IN EFFICIENCY			CIRCULAR ECONOMY								
	Production	Usage	Disposal	Whole Life-cycle	Toxic substances	Harmful substances	Emissions	Pollution	In general	Energy	Water	Materials	Reduced waste	Less packaging	Contain high recycled content	Recyclable	Reusable	Renewable materials	Natural/ biodegradable materials	Long useful life	Design aligned
Dangelico, Pontrandolfo (2010) [50]				X	X		X		X	X		X									
Pavan (2010) [74]					X			X	X	X		X	X		X	X	X		X		
Peter (2011) [75]	X								X												
Wee et al. (2011) [76]					X					X		X			X						X
Kam-Sing Wong (2012) [77]				X	X			X	X	X					X	X					
Chen and Chang (2012) [78]									X	X		X		X	X						
Tseng and Hung (2013) [79]				X					X			X									X
Tomasin et al. (2013) [80]						X			X				X								X
Driessen et al. (2013) [81]																					
Ritter et al. (2015) [82]				X	X			X	X	X		X	X								
Mohd-Suki (2015) [83]					X				X						X	X					
Esmaili and Fazeli (2015) [84]	X	X				X			X							X					
Biswas and Roy (2016) [85]				X					X			X				X					
Maniatis (2016) [86]				X					X												
Moser (2016) [87]									X												
de Medeiros and Ribeiro (2017) [88]																					
De Silva et al. (2021) [89]					X		X	X		X		X	X								
Dong et al. (2023) [90]	X							X	X	X		X									
Chen, Zhang et. (2024) [91]				X				X	X	X		X	X								X
Liang, Huang, Wang (2024) [92]				X					X												
Li, Wang, Shi, Sun (2024) [93]				X					X												

emissions during the production phase when compared across alternative supply chains. The assessment should be performed on a set of representative products at the global level.

3. Methodologies

A **multilayered integrated framework** has been developed to assess the greenness of a product based on its country of production (origin country). This framework consists of three layers of analysis with varying degrees of granularity, which, when integrated, allow for the estimation of the CO_2 emissions associated with the production of a given product in a specific country and provide insights into possible levers for their reduction. It integrates well-established methodologies for CO_2 estimation, allowing application across different levels of product aggregation (according to the Harmonized System [16]), industrial sectors and origin countries. CO_2 emissions for generic product (HS2 level) are calculated by combining the consumption of energy commodities with corresponding emission factors, while a carbon mass balance approach is applied to determine CO_2 emissions associated with the production of specific products (HS4, HS6 and CN8 levels).

The first layer evaluates CO_2 emissions related to the production of a generic product (HS2 level [16] as defined by the Harmonized System), while the second layer allows to assessment of CO_2 emissions for specific products (HS4, HS6 and CN8 [94]). A third layer has been introduced to enable analysis of specific products when the necessary data for applying the second layer in the origin country are unavailable. This final layer adjusts the results from the second layer, which are calculated based on a reference country, by integrating country-specific characteristics. The quantitative results of the methodology could be used to estimate the environmental performance of a product among its competitors, as well as the impact of introducing carbon pricing policies.

The **first layer** provides an estimation of the CO_2 emissions associated with the production of a generic product (HS2 level) in a given origin country. This estimation is derived from the CO_2 emissions generated by a specific industrial sector, calculated by the energy consumption data for different energy commodities and their respective emission factors. The consumption of energy commodities should cover both fuel use for combustion and use as process agents, when relevant to the industrial activity. Emission factors could be selected at different levels of detail, using default values, country -specific values, or more specific factors reflecting the industrial sector or a particular application [95,96]. The CO_2 emissions of a given industrial sector in an origin country can be estimated as follows (Equation (1)):

$$E_{t,z} = \sum_{l=1}^{L} C_{l,t,z} {}^{*} F_{l,t,z} \tag{1}$$

where $E_{t,z}$ represents total emissions for a given industry t in country z , $C_{l,t,z}$ indicates the consumption of energy commodity l for a given industry t in country z, and $F_{l,t,z}$ is the corresponding emission factor.

An origin country might trade subproducts (i.e., intermediate goods derived from industrial processes that are further used either domestically of abroad to produce final products), which can cause the total emissions of its industrial sector to not accurately reflect the CO_2 emissions required to produce its final products. To prevent the underestimation of emissions for net importers and the overestimation for net exporters, adjustments are made to account for the trade of subproducts. This is done by calculating the emissions generated by a specific subprocess using Equation (1) applied to its energy consumption. The average emissions per ton of subproduct are then obtained by dividing the subprocess emissions by the quantity of subproduct produced. These values are used to perform necessary adjustments: for imported subproducts, the emissions that would have resulted from their domestic production are added to the total industrial emissions, while for exported subproducts, the emissions associated with their production are subtracted from the total industrial emissions. This ensures that the adjusted total emissions for a given industry ($E_{t,z}{}'$) reflect a scenario in which all subproducts are produced domestically, thereby providing an accurate estimate of the CO_2 emissions generated when producing a product in a specific origin country.

Once the total adjusted industrial emissions are determined, the unit emissions per ton of the generic HS2 product ($U_{h,t,z}$) are estimated by dividing the total adjusted emissions $E_{t,z}{}'$ for a given industry t in country z by the quantity of HS2 products h generated in a given country z by a specific industry t ($Q_{h,t,z}$) (Equation (2)):

$$U_{h,t,z} = E_{t,z}{}' / Q_{h,t,z} \tag{2}$$

The **second layer** calculates CO_2 emissions generated in the production of a specific product (HS4, HS6 or CN8) in a given origin country. Each product is associated with multiple potential production processes, each characterized by different subprocesses generating subproducts. Products' emissions are calculated by adding the CO_2 emissions from the various subprocesses composing its production processes. CO_2 unit emissions generated in each subprocess are divided into.

- Scope 1 (direct) unit emissions obtained by a carbon mass balance approach, which identifies direct CO_2 emissions per ton of subproduct j created through a process m in a given industry t of an origin country z by subtracting the carbon content of all output materials from the carbon content of all input materials of the subprocess and multiplying the result for the weight ratio of CO_2 molecule in respect to carbon, 44/12 (Equation (3)):

$$U_{j,t,z,m,s=1} = \left[\sum_{a=1}^{A} \left(Q_{a,j,t,z,m} {}^{*} D_a \right) - \sum_{b=1}^{B} \left(Q_{b,j,t,z,m} {}^{*} D_b \right) \right] {}^{*} \frac{44}{12} \tag{3}$$

Where $Q_{a,j,t,z,m}$ is the quantity of input material a consumed to produce subproduct j in the industry t of the origin country z using the process m, $Q_{b,j,t,zm}$ is the quantity of output material b generated in the production of the subproduct j in the industry t of the origin country z via process m, and D is the carbon content of each input material a or output material b. The factor 44/12 is the weight ratio of a molecule of CO_2 in respect to carbon, expressed in tons of CO_2 per ton of carbon.

- Scope 2 (indirect) unit emissions account for the consumption of externally produced electricity and steam. These unit emissions are calculated by multiplying the energy consumption of a commodity l required to produce one ton of subproduct j in a given industry t of an origin country z using the process m by its emission factor, which depends on the energy mix used in the specific process m of an origin country z for the production of one ton of subproduct j in a given industry t (Equation (4)):

$$U_{j,t,z,m,s=2} = \sum_{l=1}^{2} C_{l,j,t,z,m} {}^{*} F_{l,j,t,z,m} \tag{4}$$

The total unit CO_2 emissions per ton of subproduct j produced in a given industry t of an origin country z through process m are then determined by summing Scope 1 and Scope 2 emissions (Equation (5)):

$$U_{j,t,z,m} = U_{j,t,z,m,s=1} + U_{j,t,z,m,s=2} \tag{5}$$

The unit CO_2 emissions associated with the production of one ton of specific product i in a given industry t of an origin country z through a process m are calculated multiplying the subproduct's unit emissions ($U_{j,t,z,m}$) by the quantity of subproduct j necessary to produce one ton of product i ($Q_{j,i,t,z,m}$). This is summed across all subproducts j required to produce the product i in the production process m (Equation (6)):

$$U_{i,t,z,m} = \sum_{j=1}^{J} U_{j,t,z,m} {}^{*} Q_{j,i,t,z,m} \tag{6}$$

The average unit CO_2 emissions per ton of specific product i ($U_{i,t,z}$) in an industry t of origin country z are calculated as the sum of the products of unit CO_2 emissions per ton of specific product i in the industry t of origin country z using the production process m ($U_{i,t,z,m}$) times the percentage of utilization of the process m in the industry t of origin country z for the specific product i ($P_{i,t,z,m}$) This formulation allows to differentiate the contribution of various production routes depending on their utilization for the specific product i (Equation (7)):

$$U_{i,t,z} = \sum_{m=1}^{M} P_{i,t,z,m} * U_{i,t,z,m} \tag{7}$$

When input data on energy commodity or material consumption for each subprocess are unavailable for every origin country, the second layer can still be applied by utilizing consumption data from a reference country. To account from country-specific differences, the emission factors for electricity and steam ($F_{l,j,t,z,m}$), as well as the percentage of utilization of the process m ($P_{i,t,z,m}$) can be specific to the origin country. In this case, a third layer is introduced to further adjust the subproduct's unit emissions ($U_{j,t,z,m}$) obtained through the second layer. This additional layer is designed to provide a more accurate and refined estimate of emissions tailored to the specific origin country. The **third layer** uses as inputs the results of the first two, providing a more precise evaluation of CO_2 emissions associated with specific products (HS4, HS6, or CN8) in their respective origin countries. Its logic is the reverse of the second layer. It considers the total emissions of an industrial sector t in a given country z ($E_{t,z}{'}$), as estimated in the first layer, as the sum of the emissions for each product produced within that industrial sector ($E_{i,t,z}$) (Equation (8)). This can further be seen as the product between unit emissions for each product ($U_{i,t,z}$) and the quantity of product generated ($Q_{i,t,z}$), or as the product between unit emissions for each product produced through process m ($U_{i,t,z,m}$) and the quantity of product generated through that process ($P_{i,t,z,m}{*}Q_{i,t,z}$).

$$E_{t,z}{'} = \sum_{i=1}^{I} E_{i,t,z} = \sum_{i=1}^{I} U_{i,t,z} {*} Q_{i,t,z} = \sum_{i=1}^{I}\sum_{m=1}^{M} P_{i,t,z,m} * U_{i,t,z,m} {*} Q_{i,t,z} \tag{8}$$

The unit emissions of each product generated through process m are then derived by applying, in reverse, Equation (8) (Equation (9)).

$$U_{i=1,t,z,m=1} = E_{t,z} \Bigg/ \left(P_{i,t,z,m=1} {*} Q_{i=1,t,z} + \sum_{i=2}^{I}\sum_{m=1}^{M} P_{i,t,z,m} * U_{i,t,z,m} \Big/ U_{i=1,t,z,m=1} {*} Q_{i,t,z} \right) \tag{9}$$

The results of the second layer are used to calculate the ratio between unit emissions of different subprocesses. Once the unit emissions to produce one ton of specific product i in an industry t in a given country z using a specific process $m = 1$ are calculated, the unit emissions to produce one ton of the other specific products i in an industry t in a given country z using processes m can be estimated. This is done by applying the ratios between unit emissions to produce the respective products and processes, as resulted from the second layer.

The proposed framework estimates CO_2 emissions per ton of product by integrating information on the origin country, production processes, energy mix, and product type. When applied across multiple origin countries or supply chains, the framework enables the establishment of a ranking of products based on unit CO_2 emissions, using either average country-level data or more detailed product-specific information where available. This allows for the identification of the green product, defined as the variant with the lowest CO_2 emissions during the production phase when compared across alternative supply chains.

The resulting unit CO_2 emissions are then combined with two complementary indicators – price and quantity (imported, exported, or produced volumes, depending on the scope of the analysis) – to assess the relative performance of products among competitors. In addition, unit CO_2 emission can be used to evaluate the potential impact of carbon pricing policies and to reassess product performance following their implementation.

4. Case study: analysis of greenness in the iron and steel sector from an European perspective

4.1. Scope of analysis and data sources

The multilayered integrated framework is applied to estimate CO_2 emissions associated with iron and steel production across the EU and the major exporter countries to the EU. The resulting data are used to assess the EU's iron and steel greenness and performance relative to its main trading partners, and to estimate the financial implication of CBAM's full implementation.

The first layer is applied to evaluate the greenness of a generic iron and steel product (HS72 according to the Harmonized System [16]) in a given origin country. In addition to the EU, the analysis covers the largest iron and steel exporters to the EU in 2023, representing 70 % of total imports: China, South Korea, India, United Kingdom, Russia, Turkey, Taiwan, Vietnam, Brazil and Japan (Ukraine is excluded due to the ongoing geopolitical conflict) [15]. Data on energy commodity consumption for the iron and steel industry refer to 2022 (the most recent year for which complete data are available) [97]. Three energy-use categories are considered: Transformation Processes, Energy Industry Own Use, and Total Final Consumption. The analysis includes emission sources currently covered by the CBAM transitional phase: direct emissions from sources owned or controlled by the reporting entity (Scope 1) and indirect emissions from electricity, steam, heat, and cooling externally produced (Scope 2) [98,99]. Coke is currently not included in the list of CBAM-covered precursors. The subprocesses analyzed are the blast furnace and the iron and steel industry. Electricity emission factors are based on national energy mix [96], while emission factors for other commodities are derived from default values [100, 101]. All emissions are allocated to primary products, with no allocation to by-products. To incorporate the influence of trade in precursors and intermediate products, the calculated emissions from the iron and steel industry are adjusted to reflect net trade in pig iron and pellets [14,102].

The second and third layer are applied to assess the greenness of the three of the most imported iron and steel products to the EU from their main exporter countries, covering 30 % of the sector's total import financial value: HS7208 "Flat-rolled products of iron or non-alloy steel, of a width $\geq$ 600 mm, hot-rolled, not clad, plated or coated", HS7210 "Flat-rolled products of iron or non-alloy steel, of a width $\geq$ 600 mm, hot-rolled or cold-rolled cold-reduced, clad, plated or coated" and HS7207 "Semi-finished products of iron or non-alloy steel". For each product the analysis focuses on the EU and its major exporting partners (together accounting for approximately 80 % of product's imports). Each specific product can be manufactured through multiple processes, involving various subprocesses [103,104]. Unit CO_2 emissions per ton of subproduct (e.g., sinter, pellet, pig iron) are calculated using the second layer of the framework, with the EU as a reference country for energy consumption and material input data [105,106], and then refined through the third layer to better estimate results based on the origin country The three analyzed products are generated through different subprocesses, which lead to varying average unit emissions. The HS7207, in particular, includes distinct both bars and forgings, for which separate results are calculated.

The results, expressed as average unit CO_2 emissions per ton of generic (HS72) and specific products (HS7207, HS7208 and HS7210), are then combined with average import prices and quantities [15] to evaluate the performance of EU products relative to their main competitors. For specific products, the average unit emissions and import prices are further used to estimate the potential impact of the introduction of CBAM on prices. The following assumptions were made: average import prices of products to the EU in 2023 are used [15]; the carbon price already paid in the origin country was considered based on average carbon taxes or ETS prices covering the industrial sector; the EU ETS price was set as the annual mean in 2023. Free allowances were assumed to be 97.5 % of a weighted average benchmark of 0.82 tCO_2/t, calculated based on EAF carbon steel and hot metal benchmarks values, adjusted for the percentage utilization of the respective production processes [107–109].

4.2. Results

The result from the application of the first layer to the iron and steel sector of the EU and the major exporters to the EU is a ranking of the countries based on the CO_2 emissions emitted to produce one ton of a generic iron and steel product. Fig. 4 presents the evaluation of the greenness of iron and steel products in the analyzed origin countries, alongside the corresponding normalized quantities of imports to the EU and the normalized average import prices. Fig. 5 presents the greenness of iron and steel products in the analyzed origin countries, in relation with the respective electricity emission factors. Fig. 6 analyzes the percentage of utilization of the most diffused production processes for iron and steel in the origin countries. For Brazil and Russia, the sum of the percentages of the processes is less than 100 %, as both countries report minimal use of other production processes not included in the analysis.

On average, 1.32 tCO_2 are emitted in the EU to produce one ton of iron and steel products. Compared to the other analyzed countries, the EU reports the third lowest emissions per ton of product, mainly due to the production processes used. In fact, 56.3 % of EU steel was produced via the blast furnace-basic oxygen furnace process (BF-BOF), referred to here as the primary process. This process is the most carbon intensive as it uses coal as the main energy input [14,110]. In contract, the least emissive method, the electric arc furnace (EAF) which uses recycled scrap (secondary process), accounted for 43.5 % of production [14,110]. Less than 1 % of European steel was produced by direct reduced iron as input of an electric arc furnace (DRI-EAF) (tertiary process) [110]. This process emits, on average, about half the CO_2 in respect to BF-BOF, due to its reliance on gas-based iron ore production and electricity-based steel production [110]. Beyond emissions, differences in steel quality arise from production processes, as secondary steel cannot meet the requirements of all industrial applications.

Among the major exporters to the EU, only Turkey demonstrates better greenness, while South Korea performs at a level approximately comparable to the EU. Turkey produces about 75 % of its steel using the secondary process [14], resulting in a lower amount of CO_2 emissions per ton of product (0.91 tCO_2/ton). South Korea, while being more reliant on the primary process and having a higher electricity emission factor than the EU [14,96], achieves comparable performance (1.31 tCO_2/ton), likely due to a higher process efficiency. The other exporting countries rank below the EU, mainly due either to greater reliance on carbon-intensive processes (primary or tertiary using coal as reducing agent) or to higher electricity emission factors [14,96]. Russia and India, the two major exporters of iron and steel to the EU, recorded the highest CO_2 emissions per ton of product among the analyzed countries, with 3.14 tCO_2/t and 3.17 tCO_2/t respectively. The elevated emissions value for Russia can only be partially attributed to the high utilization of the primary process. Specifically, the country's iron and steel sector shows high total emissions (224.4 $MtCO_2$/y) despite a limited production volume (71.5 Mt/y in 2022), raising the question of whether this discrepancy may be due to steel production dedicated to military efforts, which could be not fully captured in official data. In contrast, India's high unit emissions are primarily linked to the extensive use of the tertiary process with coal as reducing agent, combined with the highest electricity emission factor among the analyzed countries.

The application of the second and third layers to HS7207, HS7208 and HS7210 produced in the EU and in the major exporting countries to the EU, presented in Table 2, reveal a ranking of average unit emissions that is consistent with the analysis of generic iron and steel products (HS72). The EU reports relatively low average unit CO_2 emissions across all specific products analyzed when compared to its major exporting partners, but its performance is surpassed by Turkey and Egypt and is comparable to that of South Korea. Egypt's low average unit emissions are mainly attributed to its exclusive reliance on the second (31 %) and tertiary (69 %) production processes. In contrast, the remaining countries exhibit higher average unit emissions, with Indonesia, Russia, and India demonstrating the highest values. Indonesia's poor performance could be explained by its extensive use of the primary production process (93.1 %) combined with a high electricity emission factor (0.675 tCO_2/MWh). When accounting for the total quantities imported by the EU, it becomes evident that substantial share of imports in each product category originates from countries with higher unit emissions than the EU itself.

Fig. 4. Per unit evaluation of the CO_2 emitted to produce one ton of HS72 (Turkey as reference), total import to the EU in 2023 (Brazil as reference) and average import price in 2023 (Russia as reference) of the major exporter Countries of iron and steel to the EU.

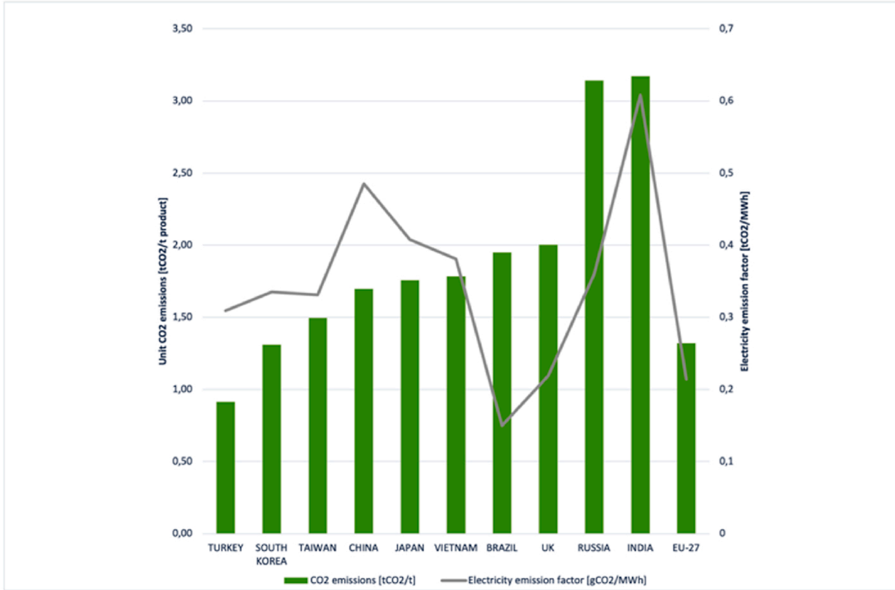

Fig. 5. Evaluation of the CO_2 emitted to produce one ton of HS72 in the major exporting countries of iron and steel products to the EU and in the EU and their electricity emission factors.

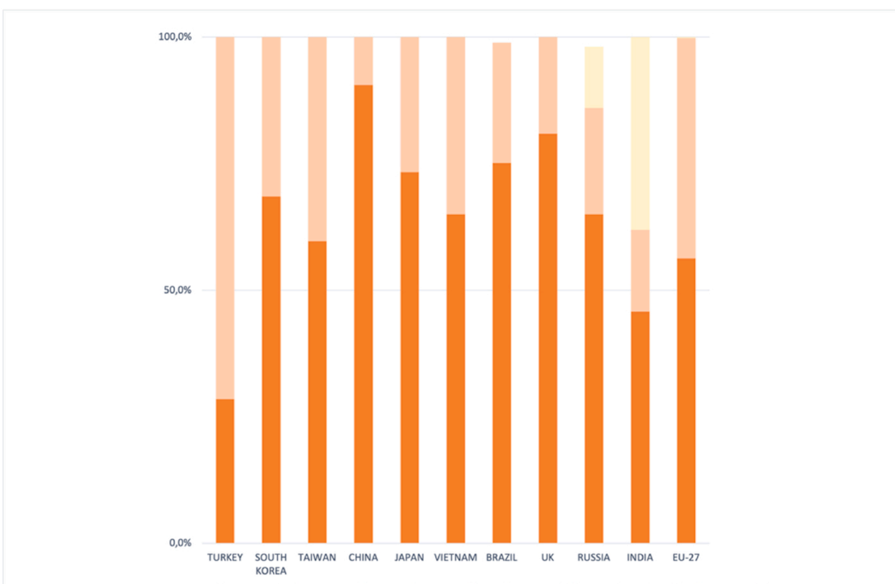

Fig. 6. Percentage of utilization of the main iron and steel production processes (primary, secondary and tertiary) in the major exporting countries to the EU and in the EU.

To illustrate the validity of the methodology to give insights for greenshoring strategies and re-evaluate the EU iron and steel sector's performance, the outputs of the framework were used to simulate the financial impact of CBAM introduction. The analysis reveals that, although EU products generally have higher average prices than imported ones, the introduction of CBAM would significantly alter this situation. Once the carbon border tax is applied, European products would become more financially competitive, highlighting CBAM's potential to level the playing field [111]. Price increases would be particularly relevant for imports from countries with high reliance on carbon-intensive production processes and high electricity emission factors, such as Russia, India, and Indonesia.

4.3. Sensitivity analysis

A sensitivity analysis was conducted to test the framework's stability and reliability under varying conditions. The first layer was tested considering four significant variables: the emission factor of electricity and the consumption of three key commodities (other bituminous coal, coke oven coke and electricity). Consistent with the theoretical framework, the sensitivity analysis shows a linear correlation between the variation in input variables and the variation of the average unit CO_2 emissions of a generic iron and steel product (see Table 3). The magnitude of these variations depends on the specific consumption of different commodities in the origin countries. Indonesia presents a unique case and has therefore been excluded from the table: in the initial dataset used for energy consumption, no consumption of electricity or

Table 2
Average unit CO_2 emissions [tCO_2/t], total import to the EU [Mt], average price in 2023 [€/t], average ETS price in 2023 [€/tCO_2] and price estimation after the application of CBAM [€/t] (sorted by increasing average unit CO_2 emissions).

PRODUCT	ORIGIN COUNTRIES	TOTAL IMPORT [Mt]	AVERAGE PRICE [€/t]	AVERAGE UNIT CO_2 EMISSIONS [tCO_2/t]	ETS PRICE [€/tCO_2]	PRICE ESTIMATION AFTER CBAM [€/t]
HS7208	Turkey	0.62	698.7	0.96	/	712.8
	Egypt	0.75	705.5	0.98	/	721.7
	South Korea	1.38	823.6	1.34	10.11	866.1
	EU	/	873.9	1.37	88.55	873.9
	Taiwan	1.05	716.5	1.39	/	768.7
	Japan	1.34	748.6	1.76	/	833.6
	Vietnam	1.12	660.0	1.84	/	752.4
	Indonesia	0.60	746.0	2.65	/	909.6
	India	1.39	725.3	2.85	/	907.3
HS7210	South Korea	1.06	1089.2	1.56	10.11	1177.0
	EU	/	1117.5	1.57	88.55	1117.5
	Taiwan	0.63	903.5	1.60	/	974.5
	China	1.03	1072.8	1.99	/	1178.3
	Vietnam	0.79	839.9	2.08	/	953.2
	India	0.87	925.5	3.23	/	1140.6
HS7207	EU	/	707.9	1.33 (bars)	88.55	707.9
				2.88 (forgings)		707.9
	Brazil	0.55	637.8	1.67 (bars)	/	714.6
				3.17 (forgings)		847.6
	China	0.71	697.8	1.71 (bars)	/	778.1
				3.38 (forgings)		926.8
	Vietnam	0.41	597.1	1.79 (bars)	/	685.2
				3.42 (forgings)		829.6
	UK	0.15	781.6	1.91 (bars)	41.92	787.5
				3.47 (forgings)		795.8
	Indonesia	0.26	603.9	2.60 (bars)	/	763.7
				4.37 (forgings)		857.4
	Russia	3.12	541.0	2.75 (bars)	/	713.8
				4.34 (forgings)		917.4
	India	0.22	616.7	2.85 (bars)	/	798.6
				4.59 (forgings)		952.4

coke oven coke is recorded. Consequently, varying the consumption or emission factor of these commodities does not affect Indonesia's average unit emissions in the framework.

The sensitivity analysis was also conducted on a representative product (HS7208) and origin country (India) of the second and third layers, as the methodology remains consistent for any product or country under consideration. Three variables were considered: the change in total product output while keeping total emissions constant (corresponding to an increase in production efficiency), the variation in the electricity emission factor, and the change in the percentage of primary process utilization. The results obtained (Table 4) are consistent with the underlying theory presented in Equations (8) and (9).

4.4. Discussion

The proposed framework provides a valuable tool for assessing the average unit CO_2 emissions of products, both at generic (HS2) and specific level (HS4, HS6 and CN8). Its integrated structure allows for the application to different origin countries, production processes, and products using either average country-level data or more detailed information. The case study on the iron and steel sector demonstrates both the applicability and the accuracy of the methodology, as the results are consistent with previous studies on the subject [103,104]. Only the results for Russia are considered an anomaly, since high sector emissions are linked to low production volume, which may be due to the ongoing geopolitical conflict, potentially leading to inaccurate assessments of the country's production. Future research will test the robustness and accuracy of the methodology in other industrial sectors.

The evaluation of average unit CO_2 emissions enables the identification of the green product, namely the variant that achieves the lowest CO_2 emissions during the production phase compared across alternative supply chains. When combined with price and quantity indicators, this assessment allows for a more comprehensive evaluation of product performance in both environmental and economic terms, highlighting which producers or countries hold a competitive advantage. For the iron and steel sector, in both the generic and specific product analyses, EU iron and steel products exhibit lower average unit CO_2 emissions than many of their major trading partners. However, Turkey and Egypt demonstrate better greenness than the EU, while South Korea shows comparable results. The other main exporters to the EU supply iron and steel products with higher average unit CO_2 emissions. In particular, the largest exporters by volume (Russia and India) offer products at relatively low import prices but significantly higher average unit CO_2 emissions than the EU.

The data of unit emissions and import prices provide also the baseline for assessing the potential impact of carbon pricing policies. Such policies would lead to increases in product prices, potentially altering the competitiveness among suppliers. This becomes evident in the case study analyzing the expected effects of the introduction of CBAM on iron and steel products. Most major exporters to the EU currently lack active carbon pricing systems or apply them at prices significantly lower than the EU ETS. Consequently, as observed for specific products, the introduction of CBAM is expected to increase import prices substantially - by between 1 % and 60 % compared to 2023 average import prices - depending on product type, initial import prices, and the presence or absence of active carbon pricing systems in origin countries. Such significant price increases could act as a catalyst for the adoption of greenshoring strategies aimed at reducing these financial burdens. The methodology provides a preliminary guide for targeting these strategies. Nonetheless, a more specific assessment requires considering product-specific CO_2 emissions, based on the actual electricity emission factor, the industrial process applied, and its efficiency, as well as specific product prices. Additionally, while this analysis focuses on a short-to-medium-term evaluation around CBAM implementation, a more complete assessment of greenshoring strategies would benefit from medium-to-long-term scenarios that also account other economic factors linked

Table 3
Sensitivity analysis applied to the first layer of the framework; input variables: electricity emission factor and consumption of coke oven coke, electricity and other bituminous coal relative to the reference scenario.

	Reference scenario	Emission factor electricity −10 %		Emission factor electricity +10 %		Other bituminous coal consumption −10 %		Other bituminous coal consumption +10 %		Electricity consumption −10 %		Electricity consumption −10 %		Coke oven coke consumption −10 %		Coke oven coke consumption +10 %	
	Unit em. [tCO2/t]	Unit em. [tCO2/t]	Var. [%]	Unit em. [tCO2/t]	Var. [%]	Unit em. [tCO2/t]	Var. [%]	Unit em. [tCO2/t]	Var. [%]	Unit em. [tCO2/t]	Var. [%]	Unit em. [tCO2/t]	Var. [%]	Unit em. [tCO2/t]	Var. [%]	Unit em. [tCO2/t]	Var. [%]
Turkey	0,91	0,89	−3 %	0,94	3 %	0,91	−1 %	0,92	1 %	0,89	−3 %	0,90	−1 %	0,88	−4 %	0,95	4 %
South Korea	1,31	1,29	−2 %	1,33	2 %	1,28	−2 %	1,33	2 %	1,29	−2 %	1,30	−1 %	1,24	−5 %	1,37	5 %
EU-27	1,32	1,30	−1 %	1,34	1 %	1,30	−2 %	1,34	2 %	1,30	−1 %	1,31	−1 %	1,26	−5 %	1,38	5 %
Taiwan	1,49	1,47	−2 %	1,52	2 %	1,47	−2 %	1,52	2 %	1,47	−2 %	1,48	−1 %	1,41	−6 %	1,58	6 %
China	1,70	1,66	−2 %	1,73	2 %	1,68	−1 %	1,72	1 %	1,66	−2 %	1,68	−1 %	1,59	−7 %	1,81	7 %
Japan	1,76	1,73	−2 %	1,79	2 %	1,75	−1 %	1,77	1 %	1,73	−2 %	1,74	−1 %	1,67	−5 %	1,85	5 %
Vietnam	1,78	1,75	−2 %	1,82	2 %	1,77	0 %	1,79	1 %	1,75	−2 %	1,77	−1 %	1,67	−6 %	1,90	6 %
Brazil	1,95	1,93	−1 %	1,96	1 %	1,92	−1 %	1,97	1 %	1,93	−1 %	1,94	0 %	1,85	−5 %	2,04	5 %
UK	2,00	1,99	0 %	2,01	0 %	2,00	0 %	2,00	0 %	1,99	0 %	2,00	0 %	1,87	−6 %	2,13	6 %
Russia	3,14	3,11	−1 %	3,17	1 %	3,12	−1 %	3,16	1 %	3,11	−1 %	3,12	−1 %	2,95	−6 %	3,33	6 %
India	3,17	3,12	−2 %	3,23	2 %	3,04	−4 %	3,30	4 %	3,12	−2 %	3,15	−1 %	3,06	−4 %	3,28	4 %

to a potential relocation.

The presented framework integrates widely adopted methodologies to estimate CO_2 emissions into a flexible tool that is intended to be applied across different industrial sector, origin counties and levels of granularity. This integration enhances both generality and applicability while reducing data requirements. The third layer plays a key role in this regard, allowing accurate product-level (HS4, HS6, and CN8) analyses even when only limited country-specific data are available. It relies on the assumption that the ratio between the unit emissions of different subprocesses remains consistent with that obtained from the second layer, based on energy and material consumption data in the reference country, and emission factors and process utilization shares in origin countries. This approximation reduces the input data needed while maintaining a reasonable level of accuracy compared with more detailed, data-intensive methodologies. The results obtained for the iron and steel sector confirm that this trade-off does not compromise the reliability of the outcomes, which remain consistent with other studies. Future improvements could come from the identification of country-level databases with a degree of granularity comparable to that currently available for the EU (the reference country in the case study), enabling even more precise product- and country-specific assessments.

5. Conclusions

The structure of global markets has been reshaped by recent developments, including geopolitical tensions, trade disruptions, and energy security concerns, leading to a shift towards protectionism and self-sufficiency. The EU's strategic roadmap, as defined in the Competitiveness Compass [112], reflects this trend, identifying innovation, decarbonization, and reduced dependencies as key pillars to enhance resilience and global positioning. Nevertheless, sustainability remains a fundamental principle of the EU, embedded in both policy frameworks and long-term strategic targets [113,114].

In this context, the introduction of the Carbon Border Adjustment Mechanism (CBAM) represents a policy instrument potentially capable of simultaneously addressing competitiveness and sustainability objectives. CBAM applies a carbon price to imported products equivalent to that imposed on domestic production, thereby enhancing the relative competitiveness of EU products while incentivizing global emission reductions. To mitigate these potential financial burdens, companies may adopt greenshoring strategies i.e., the relocation of industrial activities aiming to reduce the carbon footprint of supply chains.

The effective implementation of greenshoring strategies requires robust, quantitative, and comparable methodologies to evaluate the greenness of products. The methodology developed in this paper addresses this need by providing a multilayered framework that estimates CO_2 emissions associated with the production of a given product at different HS levels (HS2, HS4, HS6, CN8 accordingly to the Harmonized System) in a specific country. This approach allows for a resource-efficient assessment of average unit CO_2 emissions to produce a product, enabling the identification of the product variant that exhibits the lowest CO_2 emissions during the production phase when compared across alternative supply chains, i.e., green product, in a standardized and replicable manner. Its generality derives from utilization of widely diffused methodologies, ensuring applicability across sectors and geographies.

The application of the framework to the EU iron and steel sector demonstrates its validity and robustness. The methodology was applied to both a generic (HS72) and three specific products (HS7207, HS7208, HS7210), covering the EU and its main exporting partners. The results reveal substantial heterogeneity in average unit CO_2 emissions across countries, reflecting differences in energy mix, process efficiency, and production methods. EU iron and steel products have generally lower average unit CO_2 emissions than those of many major exporting countries. Nonetheless, Turkey and Egypt demonstrate better greenness, while South Korea shows comparable performance. The integration of

Table 4
Sensitivity analysis applied to the second and third layers of the framework; input variables: overall products' production, electricity emission factor and percentage utilization of the primary process.

Input variable						
Variation in each input variable [%]	Overall products' production		Electricity emission factor		Percentage utilization of the primary process	
	Average unit emissions [tCO2/t]	Variation in average unit emissions [%]	Average unit emissions [tCO2/t]	Variation in average unit emissions [%]	Average unit emissions [tCO2/t]	Variation in average unit emissions [%]
−30 %	4,20	43 %	2,76	−6 %	2,67	−9 %
−20 %	3,67	25 %	2,82	−4 %	2,76	−6 %
−10 %	3,27	11 %	2,88	−2 %	2,85	−3 %
0 %	2,94	0 %	2,94	0 %	2,94	0 %
10 %	2,67	−9 %	3,00	2 %	3,03	3 %
20 %	2,45	−17 %	3,06	4 %	3,12	6 %
30 %	2,26	−23 %	3,12	6 %	3,21	9 %

the results with import prices and trade volumes enable for an evaluation of a product performance compared to its competitors. When applied in the context of carbon pricing policies, such as CBAM, this approach allows for the estimation of price variations for imports, which in the case study range between 1 % and 60 % of average import prices, depending on the product, origin country, and existing carbon pricing mechanisms. These results show the potential role of CBAM in influencing trade dynamics, strengthening the competitiveness of EU products, and incentivizing the adoption of greenshoring strategies, particularly for high-carbon-intensity products.

From a methodological perspective, the case study and its sensitivity analysis confirm the robustness and applicability of the proposed framework. In particular, the alignment of its results with existing studies and their stability under varying input assumptions demonstrate the framework's reliability in capturing cross-country differences in production-related emissions. The integrated use of widely adopted methodologies allows for precise and resource-efficient assessments. The third layer enables detailed product-level analysis even with limited data by adjusting reference-country information using key country-specific parameters. While this introduces some approximation, it substantially reduces data requirements and broadens the framework's applicability across sectors, countries, and product types.

Future research should extend the application of the framework to additional sectors and products to further validate it. The identification of more granular, country-specific dataset could enhance precision and enable the direct use of specific country data. Overall, the framework provides a scalable, resource-efficient tool for ex-ante assessment of product greenness, performance, and potential policy impacts, offering a foundation for informed industrial strategy and the design of greenshoring interventions.

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.

APPENDIX

Mathematical notation.

Sets

$\mathbf{Z} = \{z_1, \dots, z_z, \dots, z_Z\}$ set of origin Countries, dim $\mathbf{Z} = \mathbf{Z}$
$\mathbf{T} = \{t_1, \dots, t_t, \dots, t_T\}$ set of industries, dim $\mathbf{T} = \mathbf{T}$
$\mathbf{L} = \{l_1, \dots, l_l, \dots, l_L\}$ set of energy commodities, dim $\mathbf{L} = \mathbf{L}$
$\mathbf{F} = \{f_1, \dots, f_f, \dots, f_F\}$ set of emission factors, dim $\mathbf{F} = \mathbf{F}$, $\forall t_t \epsilon \mathbf{T}, \forall l_l \epsilon \mathbf{L}, \forall z_z \epsilon \mathbf{Z}, \exists f_{t,l,z} \subset \mathbf{F} : f_{t,l,z} = \{f_f \epsilon \mathbf{F} | f_f \text{ is the emission factor of the commodity } l_l \text{ for the origin country } z_z \text{ in the industry } t_t\}$ and

$\forall l_l \epsilon \mathbf{L}, \quad \forall j_j \epsilon \mathbf{J}, \quad \forall t_t \epsilon \mathbf{T}, \quad \forall z_z \epsilon \mathbf{Z}, \quad \forall m_m \epsilon \mathbf{M}, \quad \exists f_{l,j,t,z,m} \subset \mathbf{F} : f_{l,j,t,z,m} = \left\{ f_f \epsilon \mathbf{F} \,\middle|\, f_f \text{ is the emission factor of the energy commodity } l_l \text{ to produce the subproduct } j_j \text{ in the industry } t_t \text{ of the origin country } z_z \text{ following the process } m_m \right\}$

$\mathbf{H} = \{h_1, \dots, h_h, \dots, h_H\}$ set of HS2 products, dim $\mathbf{H} = \mathbf{H}$
$\mathbf{I} = \{i_1, \dots, i_i, \dots, i_I\}$ set of specific products, dim $\mathbf{I} = \mathbf{I}$, $\forall h_h \epsilon \mathbf{H}, \exists i_h \subset \mathbf{I} : i_h = \{i_i \epsilon \mathbf{I} \mid i_i \text{ is a specific product of } h_h\}$
$\mathbf{J} = \{j_1, \dots, j_j, \dots, j_J\}$ set of subproducts, dim $\mathbf{J} = \mathbf{J}$, $\forall i_i \epsilon \mathbf{I}, \exists j_i \subset \mathbf{J} : j_i = \left\{ j_j \epsilon \mathbf{J} \,\middle|\, j_j \text{ is a subproduct of } i_i \right\}$
$\mathbf{A} = \{a_1, \dots, a_a, \dots, a_A\}$ set of input material, dim $\mathbf{A} = \mathbf{A}$, $\forall j_j \epsilon \mathbf{J}, \exists a_j \subset \mathbf{A} : a_j = \left\{ a_a \epsilon \mathbf{A} \,\middle|\, a_a \text{ is an input material of } j_j \right\}$
$\mathbf{B} = \{b_1, \dots, b_b, \dots, b_B\}$ set of output material, dim $\mathbf{B} = \mathbf{B}$, $\forall j_j \epsilon \mathbf{J}, \exists b_j \subset \mathbf{B} : b_j = \left\{ b_b \epsilon \mathbf{B} \,\middle|\, b_b \text{ is an output material of } j_j \right\}$
$\mathbf{D} = \{d_1, \dots, d_d, \dots, d_D\}$ set of carbon contents, dim $\mathbf{D} = \mathbf{D}$,
$\forall a_a \epsilon \mathbf{A}, \exists d_a \subset \mathbf{D} : d_a = \{d_d \epsilon \mathbf{D} \mid d_d \text{ is the carbon content of the input material } a_a\}$
And.
$\forall b_b \epsilon \mathbf{B}, \exists d_b \subset \mathbf{D} : d_b = \{d_d \epsilon \mathbf{D} \mid d_d \text{ is the carbon content of the output material } b_b\}$
$\mathbf{M} = \{m_1, \dots, m_m, \dots, m_M\}$ set of processes, dim $\mathbf{M} = \mathbf{M}$
$\forall i_i \epsilon \mathbf{I}, \exists m_i \subset \mathbf{M} : m_i = \{m_m \epsilon \mathbf{M} \mid m_m \text{ is a process to produce the specific product } i_i\}$
$\mathbf{P} = \{p_1, \dots, p_p, \dots, p_P\}$ set of percentage of usage of processes, dim $\mathbf{P} = \mathbf{P}$,

$\forall m_m \epsilon \mathbf{M}, \quad \forall t_t \epsilon \mathbf{T}, \quad \forall z_z \epsilon \mathbf{Z}, \quad \forall i_i \epsilon \mathbf{I} \exists p_{it,z,m} \subset \mathbf{P} : p_{i,t,z,m} = \left\{ p_p \epsilon \mathbf{P} \,\middle|\, p_p \text{ is the percentage of usage of process } m_m \text{ in the industry } t_t \text{ of the origin country } z_z \text{ to produce the product } i_i \right\}$

$\mathbf{S} = \{s_1, \ldots, s_s, \ldots, s_S\}$ set of CO_2 emission scopes, dim $\mathbf{S} = \mathbf{3}$
$\mathbf{Q} = \{q_1, \ldots, q_q, \ldots, q_Q\}$ set of quantities dim $\mathbf{Q} = \mathbf{Q}$,
$\forall a_a \epsilon \mathbf{A}, \forall j_j \epsilon \mathbf{J}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \forall m_m \epsilon \mathbf{M}, \exists q_{a,j,t,z,m} \subset \mathbf{Q} : q_{a,j,t,z,m} =$
$\{q_q \epsilon \mathbf{Q} \mid q_q$ is the quantity of input product a_a to create subproduct j_j in the industry t_t of the origin country z_z following the process $m_m\}$ and
$\forall b_b \epsilon \mathbf{B}, \forall j_j \epsilon \mathbf{J}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \forall m_m \epsilon \mathbf{M}, \exists q_{b,j,t,z,m} \subset \mathbf{Q} : q_{b,j,t,z,m} =$
$\{q_q \epsilon \mathbf{Q} \mid q_q$ is the quantity of output product b_b of subproduct j_j in the industry t_t of the origin country z_z following the process $m_m\}$ and
$\forall j_j \epsilon \mathbf{J}, \forall i_i \epsilon \mathbf{I}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \forall m_m \epsilon \mathbf{M}, \exists q_{j,i,t,z,m} \subset \mathbf{Q} : q_{j,i,t,z,m} =$
$\{q_q \epsilon \mathbf{Q} \mid q_q$ is the quantity of subproduct j_j to produce i_i in the industry t_t in origin country $z_z$following the process $m_m\}$ and
$\forall i_i \epsilon \mathbf{I}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \exists q_{i,t,z} \subset \mathbf{Q} : q_{i,t,z} = \{q_q \epsilon \mathbf{Q} \mid q_q$ is the quantity of specific product i_i produced in the industry t_t in origin country $z_z\}$
$\forall h_h \epsilon \mathbf{H}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \exists q_{i,z} \subset \mathbf{Q} : q_{h,t,z} = \{q_q \epsilon \mathbf{Q} \mid q_q$ is the quantity of HS2 product h_h produced in the industry t_t in origin country $z_z\}$
$\mathbf{C} = \{c_1, \ldots, c_c, \ldots, c_C\}$ set of energy consumption dim $\mathbf{C} = \mathbf{C}$,
$\forall l_l \epsilon \mathbf{L}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \exists c_{l,t,z} \subset \mathbf{C} : c_{l,t,z} = \{c_c \epsilon \mathbf{C} \mid c_c$ is the energy consumption of the energy commodity l_l in the industry t_t of the origin country $z_z\}$ and
$\forall l_l \epsilon \mathbf{L}, \forall j_i \epsilon \mathbf{J}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \forall m_m \epsilon \mathbf{M}, \exists c_{l,j,t,z,m} \subset \mathbf{C} : c_{l,j,t,z,m} = \{c_c \epsilon \mathbf{C} \mid c_c$ is the energy consumption of the energy commodity l_l to produce the subproduct j_j in the industry t_t of the origin country z_z following the process $m_m\}$
$\mathbf{E} = \{e_1, \ldots, e_e, \ldots, e_E\}$ set of emissions dim $\mathbf{E} = \mathbf{E}$,
$\forall l_l \epsilon \mathbf{L}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \exists e_{l,t,z} \subset \mathbf{E} : e_{l,t,z} = \{e_e \epsilon \mathbf{E} \mid e_e$ is the emission generated by the consumption of the commodity l_l in the industry t_t of the origin country $z_z\}$
$\mathbf{U} = \{u_1, \ldots, u_u, \ldots, u_U\}$ set of unit emissions dim $\mathbf{U} = \mathbf{U}$,
$\forall h_h \epsilon \mathbf{H}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \exists u_{h,t,z} \subset \mathbf{U} : u_{h,t,z} =$
$\{u_u \epsilon \mathbf{U} \mid u_u$ is the unit emission to produce one ton of the HS2 product h_h in the industry t_t of the origin country $z_z\}$ and
$\forall j_j \epsilon \mathbf{J}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \forall m_m \epsilon \mathbf{M}, \forall s_s \epsilon \mathbf{S}, \exists u_{j,t,z,m,s} \subset \mathbf{U} : u_{j,t,z,m,s} =$
$\{u_u \epsilon \mathbf{U} \mid u_u$ is the unit emission to produce one ton of subproduct j_j in the industry t_t of the origin country z_z using the process m_m in the scope $s_s\}$ and
$\forall i_i \epsilon \mathbf{I}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \forall m_m \epsilon \mathbf{M}, \exists u_{i,t,z,m} \subset \mathbf{U} : u_{i,t,z,m} =$
$\{u_u \epsilon \mathbf{U} \mid u_u$ is the unit emission to produce one ton of specific product i_i in the industry t_t of the origin country z_z using the process $m_m\}$ and
$\forall i_i \epsilon \mathbf{I}, \forall t_t \epsilon \mathbf{T}, \forall z_z \epsilon \mathbf{Z}, \exists u_{i,t,z} \subset \mathbf{U} : u_{i,t,z} = \{u_u \epsilon \mathbf{U} \mid u_u$ is the average unit emission to produce one ton of specific product i_i in the industry t_t of the origin country $z_z\}$

Indices

z	origin country
t	industries
l	energy commodities
h	HS2 product
i	specific product
j	subproduct
a	input material
b	output material
m	process

Parameters

F	emission factor, in tCO_2/GJ
D	carbon content, in tCO_2/tC
P	percentage of usage of processes, in %
Q	quantity, in t
C	energy consumption, in GJ

Variables

E	CO_2 emissions, in tCO_2
U	unit CO_2 emissions, in tCO_2/t of product

Data availability

The data that has been used is confidential.

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