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Incorporating composition into life cycle assessment of steel grades

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ABSTRACT

Steel is a vital material in modern industries due to its versatility and remarkable properties. In a world that is increasingly concerned about the environment, it is necessary to incorporate good practices that help reduce the environmental impact of our economies. An important aspect is evaluating the environmental impact of materials throughout their life cycle. However, calculating this impact using generic databases can be challenging, as they may lack the necessary specificity. To obtain more accurate environmental impact calculations, it is essential to consider the composition of the materials. Each steel grade, for example, can vary in the content of alloying elements, which influences its environmental impact. Therefore, particularising calculations based on compositions is essential for making informed and sustainable material selection decisions. This article presents a calculation methodology to establish a Life Cycle Inventory of steel, emphasising the specific composition and using datasets of steel production in a Basic Oxygen Furnace (BOF) developed by ecoinvent as reference. The methodology presented seeks to allow the systematic calculation of the environmental impact of any steel considering its composition, contribute to the incorporation of environmental criteria in the selection of materials, and quantify the content of critical raw materials according to the latest report published by the European Union. Likewise, a case study is included, in which the composition's influence on the environmental impact of 10 steel grades widely used in induction cooktops has been analysed.

1. Introduction

For centuries, steel has been a vital material in industries (Kim et al., 2022), offering excellent physical, mechanical, chemical, and manufacturing properties (Murray, 1997; Shi et al., 2022). It is widely used in the construction and automotive sectors (Hua et al., 2022; Nezamoleslami and Hosseinian, 2020), in household appliances, machinery manufacture, and the infrastructure of several industries (Black et al., 2008). In 2021, world crude steel production reached 1951 million tons (World Steel Association, 2022) due to its availability, low cost, and good mechanical properties. The steel industry is, therefore, a strategic sector in the modern world and is a vital component in many national economies (Fan and Friedmann, 2021). However, steel production is energy-intensive with significant environmental impacts on the industry, including high carbon emissions (Kappenthuler and Seeger, 2021; Mitrašinović and Tomić, 2022) and the use of non-renewable steel alloying elements with high supply vulnerability (Graedel et al., 2015). Most research in the field of steel industry sustainability has focused on improving energy efficiency (He and Wang, 2017; Hu and Zhang, 2017; Rojas-Cardenas et al., 2017), reducing CO_2 emissions (Axelson et al., 2021; Duan et al., 2017; Kildahl et al., 2023; van Dijk et al., 2017), and the recycling of steel scrap (Nechifor et al., 2020; Panasiuk et al., 2022; Wang et al., 2018).

Ecological deterioration and climate change have become significant concerns (Li et al., 2021; Sen et al., 2021), prompting the European Union (EU) to focus on sustainable development through environmental protection policies (Sala et al., 2021). One such policy is "The Ecodesign Directive" (2009/125/EC) (European Parliament, 2017), which aims to reduce the impact of a product's entire life cycle by incorporating environmental criteria into design decisions (Baki, 2022; Zhao et al., 2016).

A new production model called Circular Economy (CE) has also emerged, focusing on improving material applications, extending product lifespan, and achieving efficient resource management (Gillott et al., 2023; Godoy León et al., 2022; Pollard et al., 2021; Wang et al., 2018). The EU has established a sustainability strategy in the CE framework (European Commission, 2020). Regarding the efficient management of resources, the EU created in 2015 a list of Critical Raw Materials (CRM) (European Commission, 2014) that combines economic

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Abbreviations

BOF	Basic Oxygen Furnace
CE	Circular Economy
CRM	Critical Raw Materials
EU	European Union
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

importance and high-supply risk, which is reviewed and updated every three years (the last one was published in 2023) (Milan et al., 2023).

Material selection is a critical phase in product design, production, and marketing (Ajith et al., 2022), as it involves balancing economic, social, and environmental criteria (Casanovas-Rubio and Armengou, 2018; Lütkehaus et al., 2022), sometimes conflicting (Dornfeld, 2014; Emovon, 2020). While functional and cost factors are usually the main criteria, and the predominant literature on materials research focuses on technical and mechanical studies, there is limited understanding of the decision-making process from a sustainability perspective (Pollini and Rognoli, 2021). This lack of knowledge is often a significant barrier to incorporating environmental criteria into material selection processes. Nonetheless, more studies are progressively considering the environmental impact assessment in the material selection phase (Aghazadeh and Yildirim, 2021; Almeida et al., 2017; Borchardt et al., 2011; Giudice et al., 2005; Ogunseitan and Schoenung, 2012). Life Cycle Assessment (LCA) provides a practical and widely recognised approach to determining a material's potential environmental impact throughout its life cycle (Crenna et al., 2019; Mendoza Beltran et al., 2020; Wiedema et al., 2013) by identifying and quantifying energy and material inputs and outputs (Brondi and Carpanzano, 2011; Liu et al., 2022; Pons et al., 2020), which is known as Life Cycle Inventory (LCI).

However, LCI development, the most challenging phase of an LCA performance (Dér et al., 2022; Meng et al., 2015), is often hindered by the complexity and interconnections involved in primary data collection (Iosif et al., 2008; Schneider et al., 2019), which leads to the creation of databases with inherent difficulties and constraints, such as a lack of transparency of data origin or the inadequacy of data for projecting conditions (Ferrari et al., 2021; Frischknecht and Rebitzer, 2005; Margallo et al., 2021; Rödger et al., 2021).

Researchers focusing on the global steel industry have highlighted the importance of LCA in environmental assessment (Burchart-Korol, 2013). The studies usually focus on assessing the environmental implications of different manufacturing processes. Efforts are also being made to have a more comprehensive understanding of the environmental performance of technological innovations in steel production, which can potentially lead to improvements in the sustainability of the sector, with advancements such as, direct reduction with electrical melting (Suer et al., 2022), "Power to gas" (Perpiñán et al., 2023), or "Power to X" (Bailera et al., 2021; Otto et al., 2017), which aim to integrate renewable power into the steel manufacturing process.

Regarding steel material selection, the intentional alloying of steel has only been practised for about 150 years (Seetharaman et al., 2014), allowing for the remarkable development of the steel industry. The addition of alloying elements, such as manganese, chromium, and copper, modifies steel's physical and mechanical properties. The effects of different alloying elements used in steel production have been widely explained in the literature (Han et al., 2019; IMOA et al., 2020; Kalpakjian et al., 2008; Yang et al., 2022). The steel industry has developed many alloys, and more than 3500 steel grades are available on the market (Worldsteel Association, 2021).

According to EN 10020:2001 (AENOR, 2001), steel is classified into three types depending on the amount of alloying elements present in their composition: carbon steel, alloy steel, and stainless steel. Carbon steel has a low content of alloying elements, alloy steel has a significant number of alloying elements, and stainless steel has high corrosion resistance due to its high chromium content. Many of these alloying elements are considered CRM for the EU.

It should be noted that each alloying element has different negative effects on the environment, implying that the different steel grades (which have varied compositions) show different environmental impacts. Several LCA studies in the steel industry in the literature focus on the environmental implications of the different existing steel-making processes. In particular, Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) (Backes et al., 2021), which are predominant in the industry (Burchart-Korol, 2013).

The environmental impact of steel lies not only in its production process but also in the specific applications in which it is used, as well as in the use phase and the end-of-life stages, as it is a promising material in the circular economy model (Nechifor et al., 2020; Roy et al., 2022b). The use of steel in a specific application implies significant impacts on the environment, primarily if used in large quantities, as in the construction sector, for example (Johnston et al., 2018), which is a sector with high environmental impacts (Dani et al., 2022; Roy et al., 2022a).

There is extensive research on analysing the composition of steel alloys and their properties for particular applications (Chen et al., 2022; Feng et al., 2023). However, although no special emphasis has been placed on the influence of alloying elements, for certain grades of steel and impact categories, the environmental impact caused by the alloying elements can account for more than 50% of the total impact and even higher in some cases.

A more in-depth understanding of the environmental implications of adding these alloying elements will help to gain a more holistic perspective within this field of study and allow engineers to select material grades in a more environmentally conscious way.

As mentioned above, databases are commonly used to develop an LCI. The ecoinvent database only provides information on three generic types of steel (corresponding to the categories included in EN 10020:2001 (AENOR, 2001) standard): carbon, alloyed, and stainless steel (Classen et al., 2009). The composition given by these datasets may differ significantly from the actual composition of the over 3500 grades of steel on the market. Therefore, when calculating the environmental impact of a product containing steel, it is common to approximate the actual steel grade with one of the three generic steel grades available in the database. This lack of discretisation of the environmental impact according to the composition not only incurs an approximation but also hinders the decision-making process when selecting one steel grade or another.

This study aims to develop a methodology that allows a more accurate calculation of the environmental impact of steel, considering the specific composition. It proposes to systematise the characterization of this vital material's environmental impact in industries, emphasising composition, and thus allowing the consideration of more accurate environmental criteria in the material selection process of steel grades.

2. Life cycle assessment methodology

2.1. Objective definition and functional unit

The main objective of this research is the development of a methodology to incorporate the composition in the LCA of Steel Grades, allowing for a better material selection process. This methodology will pursue:

- The systematic calculation of the environmental impact of any steel grade considering its composition.
- To contribute to incorporating environmental criteria in the material selection process.

- To quantify CRM content according to the latest list published by the EU (Milan et al., 2023), thus contributing to a better management of critical materials in the industry.

The study was conducted with an LCA approach following the requirements established by ISO 14040 (AENOR, 2006a) and ISO 14044 (AENOR, 2006b) international standards. The functional unit is defined as the production of 1 kg of steel produced in a BOF.

2.2. Software, database, and impact methodologies

The study used the software SimaPro 9.3.0.3 (Various authors PRé Sustainability, 2020) and ecoinvent v3.8 database (About ecoinvent, 2022) to perform the LCA. The environmental impact assessment methodology applied was CML-IA baseline V3.07/EU25 (Leiden University, 2016). The CML methodology has a *midpoint* approach and includes 11 impact categories that are assessed objectively and independently (Leiden University, 2016).

It should be noted that the calculation methodology presented in this article is used to establish the LCI of steel production and is therefore applicable to other different environmental impact methodologies.

2.3. System Boundaries and assumptions

This methodology focuses on steel produced in a BOF, as this manufacturing route is the dominant worldwide process in steel production and the most energy-intensive process (Song et al., 2019; The European Steel Association, 2021). Fig. 1 shows all material and energy inputs and outputs considered in steel production in a BOF with a cradle-to-gate scope. This LCI is based on ecoinvent v3.8 datasets for steel making via BOF (Ecoinvent Centre, 2021a, 2021b), which establishes its data on primary information provided by 21 BOF factories throughout Europe (Commission of the European Union and Joint Research Centre. Institute for Prospective Technological Studies, 2013). These datasets available from ecoinvent (Classen et al., 2009) are backed up by high-quality reports that also include an LCI characterisation of the steel industry by-products (Commission of the European Union and Joint Research Centre. Institute for Prospective Technological Studies, 2013; Turner and Symeonidis, 2020). Therefore, it has been considered:

- The acquisitions of raw materials, including the extraction and processing of the *gross metallic charge*, the different *alloying elements*, and the auxiliary materials necessary to steel production.
- The transport of the raw materials to the steel production plant.
- The steel production stages in a BOF, including 1) pre-treatment of hot metal (pig iron) from the blast furnace; 2) mixing of charge (including alloying additions), weighing, transfer, and reloading; 3) oxidation in the BOF; 4) secondary metallurgical treatment in a ladle furnace; and 5) casting (Ecoinvent Centre, 2021a, 2021b).

It should be noted that the calculation methodology developed in this paper concerns the calculation of the quantity of *raw materials* (*gross metallic charge* -pig iron, iron ore, and iron scrap-, and all *alloying elements*) needed for the inventory from a given steel composition. This calculation methodology is detailed in the following subsection. The rest of the elements involved as inputs and outputs of the production system (energy, water, auxiliary raw materials, emissions, and by-products) are directly taken from the ecoinvent v3.8 dataset for steel making via BOF (Ecoinvent Centre, 2021a, 2021b), as the aim is to analyse the influence of the composition from a material selection perspective. These will be treated as a whole "production process", invariable for the different steel grades.

2.4. Calculation methodology of raw materials

The systematic method for establishing the amount of raw materials to be considered in the LCI of the production of a steel grade (given its composition) is shown in this section. For the development of this methodology, an exhaustive analysis of the information provided by a series of documents on steel manufacturing has been carried out, specifically:

- The datasets for the characterisation of steel available in the latest version of ecoinvent v3.8, particularly those corresponding to "Steel, low-alloyed {RER}| steel production, converter, low-alloyed" (Ecoinvent Centre, 2021a) and "Steel, unalloyed {RER}| steel production, converter, unalloyed" (Ecoinvent Centre, 2021b).
- The "Best Available Techniques (BAT) in Iron and Steel Production in the European Union" report (Commission of the European Union and Joint Research Centre. Institute for Prospective Technological Studies, 2013), developed by the Institute for Prospective Technological Studies of the Joint Research Centre of the European Commission, on which the above-mentioned ecoinvent databases are based and considered data from primary information provided by 21 BOF factories through Europe.

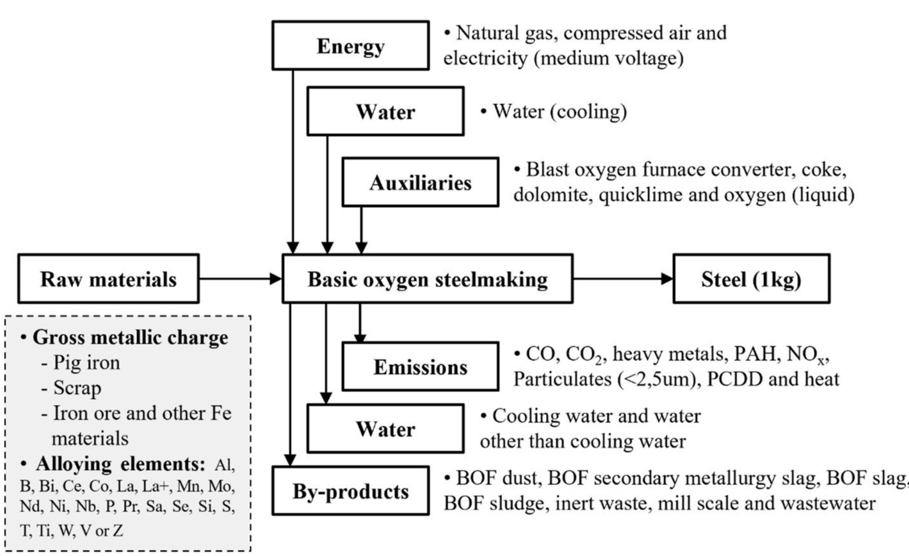

Fig. 1. System boundaries.

- The document for the life cycle inventory of metals developed by ecoinvent (Classen et al., 2009).

To produce 1 kg of steel, it is necessary to incorporate 10.4% additional raw materials, according to ecoinvent data, meaning that the total sum of raw materials (*gross metallic charge* and the *alloying elements)* required for producing 1 kg of steel is 1.104 kg (Ecoinvent Centre, 2021b).

The *alloying elements* will vary in type and quantity depending on the steel grade composition obtained from the standard. The composition adjustment is usually made by ferro alloying (e.g., Fe/Ni, Fe/Mo, Fe/Mn, Fe/Cr), presented in solid or wire form, or by powder injection through lances (Commission of the European Union and Joint Research Centre. Institute for Prospective Technological Studies, 2013). A list of the most frequent alloying elements and their allocation with the datasets available in ecoinvent are presented in Table 1. These have been allocated to different datasets, following the same ecoinvent methodology (Classen et al., 2009). To consider the transportation of raw materials to the steel production plant, "market for" datasets have been selected. The richness of the material assigned has been considered for this calculation in the same way as ecoinvent does. Thus, for example, in the inventory proposed by ecoinvent for low-alloyed steel in its final report on Life Cycle Inventories of Metals (Classen et al., 2009), for a 2.15% Cr content, which would require an input of 0.0215 kg, as it is assigned as ferrochromium with a richness of 68%, resulting in 0.0316 kg of Cr being introduced.

It should be noted that the composition of steel grades is often specified in the standards by composition ranges, which establish a minimum and maximum content for each alloyant. Thus, to calculate the average environmental impact of each steel grade, the average value of each alloying element, according to the composition ranges established by the standard, is entered in the LCI. These results in an LCI model that provides the average environmental impact, which is taken as a reference when presenting the results.

However, since each alloying element has different environmental impacts, which are also different depending on the selected environmental categories, different combinations of them (within the composition range stipulated by the standard) can result in different environmental impacts. Therefore, the methodology requires two additional LCI models for each environmental impact category, allowing for analysis of the variability of results. Rather than just considering the average value of the result, it is possible to assess the inherent uncertainty caused by the composition ranges specified in the standards.

- **Minimum impact composition model:** this composition results in the lowest possible environmental impact, assigning the maximum composition range to those alloying elements with the lowest environmental impact, up to 100% of the composition.
- **Maximum impact composition model:** this composition gives rise to the highest possible environmental impact, assigning the maximum composition range to those alloying elements with the highest environmental impact.

Table 1
Main dataset ecoinvent for alloying elements.

Alloying Element	Dataset ecoinvent 3.8
Al	Aluminium, cast alloy {GLO}| market for
S	Sulfur {GLO}| market for
Ti	Titanium {GLO}| market for titanium
Cu	Copper oxide {GLO}| market for
B	Boron carbide {GLO}| market for
Mn	Ferromanganese, high-coal, 74.5% Mn {GLO}| market for
Cr	Ferrochromium, high-carbon, 68% Cr {GLO}| market for
Mo	Molybdenite {GLO}| market for
Si	Ferrosilicon {GLO}| market for
P	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market for
Ni	Ferronickel {GLO}| market for ferronickel

Fig. 2 shows graphically the assignment process of allocating the content of alloying elements of a given steel grade. First, the alloying elements must be ordered according to the environmental impact per kilogram and the impact category analysed. Consequently, for calculating the maximum environmental impact, the methodology assigns the highest possible content to those alloying elements with a higher environmental impact than the gross metallic charge, always complying with the composition ranges established in the standard. Analogously, it applies to the case of minimum environmental impact, where the highest possible content is assigned to those elements with lower environmental impacts. In the example in Fig. 2, the assignment is made for the specific steel case 1.4016 and the Global Warming impact category (GWP100y). Therefore, the allocation will be different for each steel grade (due to the different composition ranges), and also for each impact category (due to the reordering of the alloying elements according to their environmental impact per kilogram).

Once the amount of *alloying elements* considered in the steel grade has been established, the *gross metallic charge* content is calculated. Three types are distinguished, whose quantity per kg of steel produced has been established as follows:

- **Pig iron:** variable quantity according to the alloy content of the steel grade produced. Due to the limitations of the production process, it cannot exceed 70–80% of the total mass (Wang, 2016). A maximum pig iron content of 0.865 kg (78.4%) has been established, according to data provided by ecoinvent (Ecoinvent Centre, 2021b).
- **Iron scrap:** also variable quantity according to the alloy content. In the case of steel grades with low alloy content, scrap is added up to achieve1.104 kg of raw materials so as not to exceed 0.865 kg of pig iron (Ecoinvent Centre, 2021b).
- **Iron ore:** this quantity is set at $6.00 \cdot 10^{-4}$ kg according to average data in Europe (Commission of the European Union and Joint Research Centre. Institute for Prospective Technological Studies, 2013; Ecoinvent Centre, 2021a, 2021b) and has been considered invariable regardless of the composition of the steel grade.

Thus, the methodology first calculates the content of *alloying elements* present in the steel grade according to the composition established by the standard. Once the alloy content has been selected, it calculates the necessary amount of *metallic charge* (pig iron and iron scrap) according to the limits mentioned above: it will include the required amount of pig iron without exceeding the limit of 0.865 kg and, in case the total amount of 1.104 kg is not reached, it will complete the inventory with the necessary amount of scrap, as explained in Fig. 3. This way, knowing the composition of the analysed material, it is possible to establish the content needed for the rest of the raw materials.

For example, for a steel grade with an alloying element content of 0.27 kg, 0.813 kg of Pig Iron will be added to complete the 1.104 kg of raw material (including $6.00 \cdot 10^{-4}$ kg of iron ore). In case a steel grade has a lower amount of alloying elements, 0.12 kg, for example, pig iron will be added up to the limit of 0.865 kg, having to add the remaining 0.118 kg of iron scrap to complete the 1.104 kg of raw material.

The methodology proposed in this study can be helpful for both suppliers of steel grades to quantify their environmental impact on their customers and for companies that use steel in their products to include this environmental information in the decision-making in the design phase of their products (for material selection) or to opt for suppliers that provide steel grades with specific common characteristics, but different compositions with lower environmental impact, or CRM presence. This methodology is an iteration based on current ecoinvent steel datasets and methodology, but allowing to take into account the composition, instead of choosing between the only two BOF steel datasets available in ecoinvent.

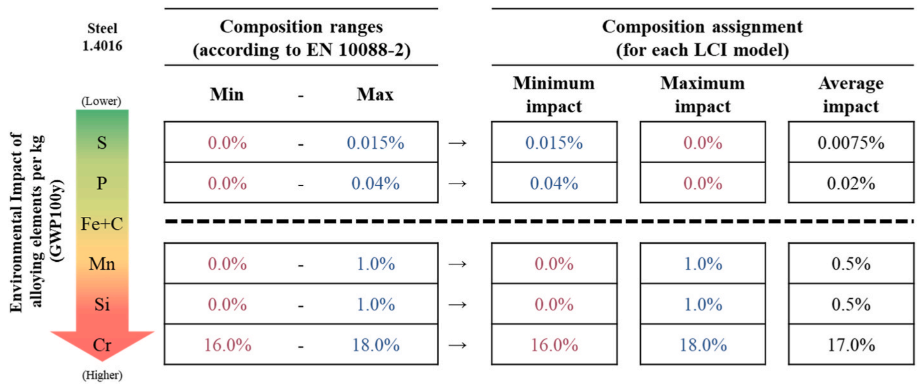

Fig. 2. Composition assignment example (calculation of alloying elements content).

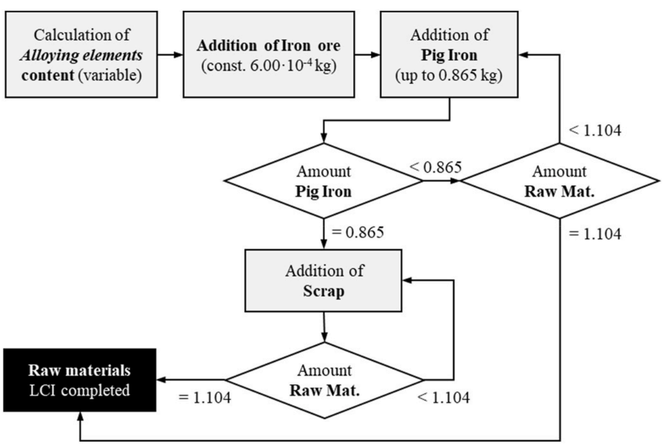

Fig. 3. Flow chart calculation of raw materials for 1 kg of steel.

It should be noted that this methodology is based on both primary and secondary data. Therefore, it is still an approximation in calculating the environmental impact of steel grades. Obtaining primary data for specific steel grades would always lead to more accurate results on the environmental impact of steel.

The environmental impact can be calculated from the composition specified by the standards, which specify the properties and supply compositions of different steel grades. This already provides a more accurate environmental impact calculation compared to generic databases. However, this calculation can be further particularised through spectrometry analysis that provides the exact composition of samples of the material to be studied. It is also possible to further improve the accuracy of the calculation through other specific information (e.g. energy consumption of the manufacturing process, transports between manufacturing plants, etc.), which steel suppliers could provide to their clients or LCA practitioners.

The methodology allows for establishing an LCI of steel production based on its composition. To compare the LCI proposed by this methodology with that obtained by ecoinvent, the variations in the impact resulting from introducing the composition of the unalloyed and low-alloyed steels included by ecoinvent v3.8 in the methodology explained in this section are shown in Table 2. The results vary by less than 1.69% at most for Alloy steel and 0.15% for Carbon steel, which is considered an adequate fit.

2.5. *Critical raw materials content*

As a result of this methodology, in which the amount of raw materials used for the production of steel, both the *metallic charge* and the *alloying elements*, is calculated, it is possible to calculate the CRM content according to the EU. Of the more than 25 alloying elements that can be part of the composition of steel, according to EN 10020:2001 (AENOR, 2001) standard, sixteen of them are considered to be CRM according to the 2023 list (Milan et al., 2023): aluminium, borate, bismuth, cobalt, Heavy Rare Earth Elements (such as cerium, neodymium, praseodymium, and samarium), Light Rare Earth Elements (such as lanthanum); manganese, niobium, phosphorus, silicon, titanium, vanadium, and tungsten.

3. Case study: steel grades used in induction cooktops

In order to demonstrate the methodology's usefulness, the following case study analyses the environmental impact per kilogram of 10 steel grades that engineers commonly use in the mechanical architecture of induction cooktops. Steel is the second most used material (by weight) in standard induction cooktops after ceramic glass (Pina et al., 2015). Thanks to the calculation methodology presented in this paper, it has

Table 2
Comparison of the environmental impact results of methodology to ecoinvent v3.8

		Carbon Steel			Alloy Steel		
Category	Unit	ecoinvent	Method	Dif.	ecoinvent	Method	Dif.
Abiotic depletion	kg Sb eq	3,80E-06	3,79E-06	0,09%	3,44E-05	3,38E-05	1,69%
Abiotic depletion (fossil fuels)	MJ	1,41E+01	1,41E+01	0,14%	1,83E+01	1,83E+01	−0,29%
Global warming (GWP100a)	kg CO2 eq	1,68E+00	1,67E+00	0,14%	2,08E+00	2,09E+00	−0,26%
Ozone layer depletion (ODP)	kg CFC-11 eq	7,16E-08	7,15E-08	0,13%	8,78E-08	8,83E-08	−0,55%
Human toxicity	kg 1,4-DB eq	2,23E+00	2,23E+00	0,07%	3,22E+00	3,21E+00	0,09%
Fresh water aquatic ecotox.	kg 1,4-DB eq	3,85E+00	3,85E+00	0,03%	6,00E+00	6,00E+00	0,01%
Marine aquatic ecotoxicity	kg 1,4-DB eq	4,70E+03	4,70E+03	0,06%	6,96E+03	6,96E+03	0,00%
Terrestrial ecotoxicity	kg 1,4-DB eq	1,18E-03	1,18E-03	0,12%	2,29E-03	2,31E-03	−0,63%
Photochemical oxidation	kg C2H4 eq	8,43E-04	8,42E-04	0,14%	9,46E-04	9,49E-04	−0,27%
Acidification	kg SO2 eq	5,02E-03	5,01E-03	0,15%	7,33E-03	7,36E-03	−0,31%
Eutrophication	kg PO4— eq	2,94E-03	2,94E-03	0,11%	3,73E-03	3,74E-03	−0,16%

been possible:

- To assess the variability of the environmental impact results of the different types of steel studied (comparing the results with the environmental impact of the three generic steel types available in ecoinvent).
- To analyse the influence of the composition on the environmental impact of steel grades.
- To quantify the CRM content.

3.1. Steel grades compositions

Table 3 shows the composition of the ten steel grades. These compositions have been obtained from the different standards that establish the supply conditions for steel grades, including the composition, among other parameters. These materials, in the case of using the ecoinvent database, instead of being particularised, should be approximated according to the three types of steel available:

- **Carbon steel:** EN-10270 SH and 1.0347
- **Alloy steel:** 1.0917, 1.0951, 1.1231, and 1.5525
- **Stainless steel:** 1.4016, 1.4104, 1.4301, and 1.4509

Table 3 also shows the average compositions of the generic steel grades included in ecoinvent v3.8, given by their datasets.

3.2. Environmental impact of steel in an induction cooktop

Based on the compositions obtained from standards and using the methodology presented in section 2.3, an LCI was carried out for the 10 steel grades included in the case study. These inventories particularised according to the actual steel composition, allowed a more accurate calculation of the environmental impact.

Table 4 shows the results of the average environmental impact per kilogram of material of the different analysed steel grades, according to CML methodology. The results presented are the percentage of the impact relative to the values obtained for each type of ecoinvent generic steel, considering these results as the 100% reference.

3.2.1. Carbon steel

The carbon steel 10270-SH has the highest environmental impact out of all carbon steel grades, including ecoinvent's generic carbon steel grades. This is mainly because it contains copper, which significantly impacts the environment. However, the impact difference between these steel grades and ecoinvent's generic carbon steel is small, except for the *abiotic depletion* category, in which the impact is almost 4.5 times higher for 10270-SH. Despite containing only 0.1% copper on average, copper has 70 times higher impact than phosphorus (the following highest environmental impact alloying element) and 930 times higher than manganese, which is the most present element in these steel grades. This is mainly due to smelting copper concentrates to produce copper anodes and electrorefining copper anodes to produce high-grade copper cathodes.

3.2.2. Alloy steel

Among the studied alloy steel grades, ecoinvent's generic alloy steel has the highest impact in 8 of the 11 categories analysed. Overall, the deviations among the analysed grades of alloy steel are moderate.

- In the *abiotic depletion* category, only 1.1231 has a higher impact than ecoinvent's generic alloy steel (178.8%). Steel grade 1.5525 has an impact of 62.1% of ecoinvent's generic alloy steel, and 1.0917 and 1.0951 have around 13% of its impact. Molybdenum and copper are two relevant alloying elements in this impact category (per kg), with orders of magnitude two or three times higher than the other alloying elements present in the studied alloy steel grades. The impact of molybdenum is given to a greater extent by mining and beneficiation of copper sulphide ores since this element is commonly obtained as a by-product of copper-molybdenum deposits (Henckens et al., 2018) The impact of copper is mainly produced by smelting copper concentrates to make copper anodes and the electrorefining of copper anodes to produce high-grade copper cathodes. Steel grades 1.1231 and 1.5525 are penalised by the presence of these two alloying elements. In contrast, 1.0917 and 1.0951 are free of both molybdenum and copper and also have lower proportions of other alloying

Table 3
Composition of steel grades used in induction cooktops.

Material		C	Si	Mn	P	S	Cr	Cu	Others	Source
Carbon Steel										
ecoinvent	Av.	–	–	0.45	–	–	–	–	–	ecoinvent (Ecoinvent Centre, 2021b)
10270 SH	Min	0.35	0.10	0.40			–		–	EN 10270-1 (AENOR, 2017a)
	Max	1.00	0.30	1.20	0.035	0.035		0.20		
1.0347	Min		–				–	–	–	EN 10152 (AENOR, 2017b)
	Max	0.10		0.45	0.035	0.035				
Alloy Steel										
ecoinvent	Av.	–	–	1.14					Mo: 0.035	ecoinvent (Ecoinvent Centre, 2021a)
									Ni: 1.125	
1.0917	Min						–	–	Ti: 0.30	EN 10346 (AENOR, 2015a)
	Max	0.18	0.50	1.20	0.12	0.045				
1.0951	Min						–	–	Ti: 0.30	EN 10346 (AENOR, 2015a)
	Max	0.12	0.50	0.60	0.10	0.045				
1.1231	Min	0.65	0.15	0.60					Mo: 0.10	EN 10132 (AENOR, 2021)
	Max	0.73	0.35	0.90	0.025	0.025	0.40	0.30	Ni: 0.40	
1.5525	Min	0.18		0.90					Al: ≥0.02	EN 10269 (AENOR, 2014)
	Max	0.23	0.3	1.20	0.025	0.025	0.3	0.25	B: 0.0008-0.005	
Stainless Steel										
ecoinvent	Av.	–	–	–	–	–	18.0	–	Ni: 8.0	ecoinvent (Ecoinvent Centre, 2021c)
1.4016	Min						16.0	–	–	EN 10088-2 (AENOR, 2015b)
	Max	0.08	1.00	1.00	0.04	0.015	18.0			
1.4104	Min	0.10				0.15	15.5	–	Mo: 0.20-0.60	EN 10088-3 (AENOR, 2015c)
	Max	0.17	1.00	1.50	0.04	0.35	17.5			
1.4301	Min						17.5	–	N: 0.10	EN 10088-2 (AENOR, 2015b)
	Max	0.07	1.00	2.00	0.045	0.015	19.5		Ni: 8.0–10.5	
1.4509	Min						17.5	–	Ti: 0.10-0.60	EN 10088-2 (AENOR, 2015b)
	Max	0.03	1.00	1.00	0.04	0.015	18.5			

Table 4
Environmental Impact per kilogram (CML-IA baseline Methodology).

		Abiotic depletion [kg Sb eq]	Abiotic depletion (fossil fuels) [MJ]	Global warming (GWP100y) [kg CO_2 eq]	Ozone layer depletion (ODP) [kg CFC-11 eq]	Human toxicity [kg 1,4-DB eq]	Freshwater aquatic ecotoxicity [kg 1,4-DB eq]	Marine aquatic ecotoxicity [kg 1,4-DB eq]	Terrestrial ecotoxicity [kg 1,4-DB eq]	Photochemical oxidation [kg C_2H_4 eq]	Acidification [kg SO_2 eq]	Eutrophication [kg PO_4— eq]
Carbon Steel	ecoinvent	3.80E-06	1.41E+01	1.68E+00	7.16E-08	2.23E+00	3.85E+00	4.70E+03	1.18E-03	8.43E-04	5.02E-03	2.94E-03
		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	10270 SH	447.9%	105.4%	103.0%	105.2%	125.6%	109.5%	109.6%	130.0%	103.8%	114.5%	109.4%
	1.0347	102.2%	99.6%	99.5%	99.8%	99.0%	99.2%	99.3%	99.5%	99.8%	99.2%	99.6%
Alloy Steel	ecoinvent	3.44E-05	1.83E+01	2.08E+00	8.78E-08	3.22E+00	6.00E+00	6.96E+03	2.29E-03	9.46E-04	7.33E-03	3.73E-03
		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	1.0917	13.4%	85.4%	86.1%	95.2%	75.7%	69.4%	74.3%	60.0%	96.0%	77.3%	87.0%
	1.0951	13.2%	84.9%	85.5%	94.8%	74.6%	68.6%	73.4%	59.3%	95.7%	76.1%	86.2%
	1.1231	178.8%	87.1%	87.7%	90.9%	148.6%	84.9%	88.1%	125.1%	96.0%	88.9%	97.8%
	1.5525	62.1%	82.9%	84.8%	88.7%	115.5%	72.3%	76.7%	103.5%	94.1%	82.8%	88.3%
Stainless Steel	ecoinvent	1.36E-04	4.90E+01	5.08E+00	2.00E-07	9.68E+01	1.76E+01	1.93E+04	9.00E-02	1.51E-03	2.36E-02	8.31E-03
		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	1.4016	67.1%	53.2%	57.5%	55.2%	91.7%	29.7%	36.2%	87.1%	73.2%	43.8%	59.5%
	1.4104	224.4%	53.6%	57.8%	55.5%	93.0%	43.9%	50.8%	85.4%	73.5%	46.5%	79.7%
	1.4301	107.1%	110.6%	108.4%	109.8%	103.4%	112.6%	112.0%	103.9%	105.0%	111.4%	110.3%
	1.4509	71.4%	57.7%	61.6%	66.3%	97.2%	33.3%	40.9%	92.5%	79.8%	48.6%	64.6%

elements that are not as significant for this category, such as manganese, presenting a lower environmental impact.

- For the impact categories *abiotic depletion (fossil fuels), global warming (GWP100y),* and *ozone layer depletion,* all the particularised steel grades have a slightly lower environmental impact than ecoinvent's generic alloy steel, with around 85% of its impact for the first two categories and 92% for the *ozone layer depletion* category.
- In *human toxicity* and *terrestrial ecotoxicity* categories, 1.1231 and 1.5525 have higher environmental impacts than ecoinvent's generic alloy steel, which has the highest environmental impact. As in the *abiotic depletion* category, molybdenum and copper are alloying elements with a high impact per kg. However, both are only one order of magnitude more than the other alloying elements on this occasion. In addition, there is the influence of chromium, which has an environmental impact of the same order of magnitude as the elements mentioned above due to the production of ferrochromium. In this case, the impact of molybdenum is produced in the management of sulphidic tailings, while in the case of copper, it is still the smelting and electrorefining operations. Steel grades 1.1231 and 1.5525 are penalised by the presence of these three alloying elements. On the other hand, 1.0917 and 1.0951 (free of these elements) have the lowest impacts, very similar to each other, and around two-thirds of the impact of ecoinvent's generic alloy steel.
- As for the impact categories *freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, acidification, and eutrophication,* all particularised alloy steel grades have lower impacts than ecoinvent's generic alloy steel, not less than 68.6% of its impact. Steel grade 1.0951 has the lowest environmental impact. In these categories, three alloying elements are the most relevant in terms of environmental impact per kg: copper (due to the operations of smelting of copper concentrates to produce copper anodes and electrorefining of copper anodes to produce high-grade copper cathodes), titanium (due to the processes related to production of titanium sponge from titanium tetrachloride), and molybdenum (due to the management of sulphidic tailings). Copper and titanium are present in similar proportions in all the analysed steel grades, so, in this case, they do not significantly influence the impact results. However, 1.1231 has the highest impact among the particularised alloy steel grades because it contains molybdenum (0.05% on average).
- Finally, for the *photochemical oxidation* category, the impacts of the particularised steel grades are very similar to those obtained for ecoinvent's generic alloy steel and to each other (around 95%).

3.2.3. Stainless steel

In the case of stainless steel grades, 1.4301 has a more significant impact than ecoinvent's generic stainless steel in all the CML categories. On the other hand, 1.4104 only has a higher impact in the *abiotic depletion* category, and 1.0917 has the lowest impact in 10 of the 11 categories analysed.

- In the *abiotic depletion* category, 1.4104 and 1.4301 show higher impacts than ecoinvent's generic stainless steel (224.4% and 107.1%). Steel grades 1.4016 and 1.4509 have similar environmental impacts, with around 70% of the impact of ecoinvent's generic stainless steel. In general, chromium is an alloying element that influences the impact results of stainless steel, not only because it is a high-impact alloying element per kg (as it is in the *abiotic depletion* category) but also because, as defined by standards, it is present in a high proportion in this type of steel grades. However, for this category, molybdenum is an alloying element with 115 times more impact (per kg) than chromium (the second highest impact alloying element according to this category). As previously mentioned, the effect of molybdenum is, according to ecoinvent, due to the mining and beneficiation of copper sulphide ores. This high impact contributes to the fact that 1.410, the only analysed steel grade with molybdenum content, has the highest impact according to this category. On the other hand, 1.4301 is penalised in its impact by the presence of nickel. According to the abiotic depletion category, this alloying element represents a moderate environmental impact. However, it is present in a high proportion in both 1.4301 and ecoinvent's generic stainless steel.

- For the impact categories *abiotic depletion (fossil fuels), global warming (GWP100y),* and *ozone layer depletion,* 1.4301 has around 110% of the impact of ecoinvent's generic stainless steel. The rest of the analysed stainless steel grades have a considerably lower impact than ecoinvent's generic stainless steel (between 53.2% and 66.3% of their impact). In these categories, nickel has a significant impact per kg due to the heat and electricity consumption required to obtain it, which justifies the considerable variation between the steel grades without nickel content and the 1.4301 and ecoinvent's generic stainless steel. Apart from the influence of nickel, titanium is a relevant alloying element in terms of environmental impact, having an impact five times greater than nickel in the *abiotic depletion (fossil fuels)* and *global warming (GWP100y)* categories and up to 16 times greater in the case of *ozone layer depletion.* The impact of this alloying element is mainly due to the production of titanium sponge from titanium tetrachloride, penalising 1.4509, the only steel grade containing titanium, with a slightly higher impact than the other two studied steel grades (1.4016 and 1.4104).
- In *human toxicity* and *terrestrial ecotoxicity* categories*,* particularised steel grades show similar environmental impacts to ecoinvent's generic stainless steel. Steel grade 1.4301 has a slightly higher impact (103%), while the rest have a lower impact than ecoinvent's generic stainless steel (between 91.7% and 97.2%). In this category, chromium is an alloying element with a high environmental impact due to the production of ferrochromium. As chromium is present in large proportions, its presence strongly influences the impact correlation and explains the slight variations between the impacts of the steel grades. Although 1.4104 has the lowest chromium content, it also contains molybdenum, another high-impact alloying element for this category, and is, therefore, penalised.
- In the *freshwater aquatic ecotoxicity* and *marine aquatic ecotoxicity* categories, 1.4301 impacts around 112% of the impact of ecoinvent's generic stainless steel. Steel grade 1.4104 impacts around half of the latter. Steel grades 1.4016 and 1.4509 have 30–40% of this impact. In these two categories, nickel plays a major role in the impact due to the treatment of nickel smelter slags in landfills. Although it is not the alloying element with the highest impact, as it is present in large proportions in the case of ecoinvent's generic stainless steel and 1.4301, these two steel grades are penalised in terms of environmental impact. The two alloying elements with the greatest impact are molybdenum (due to the management of sulphidic tailings) and titanium (due to the management and treatment of BOF slags), which penalise the impact of 1.4104 and 1.4509 over 1.4016. In 1.4301 stainless steel, the largest contribution to impact is made by nickel. Such is the case for the freshwater aquatic ecotoxicity category, in which nickel accounts for 73.6% of the total impact of 1.4301 steel, and for the marine aquatic ecotoxicity category, which accounts for 69.0%. This impact is due to the damage caused by nickel smelter slags on aquatic ecotoxicity. For this steel grade, nickel is found in a slightly higher proportion than ecoinvent's generic stainless steel (9.25% on average vs 8%). This higher nickel content, coupled with other alloying elements that contribute to the impact (although in small quantities), results in an environmental impact of 1.4301 higher than ecoinvent's generic stainless steel. As a result of this analysis, it is verified that the absence of nickel as an alloying element (especially in large proportions) contributes to reducing the environmental impact on aquatic ecotoxicity. 1.4016 and 1.4509, which do not contain nickel or alloying elements with a significant environmental impact, manage to considerably reduce their impact. In the case of 1.4104, steel also contains no nickel but molybdenum (in meagre proportions of 0.4% of average). Molybdenum is the alloying element with the highest environmental impact per kilogram and, therefore, penalises the environmental impact of this grade of steel.
- Something similar occurs with *eutrophication* and *acidification* categories. Molybdenum and titanium are the alloying elements with the highest impact according to these categories, followed by nickel. Nevertheless, nickel has a more moderate environmental impact than in the *freshwater aquatic ecotoxicity* and *marine aquatic ecotoxicity* categories. This is why the impact variations concerning ecoinvent's generic stainless steel are lower. In this case, 1.4301 has about 111% of the impact of ecoinvent's generic stainless steel, while for the other steel grades, the effect ranges from 43.8% to 79.7%.
- For the *photochemical oxidation* category, the environmental impact of 1.4301 is slightly higher than ecoinvent's generic stainless steel (105%). Steel grade 1.4509 has 79.8% of its impact, while 1.4016 and 1.4104 have around 73%. In this category, titanium is the alloying element with the highest environmental impact due to the production of titanium sponge from titanium tetrachloride, which penalises 1.4509, being the only one containing titanium. Nickel has the second highest impact as an alloying element (per kg) in this category. In the case of ecoinvent's generic stainless steel and 1.4301, nickel is the primary alloying element that contributes to environmental impact (with 45.9% and 50.6%, respectively). This contribution to the impact is due to the photochemical pollution produced by the emissions from the heat required to produce the nickel ferroalloy. The difference between the impact of these two steel grades is that the second one has a slightly higher nickel content (9.25% vs 8%) and chromium (18.5% vs 18%). Chromium accounts for 19.1% of the total impact in 1.4301. In addition, this steel grade has another series of alloying elements (Si, Mn, P, S, N, etc) that contribute to increasing the impact, although too much lesser amount. Among the rest of the stainless steel grades analysed, the absence of nickel reduces the environmental impact. Hence, 1.4016 and 1.4104 have a quarter less environmental impact. In the case of 1.4509 steel, it is penalised by titanium, which, although present in a tiny proportion (0.35 on average), accounts for 9.5% of the total impact of this steel.

Analysing globally the environmental impact of all steel grades particularised in this case study (Fig. 4), generally, stainless steel grades show the highest environmental impacts. This is because they have a higher content of alloying elements that impact more than ferrous materials. However, this differentiation is even greater in impact categories where chromium has a significant environmental impact per kilogram. Chromium is a characteristic element of stainless steel, which must contain at least 10–12% to have the corrosion resistance characteristic of this type of steel. This is the case of the terrestrial ecotoxicity, human toxicity, and abiotic depletion categories, especially in the first one, in which chromium is the element with the most significant environmental impact (due to the production of ferrochromium).

3.3. Critical raw material content

Since 2011, the European Union has drawn up lists of critical and strategic materials for European economies. The EU has established specific criteria for identifying and classifying material as critical, regularly reviewed to reflect market developments. The two criteria currently assessed are the economic importance and the material's supply risk. Based on both criteria, it establishes a list of critical materials, updated every three years, with the last update being for 2023 (Milan et al., 2023).

Once the composition of the different steel grades has been considered, it has also been possible to quantify CRM content for the EU according to the latest list published in 2023 (Milan et al., 2023). To this end, for the LCI established for the calculation of the environmental impact, those raw materials that are considered critical for the EU are

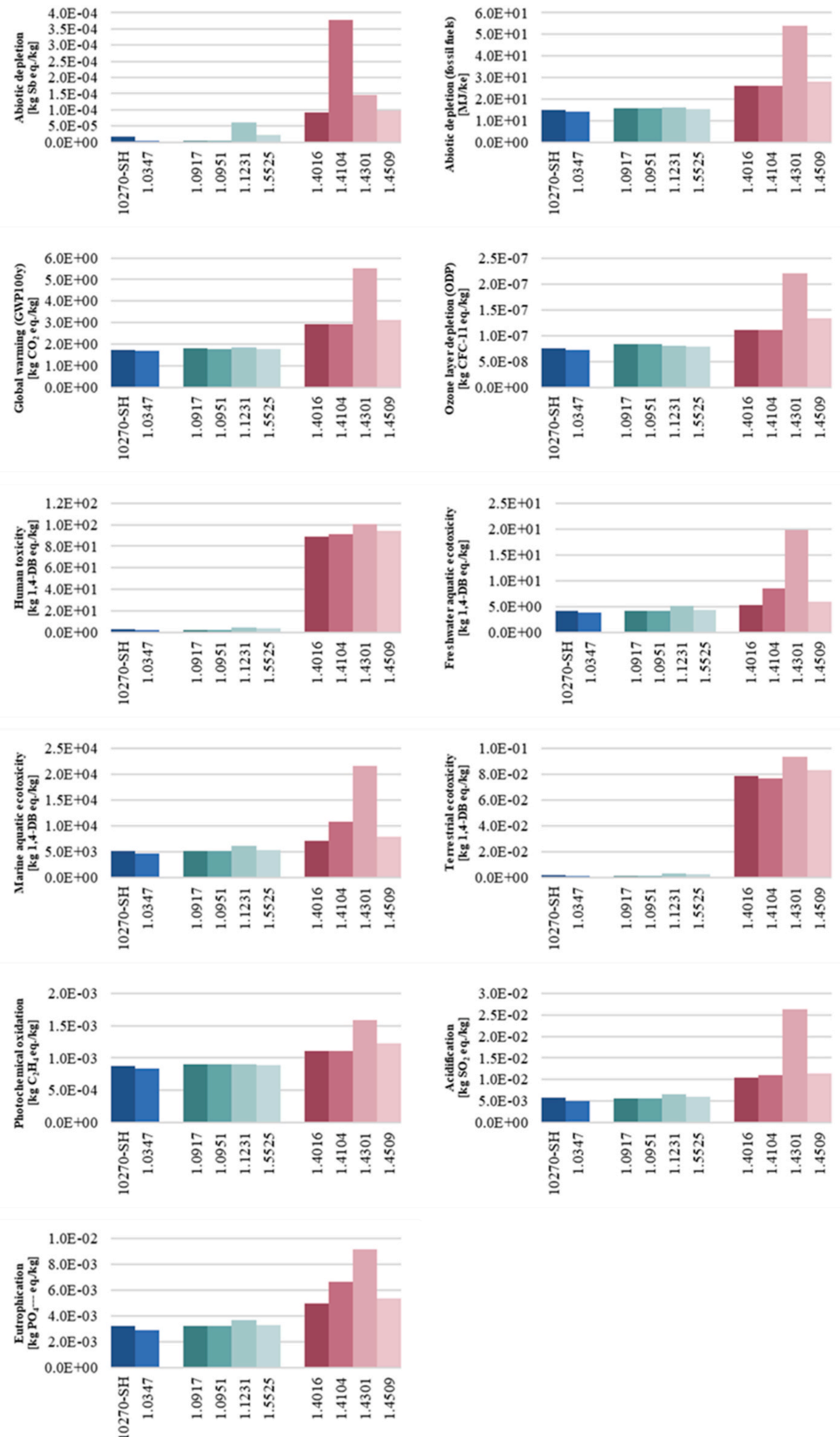

Fig. 4. Environmental impact comparison of the analysed steel grades.

added, according to the latest CRM list (2023). These results are shown in Fig. 5.

The CRM content for Carbon steel grades varies between 0% and 1.54%. As for Alloy steel grades, they are in the range of 0% and 2.13%, and in the case of stainless steel grades, they are up to 3.05%. Stainless steel grades have the highest CRM content among the types of steel studied. Stainless steel 1.4301 has the highest CRM content (1.52%). Carbon steel 1.0347 only has a CRM content of 0.24%.

It should be noted that of all the raw materials used in the manufacture of the steel studied, only certain alloying elements are currently considered CRM, according to the latest published list (2023). Specifically, aluminium, manganese, silicon, phosphorus, titanium, and boron are considered CRMs for the EU. These alloying elements are found in very low proportions in the composition of the steel grades studied, giving a low total CRM content.

Results may vary over time based on the economic and geopolitical

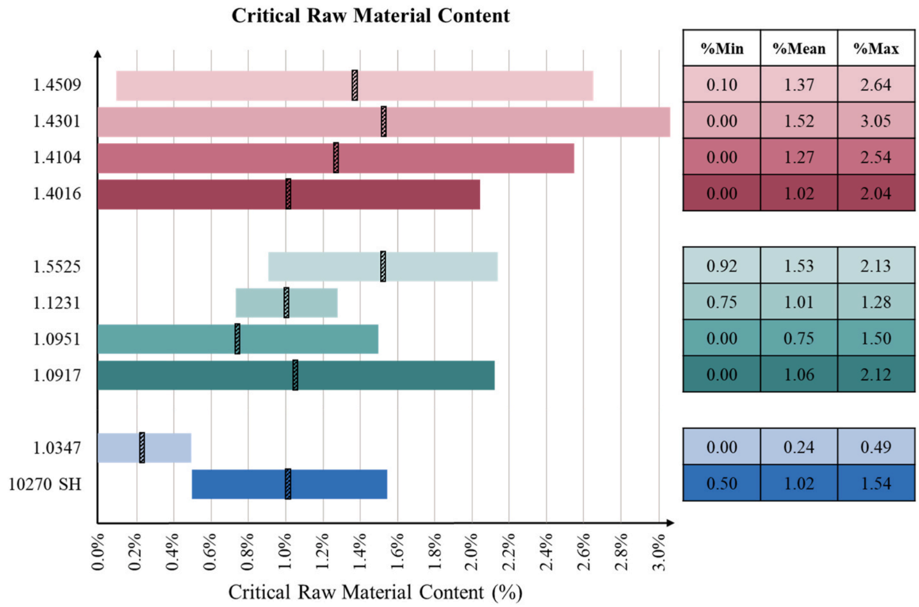

Fig. 5. CRM content according to 2023 CRM List.

situation. Results could increase if alloying elements with a greater presence in the studied steel grades were considered CRM, such as nickel (considered a strategic raw material) or chromium. Using steel grades with a lower amount of CRM allows for possible reductions in supply chain risks and price instability.

Although at present, there is no legislation restricting the use of these materials, in 2019, a European standard (EN) 45558:2019 "General method to declare the use of critical raw materials in energy-related products" (CENELEC, 2019), was published, to improve the reusability of recycled components or materials of end-of-life products. Better knowledge of the content in critical raw materials can contribute to better efficient management of valuable and scarce resources such as many alloying elements of steel. In addition, in 2022, the European Commission published a Recommendation proposing a European "Safe and Sustainable by Design" framework for safe and sustainable chemicals and materials (European Commission. Joint Research Centre, 2022). This framework mentions the need to consider the presence of CRMs qualitatively (i.e., whether they contain them or not), and recommends monitoring the use of these materials to minimise or substitute them to reduce the dependence on these resources. Therefore, as proposed in this paper, a quantitative approach would help to consider this issue.

4. Discussion

In this subsection, our findings are discussed, focusing on the contribution of alloying elements to the environmental impact and the presence of CRM in steel grades, and finally, the variability of such environmental impacts due to the composition ranges provided by the standards.

Compared to ecoinvent steel, the environmental impact of particularised steel grades varies from 0.13 to 4.5 times that of the reference. Most differences can be observed in the *abiotic depletion* category from the CML-IA methodology due to the presence of molybdenum and copper. It has been observed that certain alloying elements significantly influence the environmental impact of steel, depending on the impact category analysed.

Molybdenum, copper, and titanium are the alloying elements with the most significant impact. These alloying elements, although present in small percentages in the average composition (0.1–0.6%) in the studied grades of steel, greatly influence the environmental impact of this material.

Molybdenum has greater environmental implications than the other alloying elements, mainly in the abiotic depletion category due to the mine operation and beneficiation, with an environmental impact about 4 times more significant (per kg) than the next alloying element. It also stands out in human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and eutrophication categories because of the treatment of the sulfidic tailings in mine operations that generate damage in these categories. In all of these categories, molybdenum is the alloying element with the greatest environmental impact. This alloying element is present only in steel grades 1.1231 and 1.4104 (0.05% and 0.4% on average), penalised in environmental impact in these categories, especially in the abiotic depletion.

Copper also stands out in all impact categories, except abiotic depletion (fossil fuels) and global warming (GWP100y). In eight of the categories, copper is the second element with the highest environmental impact per kg, except in the acidification category, in which it occupies the first place. The operation of smelting of copper concentrates to produce copper anodes or cathodes is the main activity that produces an environmental impact. Copper is present in 10270 SH, 1.1231, and 1.5525 steel grades.

Titanium is a relevant alloying element in the categories of abiotic depletion (fossil fuels), global warming (GWP100y), and ozone layer depletion being the alloying element with the highest environmental impact per kg due to the processes related to the production of titanium sponge from titanium tetrachloride. The influence of titanium on the environmental impact of the steel grades analysed is not so evident. In the case of alloy steel grades, 1.0917 and 1.0951 have 0.15% (average) titanium. However, the other alloy steel grades analysed have almost twice as many alloying elements, contributing to the environmental impact. This is why all alloy steel grades have similar environmental impacts in the mentioned categories. The only stainless steel containing titanium is 1.4509 (0.35% on average). However, their contribution to the total impact is much lower than chromium, that is present in large quantities (18% on average).

Special mention should be made of chromium, not because it has a high environmental impact in most of the categories analysed, but because it is found in large proportions in the case of stainless steels. However, chromium is relevant in the case of terrestrial ecotoxicity and human toxicity categories, being the first and the third alloying elements with the highest impact per kg, respectively. For both categories, this higher impact per kg, added to high percentages in their composition, means that chromium accounts for more than 90% of the total impact in stainless steel grades.

Performing a more detailed analysis of the contribution of alloying elements to the total environmental impact, Fig. 6 shows the distribution of the impact (alloying elements, gross metallic charge, and production process) for the different categories analysed. For some impact categories (abiotic depletion, human toxicity, and terrestrial ecotoxicity), their influence is prominent (greater than 98%). It is also significant for the rest of the impact categories, resulting in values greater than 50% for many of the steel grades analysed (especially stainless steel), even when alloying elements content does not exceed 20% or 30% in the highest cases.

The influence of alloying elements is especially evident in those steel grades with higher alloying elements' content. Thus, in the case of carbon steel, the representation of the environmental impact of alloying elements over the total is very low. This influence is somewhat more significant in alloy steel, but the cases presented in this study do not contain an excessive amounts of alloying elements. In the case of stainless steels, alloying elements account for more than 98% of the total impact in three of the impact categories analysed: *abiotic depletion*, *human toxicity,* and *terrestrial ecotoxicity*. For 1.4301 steel, which has the highest alloy content of the steel grades analysed, alloying elements account for 72% or more of the impact. For the rest of the stainless steel grades studied, which have a similar total alloy content, the alloying elements account for a moderate impact percentage of 28%–61% (except for the three impact categories mentioned above).

In the case of the steel grades analysed, it has not only been possible to study the influence of the alloying elements on the environmental impact but also to obtain useful information on their sustainability, incorporating the environmental criterion when selecting the material for one or another application. Thus, for example, in the case of stainless steel grades studied, which are used for the manufacture of aesthetic parts of induction cooktops, following the environmental impact category of global warming (GWP100y) (usually the strongest impact category used by companies (Wright et al., 2011)), we can affirm that 1.4301 is the steel with the highest environmental impact. The remaining stainless steel grades have similar impacts, with 1.4016 having the lowest environmental impact.

Assessing the contribution to impact for the *Global warming (GWP100y)* category, in the case of carbon steel and alloy steel grades analysed, the fundamental contribution is due to the gross metallic charge (between 80% and 88%). The environmental impact in this category is mainly due to the sintering of iron in the production of pig iron, as is the case in *photochemical oxidation*. In the case of stainless steel grades, this contribution of gross metallic charge is lower (around 43–47%) due to the high influence of alloying elements, except for the case of stainless steel 1.4301, in which gross metallic charge only contributes 13%, due to the high Nickel environmental impact that supposes higher percentages for the alloying elements.

A similar impact distribution occurs for *ozone layer depletion* and *acidification* categories. In this case, the gross metallic charge contributes around 69–90% for the analysed carbon steel and alloy steel grades. In the case of stainless steel grades, this contribution is also lower (around 31–51%), except for the case of stainless steel 1.4301 (in which gross metallic charge only contributes 8% and 14% for each category). As seen in the previous section, Nickel is an element that considerably impacts these categories and is found in large proportions in this steel. The major contribution to the environmental impact is due to the coke needed for pig iron production. However, the sintering of iron in pig iron production also contributes to a lesser degree.

In the case of *abiotic depletion (fossil fuels)* and *eutrophication* categories, the gross metallic charge has a similar contribution for the total impact (around 82–93%), but in this case, is mainly due to the coke needed for pig iron production.

In the case of the *freshwater aquatic ecotoxicity* and *marine aquatic ecotoxicity* impact categories, the main contribution to the impact is given by the production process for the carbon steel grades analysed (between 77-85% and 62–69%, respectively) and alloy steel grades (between 64-79% and 52–63% respectively). For these categories, the impact of the production process is mainly due to the impact associated with the landfill treatment of basic oxygen furnace slag. This contribution is lower for stainless steel grades analysed, but especially significant for the case of 1.4016 and 1.4509 (around 1–18%) due to the higher contribution in the impact that alloying elements have in these categories.

In the *human toxicity* category, the contribution to the impact of the production process contributes significantly to the environmental impact, although to a lesser extent than in the previously mentioned categories. This impact is also due to the impact associated with the landfill treatment of basic oxygen furnace slag. However, in this category, and in the case of stainless steel grades, the alloying elements contribute significantly to the impact, making the production process at most 2%.

It should be noted that the environmental impact of the gross metallic charge and the process is specific to the production process through the BOF route. Therefore, producing steel through more sustainable routes, which would reduce the environmental impact of this production, would mean an increase in the percentage of impact created by the alloying.

Analysing the CRM content, it can be considered low (less than 1.6%). Although practically all the studied steel grades contain materials such as silicon or phosphorus, considered CRM for the European Union, these are found in meagre proportions and do not generate relevant environmental impacts for the studied steel grades. It should be noted that these results are variable over time and may increase considerably considering, as CRM, some alloying elements with a more significant presence in the analysed steel grades, such as nickel or chromium (with high content in stainless steel). As previously explained, the quantity of the different alloying element content is given by ranges, establishing each element's maximum and minimum content. Table 5 shows the uncertainty generated due to the alloying elements ranges in the environmental impact values.

The *abiotic depletion* category shows the largest variation between maximum and minimum environmental impact. Copper and molybdenum have much higher impacts than other alloying elements, resulting in greater variability for steel grades containing these elements (1.1231, 10270-SH, and 1.4104). For example, 1.1231 (which contains both alloying elements) has a variability of ±93.6% in this category. In this specific case, and according to EN 10132 standard, molybdenum has a composition range of 0–0.1%. The presence of this 0.1%, for the maximum impact composition, implies an increase of 7.21E-05 kg Sb eq., which corresponds to 61% of the total impact.

Although more moderate, the variability of 1.1231 and 1.5525 for *human toxicity* and *terrestrial ecotoxicity* are also significant, higher than ±50%. In this case, this uncertainty is due to these steel grades' chromium and copper content, which range from 0% up to 0.4% and 0.3% respectively as stated in the EN 10132 standard (AENOR, 2021). For 1.5525, which chromium and copper content, which range from 0% to 0.3% and 0.25%, these ranges also create uncertainties for *human toxicity* and *terrestrial ecotoxicity* near ±40%, showing again the relevance of the composition.

This variability analysis allows to study the effect on environmental impact of composition ranges given by standards. These ranges, which specify the maximum and minimum percentage of each alloying element that a steel must content to be considered as a steel grade, in order to ensure the required technical specification. However, these ranges generate uncertainty in the results, in certain cases, it can significantly influence the environmental impact. Thus, due to the way steel grades compositions are defined, the environmental impact variability is significantly high, considering that the variations in alloying elements content, range from 0.5 to 3% for both carbon steel and alloy steel, and

Fig. 6. Environmental impact distribution of the analysed steel grades. Alloying elements, gross metallic charge, and production process.

Table 5
Uncertainty Analysis due to alloying element composition ranges.

		10270 SH	1.0347	1.0917	1.0951	1.1231	1.5525	1.4016	1.4104	1.4301	1.4509
Abiotic depletion [kg Sb eq./kg]	Min	3,87E-06	3,78E-06	3,78E-06	3,78E-06	3,92E-06	3,84E-06	8,52E-05	8,27E-05	1,33E-04	9,32E-05
	Max	3,01E-05	3,98E-06	5,47E-06	5,34E-06	1,19E-04	3,89E-05	9,69E-05	5,27E-04	1,58E-04	1,01E-04
	Avg	1,70E-05	3,88E-06	4,63E-06	4,56E-06	6,15E-05	2,14E-05	9,11E-05	3,05E-04	1,46E-04	9,71E-05
	Var.	±1,31E-05	±1,00E-07	±8,45E-07	±7,80E-07	±5,75E-05	±1,75E-05	±5,85E-06	±2,22E-04	±1,25E-05	±3,90E-06
	Var.%	±77,2%	±2,6%	±18,3%	±17,2%	±93,6%	±82,0%	±6,4%	±39,8%	±8,4%	±3,9%
Abiotic depletion (fossil fuels) [MJ/kg]	Min	1,43E+01	1,39E+01	1,39E+01	1,39E+01	1,45E+01	1,42E+01	2,43E+01	2,43E+01	4,87E+01	2,55E+01
	Max	1,53E+01	1,41E+01	1,72E+01	1,70E+01	1,73E+01	1,60E+01	2,77E+01	2,82E+01	5,96E+01	3,09E+01
	Avg	1,48E+01	1,40E+01	1,56E+01	1,55E+01	1,59E+01	1,51E+01	2,60E+01	2,63E+01	5,42E+01	2,82E+01
	Var.	±5,00E-01	±1,00E-01	±1,65E+00	±1,55E+00	±1,40E+00	±9,00E-01	±1,70E+00	±1,95E+00	±5,45E+00	±2,70E+00
	Var.%	±3,4%	±0,6%	±10,6%	±10,0%	±8,6%	±5,9%	±6,4%	±7,3%	±10,1%	±9,5%
Global warming (GWP100a) [kg CO_2 eq./kg]	Min	1,69E+00	1,66E+00	1,67E+00	1,66E+00	1,70E+00	1,70E+00	2,81E+00	2,80E+00	5,05E+00	2,93E+00
	Max	1,76E+00	1,68E+00	1,92E+00	1,89E+00	1,94E+00	1,83E+00	3,03E+00	3,06E+00	5,96E+00	3,32E+00
	Avg	1,73E+00	1,67E+00	1,80E+00	1,78E+00	1,82E+00	1,77E+00	2,92E+00	2,93E+00	5,51E+00	3,13E+00
	Var.	±3,50E-02	±1,00E-02	±1,25E-01	±1,15E-01	±1,20E-01	±6,50E-02	±1,10E-01	±1,30E-01	±4,55E-01	±1,95E-01
	Var.%	±2,1%	±0,5%	±7,0%	±6,4%	±6,5%	±3,8%	±3,6%	±4,4%	±8,2%	±6,2%
Ozone layer depletion (ODP) [kg CFC-11 eq./kg]	Min	7,25E-08	7,11E-08	7,11E-08	7,11E-08	7,32E-08	7,22E-08	1,05E-07	1,05E-07	2,00E-07	1,13E-07
	Max	7,81E-08	7,18E-08	9,60E-08	9,53E-08	8,63E-08	8,35E-08	1,16E-07	1,18E-07	2,40E-07	1,53E-07
	Avg	7,53E-08	7,15E-08	8,36E-08	8,32E-08	7,98E-08	7,79E-08	1,11E-07	1,12E-07	2,20E-07	1,33E-07
	Var.	±2,80E-09	±3,50E-10	±1,25E-08	±1,21E-08	±6,55E-09	±5,65E-09	±5,50E-09	±6,50E-09	±2,00E-08	±2,00E-08
	Var.%	±3,7%	±0,4%	±14,9%	±14,5%	±8,2%	±7,3%	±5,1%	±5,8%	±9,2%	±15,0%
Human toxicity [kg 1,4-DB eq./kg]	Min	2,24E+00	2,18E+00	2,18E+00	2,18E+00	2,28E+00	2,28E+00	8,35E+01	8,09E+01	9,42E+01	9,12E+01
	Max	3,35E+00	2,23E+00	2,69E+00	2,62E+00	7,29E+00	5,15E+00	9,39E+01	9,91E+01	1,06E+02	9,70E+01
	Avg	2,80E+00	2,21E+00	2,44E+00	2,40E+00	4,79E+00	3,72E+00	8,87E+01	9,00E+01	1,00E+02	9,41E+01
	Var.	±5,55E-01	±2,50E-02	±2,55E-01	±2,20E-01	±2,51E+00	±1,44E+00	±5,20E+00	±9,10E+00	±5,90E+00	±2,90E+00
	Var.%	±19,8%	±1,3%	±10,6%	±9,3%	±52,4%	±38,6%	±5,9%	±8,6%	±5,8%	±3,1%
Freshwater aquatic Ecotoxicity [kg 1,4-DB eq./kg]	Min	3,86E+00	3,78E+00	3,78E+00	3,78E+00	3,90E+00	3,92E+00	4,99E+00	4,95E+00	1,76E+01	5,26E+00
	Max	4,57E+00	3,86E+00	4,55E+00	4,46E+00	6,30E+00	4,76E+00	5,47E+00	1,05E+01	2,21E+01	6,47E+00
	Avg	4,22E+00	3,82E+00	4,17E+00	4,12E+00	5,10E+00	4,34E+00	5,23E+00	7,73E+00	1,99E+01	5,87E+00
	Var.	±3,55E-01	±4,00E-02	±3,85E-01	±3,40E-01	±1,20E+00	±4,20E-01	±2,40E-01	±2,78E+00	±2,25E+00	±6,05E-01
	Var.%	±8,4%	±0,9%	±9,2%	±8,2%	±23,5%	±9,7%	±4,6%	±22,8%	±11,4%	±10,3%
Marine aquatic Ecotoxicity [kg 1,4-DB eq./kg]	Min	4,72E+03	4,62E+03	4,62E+03	4,62E+03	4,78E+03	4,79E+03	6,67E+03	6,60E+03	1,93E+04	7,07E+03
	Max	5,58E+03	4,72E+03	5,72E+03	5,60E+03	7,49E+03	5,88E+03	7,35E+03	1,30E+04	2,40E+04	8,77E+03
	Avg	5,15E+03	4,67E+03	5,17E+03	5,11E+03	6,14E+03	5,34E+03	7,01E+03	9,80E+03	2,17E+04	7,92E+03
	Var.	±4,30E+02	±5,00E+01	±5,50E+02	±4,90E+02	±1,36E+03	±5,45E+02	±3,40E+02	±3,20E+03	±2,35E+03	±8,50E+02
	Var.%	±8,3%	±1,0%	±10,6%	±9,6%	±22,1%	±10,3%	±4,9%	±21,1%	±11,0%	±10,7%
Terrestrial Ecotoxicity [kg 1,4-DB eq./kg]	Min	1,20E-03	1,16E-03	1,16E-03	1,16E-03	1,21E-03	1,21E-03	7,38E-02	7,19E-02	8,78E-02	8,07E-02
	Max	1,87E-03	1,19E-03	1,59E-03	1,56E-03	4,53E-03	3,54E-03	8,31E-02	8,19E-02	9,94E-02	8,58E-02
	Avg	1,54E-03	1,18E-03	1,38E-03	1,36E-03	2,87E-03	2,38E-03	7,85E-02	7,69E-02	9,36E-02	8,33E-02
	Var.	±3,35E-04	±1,50E-05	±2,15E-04	±2,00E-04	±1,66E-03	±1,17E-03	±4,65E-03	±5,00E-03	±5,80E-03	±2,55E-03
	Var.%	±22,1%	±1,3%	±15,8%	±14,8%	±57,7%	±%49,2	±5,9%	±6,6%	±6,2%	±3,1%
Photochemical Oxidation [kg C_2H_4 eq./kg]	Min	8,55E-04	8,40E-04	8,50E-04	8,45E-04	8,54E-04	8,51E-04	1,09E-03	1,09E-03	1,50E-03	1,10E-03
	Max	8,95E-04	8,43E-04	9,67E-04	9,66E-04	9,62E-04	9,30E-04	1,12E-03	1,13E-03	1,67E-03	1,32E-03
	Avg	8,75E-04	8,42E-04	9,09E-04	9,06E-04	9,08E-04	8,91E-04	1,11E-03	1,11E-03	1,59E-03	1,21E-03
	Var.	±2,00E-05	±1,50E-06	±5,85E-05	±6,05E-05	±5,40E-05	±3,95E-05	±1,50E-05	±2,00E-05	±8,50E-05	±1,10E-04
	Var.%	±2,3%	±0,2%	±6,4%	±6,7%	±5,9%	±4,4%	±1,4%	±1,9%	±5,1%	±7,8%
Acidification [kg SO_2 eq./kg]	Min	5,07E-03	4,90E-03	4,90E-03	4,90E-03	5,16E-03	5,14E-03	9,73E-03	9,95E-03	2,35E-02	1,04E-02
	Max	6,42E-03	5,06E-03	6,44E-03	6,26E-03	7,89E-03	6,99E-03	1,10E-02	1,20E-02	2,92E-02	1,26E-02
	Avg	5,75E-03	4,98E-03	5,67E-03	5,58E-03	6,53E-03	6,07E-03	1,04E-02	1,10E-02	2,64E-02	1,15E-02
	Var.	±6,75E-04	±8,00E-05	±7,70E-04	±6,80E-04	±1,37E-03	±9,25E-04	±6,35E-04	±1,03E-03	±2,85E-03	±1,10E-03
	Var.%	±11,8%	±1,6%	±13,5%	±12,2%	±21,0%	±15,2%	±6,0%	±9,3%	±10,7%	±9,9%
Eutrophication [kg PO4— eq./kg]	Min	2,99E-03	2,91E-03	2,91E-03	2,91E-03	3,03E-03	2,98E-03	4,62E-03	5,43E-03	8,27E-03	4,84E-03
	Max	3,45E-03	2,95E-03	3,59E-03	3,53E-03	4,28E-03	3,62E-03	5,27E-03	7,82E-03	1,01E-02	5,90E-03
	Avg	3,22E-03	2,93E-03	3,25E-03	3,22E-03	3,66E-03	3,30E-03	4,95E-03	6,63E-03	9,19E-03	5,37E-03
	Var.	±2,30E-04	±2,00E-05	±3,40E-04	±3,10E-04	±6,25E-04	±3,20E-04	±3,25E-04	±1,20E-03	±9,15E-04	±5,30E-04
	Var.%	±7,2%	±0,8%	±10,5%	±9,8%	±17,2%	±9,7%	±6,5%	±18,0%	±9,8%	±9,9%

from 3 to 8% for stainless steel.

To sum up, on the one hand, the developed methodology has shown that, although steel is one the more commonly used materials worldwide (World Steel Association, 2022.), the three types of steel grades available in ecoinvent are not enough to consider the influence of the alloying elements. Further research should be carried out to obtain more precise LCI, which would benefit LCA practitioners in both the academy and the industry. On the other hand, it has been shown that current steel grade standards have composition ranges that are too wide from an environmental point of view (especially for *abiotic depletion* and *human toxicity* categories). Although it presents significant technical challenges, a more precise steel grade composition could allow the steel industry to manufacture within the spec of current standards while lowering the environmental impact and CRM content. This would also help engineers to select steel grade, taking into account its environmental impact with a lower degree of uncertainty.

5. Conclusions

This study presented a step-by-step methodology to calculate the environmental impact of steel grades based on their composition, establishing a method to allocate the combination of raw materials that provide each steel grade's maximum and minimum possible environmental impact. It also helps determine the Critical Raw Material (CRM) content, aiding in the efficient use of resources, as it is currently recommended by the European Commission under the Safe and Sustainable by Design framework.

This methodology offers a valuable tool for a more accurate calculation of the environmental impact of steel. In this way, it is possible to incorporate environmental criteria into the material selection process, among those usually considered, such as mechanical properties or material price, and allow more informed decisions regarding sustainability.

Life Cycle Assessment is an iterative process that is necessary to understand the environmental impact of materials, processes, and products. Each iteration allows practitioners to obtain a deeper understanding of systems from the point of view of their impact on the environment. The calculation methodology presented in the manuscript, although it incurs a series of approximations in terms of manufacturing technology, is based on ecoinvent data, and the "Best Available Techniques (BAT) in Iron and Steel Production in the European Union" report (Commission of the European Union and Joint Research Centre. Institute for Prospective Technological Studies, 2013). If primary data were available, it should be used to further reduce the uncertainties of the results. This could be a future line of research since it would validate the methodology proposed in the study, not against the BAT report data, but with results obtained from primary data of an LCA of some specific steel grade. The methodology provides an improved understanding about the influence of alloying elements on the environmental impact of steel alloys, and on the efficient management of resources, without needing more specific primary data, except for the composition ranges established by the standards for each steel grade. That would help practitioners of the sector to make more informed and effective decisions and to understand the nature of the life cycle assessment technique, which is complex.

This study has also the potential to develop other future research lines. A promising line of research would be to perform an uncertainty analysis by comparing the results obtained with the methodology with actual data from a specific plant for the production of a specific steel alloy. In addition, it would be possible to develop an analogous methodology that allows the incorporation of composition in the Life Cycle Assessment of steel production by the EAF route, the second most predominant in the world, which mainly use scrap metal for its manufacture. In addition, considering the regulatory trends regarding the presence or absence of critical raw material, it would be interesting to study the monitoring of the CRM content of steel-based products from a life cycle approach. This will allow for better management of scarce resources. Furthermore, it would also be beneficial to explore the functional performance of specific grades of steels used for particular applications and their performance in the use phase, analysing the environmental impact considering potential trade-offs between life cycle stages.

The methodology has been applied to 10 different steel grades categorised as carbon, alloy, and stainless steel, confirming that the material composition significantly influences their environmental impacts. It has also been possible to analyse the influence of certain alloying elements, such as molybdenum, copper, titanium, or chromium, which contribute to increasing the environmental impact of steel. The variability in the environmental impact for the same grade of steel has been seen due to the wide ranges of composition given by standards. Significant differences have also been obtained in the environmental impact of these steel grades concerning the generic ecoinvent steel types.

CRediT authorship contribution statement

Isabel García Gutiérrez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Carmelo Pina:** Writing – review & editing, Supervision, Funding acquisition. **Rafael Tobajas:** Writing – review & editing, Visualization, Formal analysis. **Daniel Elduque:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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