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Influence of elemental composition in environmental impacts of steel

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Abstract

The environmental behavior of four steels was analyzed. In the operation phase of concentrating solar power plants, steels withstand high temperature because of its contact with molten salts. Hence, choosing the steel type for the molten salt tanks remains a great challenge. In the cold tank, carbon steel is usually used although an approach with low chromium content steel is being studied for these applications. Likewise, in high temperature applications, such as hot store tank, austenitic stainless steel is the most frequent choice. However, ferritic steel is being considered as a promising material in these applications. As many researchers studied the steel technical properties without considering their environmental damages, this work aimed to introduce the environmental aspects into the material choice by using the life cycle assessment technique. On one hand, the results showed the environmental adequacy of carbon steel against low chromium content steel. On the other hand, the results obtained in those steels suitable in high temperature application revealed significant environmental benefits from the ferritic steel instead of the austenitic steel.

1 Introduction

The European Union has determined renewable energy as the main route to a more sustainable and cost-effective energy system for the next 30 years [1]. Renewable energy will represent the largest growth in the next years, driven by falling costs and huge expansions in the emerging economies [2]. Wind and solar energies are the most abundant energy sources. However, these renewable sources are discontinu- ous. Nevertheless, in the case of solar energy, a solution exists to solve it. Thermal energy storage (TES) is a molten salt system for regulating the gap between energy generation and energy demand [3, 4]. As a result of TES, concentrating solar power (CSP) could be a continuous energy source [5]. This is the main advantage of CSP over other renewable energies and why it is considered as the most promising renewable technology [6–8].

CSP is immersed in a global search for improving their efficiency to get better levelized cost of energy (LCOE) [9–11]. Nowadays, more than 80% CSP plants incorporate TES, which consists of molten salts nitrates [4] within steel tanks. The use of molten salts gains thermal efficiency in the CSP plants because its working temperature range is higher and wider than other fluids used such as air, water steam or synthetic oil [12–14]. Increasing the maximum operating temperature by using molten salts allows the use of higher efficiency cycles. However, the inclusion of molten salts (with its maximum operating temperature of about 600 °C) requires suitable containment materials resistant to corrosion [15, 16]. Over many years, gains in thermal efficiency have been achieved by the development of steels with better creep properties [17]. The first CSP plants were made of carbon steel [18, 19], which ended up owing to corrosion problems. These failures resulted in the stainless steels implantation in the plant parts which support higher temperatures, such as molten salt hot storage tanks. Stainless steels present good

corrosion resistance but they involve over-cost. This fact is undesirable in a technology intending to reduce the cost per kWh [20] in order to be more competitive in the energy mix.

Regarding steel, high operation temperatures are mostly defined by the chrome content because it determines the oxide surface layer formation [21]. Low Cr content steels are indicated for low temperature applications and high Cr content steels for high temperature applications. Since the highest operating temperature of A516 steel is 427 °C (established by the American Society of Mechanical Engineers code), steels like the A516 steel are still being used, but only for low temperature applications, such as cold molten salt tank [22]. In comparison, other possible steel candidates for this use in CSP must be evaluated. Steels that improve the creep behavior with respect to A516 steel are being studied for their inclusion in CSP plants; one of these is the low-Cr (2%) alloy steel (T22). Fernández et al. [23] evaluated the corrosion ability of Hitec salt at 390 °C, and T22 presented better behavior than the A516 steel against corrosion.

High Cr content steels are suitable for CSP high temperature applications, such as the molten salt hot tank (~ 565 °C). Numerous experiments have focused on austenitic steels in the molten salts environment [24, 25], and the results showed very good properties for use at high temperatures due to their strength and resistance to oxidation. On the other hand, ferritic stainless steel could be a good candidate and low-cost alternative. Ferritic steel (e.g., P91 steel) is already being studied for CSP boilers [26]. Fernández et al. [27] studied the corrosion issues caused by solar salt on two different stainless steels, an austenitic stainless steel and a ferritic stainless steel, respectively. Both presented high corrosion resistivity due to their high Cr content. Hence, ferritic steels are great candidates in CSP high temperature applications. Based on this premise, we wanted to evaluate the environmental behavior of not only the austenitic steel (316) but also the ferritic steel (P92).

Knowing that these kinds of steels are technically suitable for using in CSP plants, we are going to assess the environ- mental behavior of A516 and T22 steels in low temperature applications and 316 and P92 steels in high temperature applications. This study presents the A516 and 316 steels as the conventional steels, and T22 and P29 steels as those which are being studied for their technical and/or economi- cal improvements. All above-mentioned work focused on technical analysis. However, there is a lack of studies about the environmental evaluations.

Cai et al. [28] stated that the iron resource efficiency and the environment of steel enterprises should be improved. The steel manufacturing is characterized by a huge produc- tion of CO_2 emissions. However, the reduction in these emis- sions is still challenging even applying the best available technology [29]. Thus, to make an appropriate steel choice will be decisive to mitigate the climate change by reducing the CO_2 emissions. Life cycle assessment (LCA) is a technique widely accepted in the evaluation of the environmental impacts of products and processes. There are some studies in the field of LCA in CSP [30–33]. However, none of them is focused on the material selection. In earlier studies, the environmental issues of steel have been carried out using LCA methods, but these research works were applied for other applications such as buildings [34, 35].

There are several studies about the steel production. Bur- chart-Korol [36] conducted an LCA study in Poland and obtained the production of pig iron in blast furnaces as the main contributor to the green gas emissions and fossil fuel consumption. Other study [37] highlighted the importance of carrying out LCA studies in the field of steel since the metallurgy sector is highly energy intensive. Furthermore, Yellishetty et al. [38] conducted an LCA by comparing steel scrap with crude steel and established that there are numer- ous advantages of scrap utilization in terms of better envi- ronmental impacts.

The main purpose of this paper is to determine the envi- ronmental behavior of four steel grades in order to know their environmental feasibility in CSP plants. Two of them are technically suitable for high temperature applications (316 and P92 steels). Likewise, the other two (A516 and T22 steels) are appropriate for low temperature applications. Then, by assessing their environmental behavior, it will be possible to determine which of them is the best choice from an environmental point of view.

This paper is another step toward a new research line to evaluate the environmental issues in CSP materials using the LCA methodology [39, 40]. According to both technical and environmental analyses, the feasibility of the appropriate material will be complete.

2 Methodology

To address the aim of this paper, the LCA methodology was applied following the ISO standards [41, 42]. LCA is a powerful tool which enables the comparison of the environmen- tal behavior of different systems. In this kind of analysis, the most important property of the product system is character- ized by its function. There are four phases in an LCA: (1)

goal and scope, (2) life cycle inventory, (3) life cycle impact assessment and (4) interpretation phase.

2.1 Goal and scope definition

In this phase, raw materials are identified, and the functional unit and the system boundaries must be defined. The func- tional unit represents the system to be analyzed. In the con- sidered system, the inputs and outputs are gathered allowing the comparability of LCA results between systems on an equal basis.

The LCA case study in this research compares the environmental behavior of four steels. For this purpose, the func- tional unit is 1 kg of steel.

The LCA boundaries of the steel processes include raw material extraction and the energy used for it and the manu- facture and production of steel in the furnace. The system boundaries of the present research work follow a cradle-to- gate approach. In this regard, it is important to highlight that each step/component along the life cycle could have environ- mental burdens which should be quantified [43]. The authors conduct a cradle-to-gate approach because for assessing the use and end-of-use processes for these steels, there are no existing plants with the new proposed steels (low Cr content steel in cold applications instead of carbon steel and ferritic steel instead of the austenitic steel).

In order to conduct this research work, we have used the SimaPro 8 software [44]. This is a very recognized soft- ware [45] in the scientific community. SimaPro provides a tool to calculate the potential environmental impacts of processes and products within the context of ISO 14040 and ISO 14044 standards.

2.2 Life cycle inventory

Life cycle inventory (LCI) is the second step of every LCA process. LCI collects the data related to all inputs–outputs for each process. The inputs are mainly energy and materials flows, and the outputs are the emissions (to air, water and soil) of the processes, waste and the coproducts.

Figure 1 provides a scheme of the considered routes to produce steel. In the present research work, LCI has been constructed based on data processes included in Ecoinvent 3 database. Low alloyed steels (A516 and T22 steels) were modeled, adapting the *Steel, low-alloyed* Ecoinvent pro- cess. Those with a higher Cr content (316 and P92 steels) were modeled, modifying the *Steel, chromium steel* Ecoin- vent process. This database contains more than 2500 back- ground items, and it is highly recognized by the scientific community [46]. The Ecoinvent models are made according to the geographic location. In this study, the model repre- sents activities conducted in Europe and they are consid- ered as average valid for all the geographic regions. In this research work, we took the Ecoinvent items and adapted them from the generic European steel to our particular steels with the chemical composition reported in Table 1. Figure 1 describes the flowchart of how Ecoinvent considers the steel production processes. According to the production processes, steel can be classified as converter (basic oxygen furnace) or electric steel. LCA databases take the informa- tion from different sources and then obtain an average for a product. In this study, dataset is related to European plants from 2001 to 2013 with mainly converter technology but also considers those plants with electric furnace where the steel comes from iron scrap. These processes involve the primary steel production, transport of raw materials to steel work, steel manufacturing and casting.

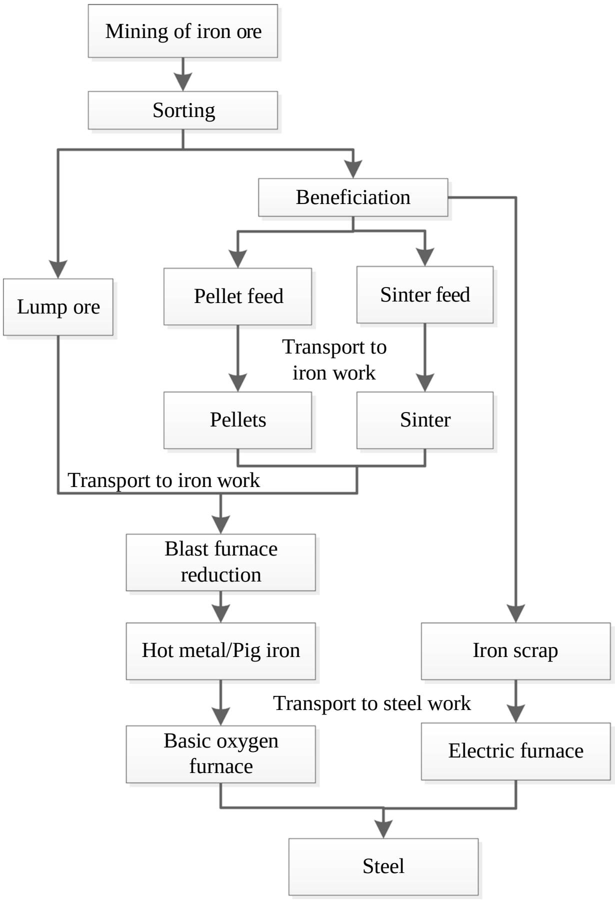

Fig. 1 Flowchart of cradle-to-gate steel production

In the European context, most of the iron ore is reduced to iron in blast furnaces. Energy use, such as coke and electricity, needs to be reduced. Iron scrap is an important resource as well. Blast furnace boundaries have lump ore, sinter and pellets (fine-grained concentrates from beneficia- tion process).

After the beneficiation, it is possible to notice the agglom- eration process because very fine material is undesirable in

Table 1 Elemental composition of four considered steels (wt.%)

Steel grade	316	P92	A516	T22
C	0.03	0.12	0.18	0.10
Mn	1.20	0.49	0.95	0.40
P	0.025	0.014	0.015	0.025
S	0.002	0.002	0.008	0.025
Mo	2.14	0.38	0.08	0.90
Si	0.36	0.21	0.40	0.50
Cr	16.88	8.70	0.30	–
Ni	10.55	0.17	0.30	–
N	0.040	0.053	0.020	–
Co	0.12	–	0.01	–
Cu	0.25	–	0.30	–
Ti	0.022	–	0.030	–
Sn	0.07	–	0.02	–
Nb	–	0.06	0.01	–
B	–	0.003	–	–
W	–	1.65	–	–
V	–	0.18	–	–
Al	–	0.01	–	–

the reduction equipment. Regarding waste produced in this part, mostly European sinter plants are operated with fully closed dust cycles and electrostatic precipitators. In the Ecoinvent assumptions, the waste of this phase is neglected because their amount is unknown but small. Regarding the transports, agglomeration (sintering and pellet production) is used to improve the permeability of the blast furnace burden. Sinter is produced near the blast furnace and pellets near the beneficiation plant. Blast furnace is the process to produce pig iron. There are iron-bearing materials such as iron ore lump, sinter and pellets, and additives such as limestone and coke (reducing agent). They are fed from the top, avoiding the blast furnace gas escape.

Scrap is performed in electric furnaces. Melting is done by graphite electrodes to the scrap. Basic oxygen furnaces reduce the carbon content and adjust other chemical elements. This is a discontinuous process: transfer of hot metal, desulphurization, oxidation, secondary treatment and casting.

According to the Ecoinvent database based on Ref. [47], in Europe, 40% of steel is produced in electric furnaces while the remaining 60% is in basic oxygen furnaces.

We have modeled the four steels on the basis of the following assumptions. Having as a base, the Ecoinvent processes, their emissions to air, their electricity consumptions, their emissions to water and the furnace processes have been adopted for the steels of this study. Then, the system mod- els were modified by introducing the weight composition of every chemical (additions). On this basis, the four steels were modeled. The weight compositions of each material are listed in Table 1. In the supplementary material, it is possible to see the LCIs of every assessed steel. With this contribution, we enlarged the LCA databases because they do not exist in the commercial LCA databases. In the LCI, all items are related to the functional unit, 1 kg of steel, assigning their inputs and outputs. As inputs, it is possible to notice the energy inputs, raw material, ancillary and others. It is just a part of the furnace involved in the process; this could be represented by the [p] unit, which means part of furnace. This means that the whole furnace is not dedicated in the 1 kg steel creation. Since a furnace is used for the creation of several steel tons, the environmental burdens are proportionate. The emissions to air and discharges to water (wastewater) are described as outputs. Waste generated in the furnace is considered as output as well. According to the inventory data values, the life cycle impact assessment was subsequently calculated.

There are two LCA approaches defined in the UNEP/SETAC [48]: attributional and consequential. In this study, the attributional approach has been conducted. Attributional approach is an approach in which inputs and outputs are attributed to the functional unit. Likewise, we have carried out our research work based on unit processes. Unit processes contain upstream emissions and resource inputs the processes involved [49]. As a result, the unit processes in this study contain data on transports of hot metal and other input materials to converter.

2.3 Life cycle impact assessment

The end of the life cycle impact assessment (LCIA) of this research work is to provide scientifically based information to understand the environmental performance of the four steels assessed. In this stage, the LCI is translated into envi- ronmental impacts by means of LCA methodologies.

This process could be iterative until meeting the goal and scope of the LCA study and it is constituted by obligatory and voluntary elements. Also selection of impact categories, category indicators and characterization models, mandatory elements is classification and characterization (calculation of category indicator results). And the optional steps are normalization and weighting.

In the classification phase, the substances are organized according to the effect they have on the environment. Characterization consists in calculating the impact category results. The substances are multiplied by their characteriza- tion factors according with the damage provoked quanti- fying the environmental damages of the functional unit in every category assessed (see Eq. 1). Then, the quantified impact is compared to a reference value; this is the nor- malization phase which divides the scores by a reference situation values (Table 2), getting the environmental impacts dimensionless.

Table 2 EU25 normalization factors [50, 51]

Impact category	Normalization factor
Abiotic depletion	1.18×10^{-8}
Abiotic depletion of fossil fuels	3.18×10^{-14}
Global warming potential (GWP100)	1.99×10^{-13}
Ozone layer depletion	1.12×10^{-8}
Human toxicity	1.29×10^{-13}
Terrestrial ecotoxicity	2.06×10^{-11}
Photochemical oxidation	1.18×10^{-10}
Acidification	3.55×10^{-11}
Eutrophication	7.58×10^{-11}

$$\mathrm{IMP}_j = \sum_i k_{i,j} \cdot \mathrm{LCI}_i \tag{1}$$

where IMP_j is the impact category j; $k_{i,j}$ is the coefficient of damage associated with the component i and impact category j; and LCI_i is the life cycle inventory, i.e., amount of item i.

In this research, the authors also conducted the normalization step. However, ISO 14044 standard (2006) considers weighting not scientifically based, and many scholars [52, 53] discourage weighting. Consequently, weighting was dismissed in this research work.

Among all LCA methodologies, CML impact assessment (CML-IA) was selected for the characterization and normalization steps. CML is the abbreviation of Centrum voor Milieukunde Leiden (in Dutch) which means the Centre of Environmental Science of Leiden University. The CML-IA baseline method developed by the Centre of Environmental Science of Leiden University is one of the most commonly used impact assessment methods in Europe [54]. The first version of this method emerged in the early beginning of the development of LCA [55], and the last update was done in August 2016. This method applies the characterization factors documented in the LCA Handbook [56]. CML- IA baseline also contains normalization values. SimaPro implements the CML-IA normalization factors to different references such as the Netherlands, the European Union (UE 25) or the European Union complemented with Iceland, Norway and Switzerland in 2000.

Table 2 shows the EU25 normalization factors (1/N), which were applied to carry out this study. In this paper, nine environmental impact categories (abiotic depletion, fossil fuels depletion, global warming, ozone layer depletion, human toxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication) were characterized and normalized using the CML-IA baseline model.

The authors do not merely use SimaPro with Ecoinvent database. This research work provides the standard steel composition as input to the software which in turn provides the impact values. This is a new contribution whatsoever from the authors themselves which enlarge the LCA database for more specific steel cases. The data were gathered and generated by the authors.

2.4 Interpretation

Interpretation is the last step of the LCA. In the interpretation step, the impacts are discussed and commented to get useful value judgments for decision-making processes, recommendations, conclusions and future improvements.

3 Results and discussion

The paper makes an effective case for focusing on steel from the standpoint of its functional demand under high temperature as used in a specific kind of solar technology.

The characterization results for the cradle-to-gate production of 1 kg of the four steels are summarized in Table 3 and in graphical form in Fig. 2. Hence, Fig. 2 and Table 3 present the characterization impact values calculated by means of the CML-IA baseline method. In Fig. 2, it is possible to notice in blue the low temperature application steels (A516, T22) and the high temperature application steels are

Table 3 Characterization of 1 kg of each material

Impact category	Abbreviation	Unit	316 steel	P92 steel	A516 steel	T22 steel
Abiotic depletion	AD	kg Sb_{eq}	1.00×10^{-3}	2.07×10^{-4}	5.48×10^{-5}	3.43×10^{-4}
Abiotic depletion (fossil fuels)	FFD	MJ	9.08×10^{1}	4.49×10^{1}	1.72×10^{1}	2.61×10^{1}
Global warming potential	GWP	kg CO_{2eq}	7.09×10^{0}	3.46×10^{0}	1.50×10^{0}	2.19×10^{0}
Ozone layer depletion	OD	kg CFC-1 $_{eq}$	4.25×10^{-7}	2.13×10^{-7}	5.77×10^{-8}	1.00×10^{-7}
Human toxicity	HT	kg 1.4-DB_{eq}	8.34×10^{1}	1.87×10^{1}	3.99×10^{0}	2.81×10^{1}
Terrestrial ecotoxicity	TE	kg 1.4-DB_{eq}	3.34×10^{-2}	1.02×10^{-2}	1.27×10^{-3}	3.86×10^{-3}
Photochemical oxidation	PO	kg C_2H_{4eq}	8.83×10^{-3}	1.40×10^{-3}	1.02×10^{-3}	1.06×10^{-3}
Acidification	AC	kg SO_{2eq}	2.25×10^{-1}	2.18×10^{-2}	1.78×10^{-2}	1.54×10^{-2}
Eutrophication	EU	kg PO_{4eq}	1.99×10^{-1}	3.69×10^{-2}	1.13×10^{-2}	7.48×10^{-2}

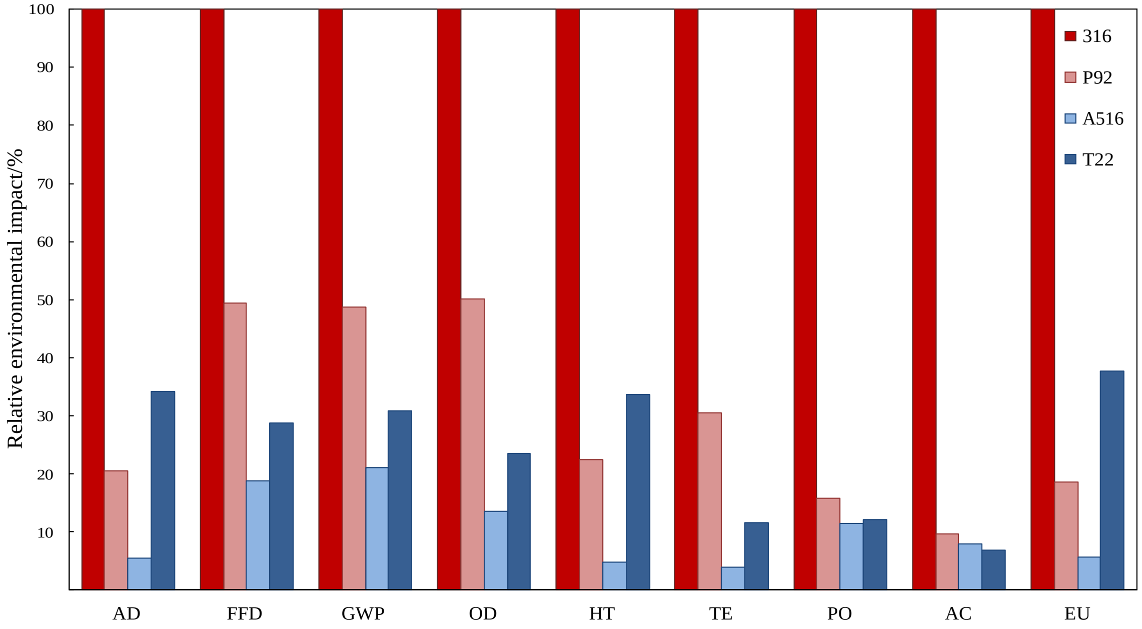

Fig. 2 Comparison of environmental impact categories for 1 kg 316, P92, A516 and T22 steels with CML-IA baseline V3.01/EU25/characterization

red tones (316, P92). The characterization results showed that the austenitic 316 steel has worse environmental performance than the ferritic P92 steel for all the environmental impacts analyzed because the impacts from 316 steel are higher than those from P92 steel. The difference between 316 and P92 steels impacts exceeds 50% in every category, which reveals an important increase in the environmental impacts in the case of using 316 steel instead of P92 steel. This finding is promising and should be explored with other ferritic steels in future works.

In those steels for colder applications, the results indicated lower impacts in 8 of the 9 analyzed categories in the A516 study case against T22 steel study case. Only acidifi- cation reaches higher values in the A516 steel than the T22 steel. Among the four steel study cases, Fig. 2 and Table 3 show the highest environmental impacts in the 316 steel and the lowest in the A516 steel. These results confirm that the more alloying elements a steel has (see Table 1), the more environmental impacts the steel gets.

abiotic depletion and human toxicity. Additionally, ozone layer depletion, terrestrial ecotoxicity and photochemical oxidation are negligible in comparison to the rest of the impact categories.

Abiotic depletion of fossil fuels, global warming and acidification presented moderated values in comparison with higher impact categories. It is possible to notice the maxi- mum impacts in the 316-steel study case and how they are significantly higher than the others in every impact category. In addition, an exhaustive study of the main contribu- tions to the total environmental impact was achieved. These analyses are shown in Fig. 4.

For the sake of completeness, an exhaustive analysis of the steels was made. The results revealed which steel com- ponents contribute to the most impactful categories. Figure 4 shows the characterization of 316, P92, A516 and T22 steels, respectively, and depicts the percentage contribution of the LCI components to the final impact. In this sense, it is pos- sible to notice that among all LCI components, molybde- num, nickel, chromium and pig iron are the most relevant. Most of impact contributions are due to them. All other LCI components did not present notable impact results either; they are negligible in comparison with molybdenum, nickel, chromium and pig iron contributions.

The results showed that the most impactful categories (eutrophication, abiotic depletion and human toxicity) are dominated (i.e., > 50%) by molybdenum. For example, between 56% (in A516 steel) and 95% (in T22 steel) of the systems, impact on eutrophication in all scenarios is due to

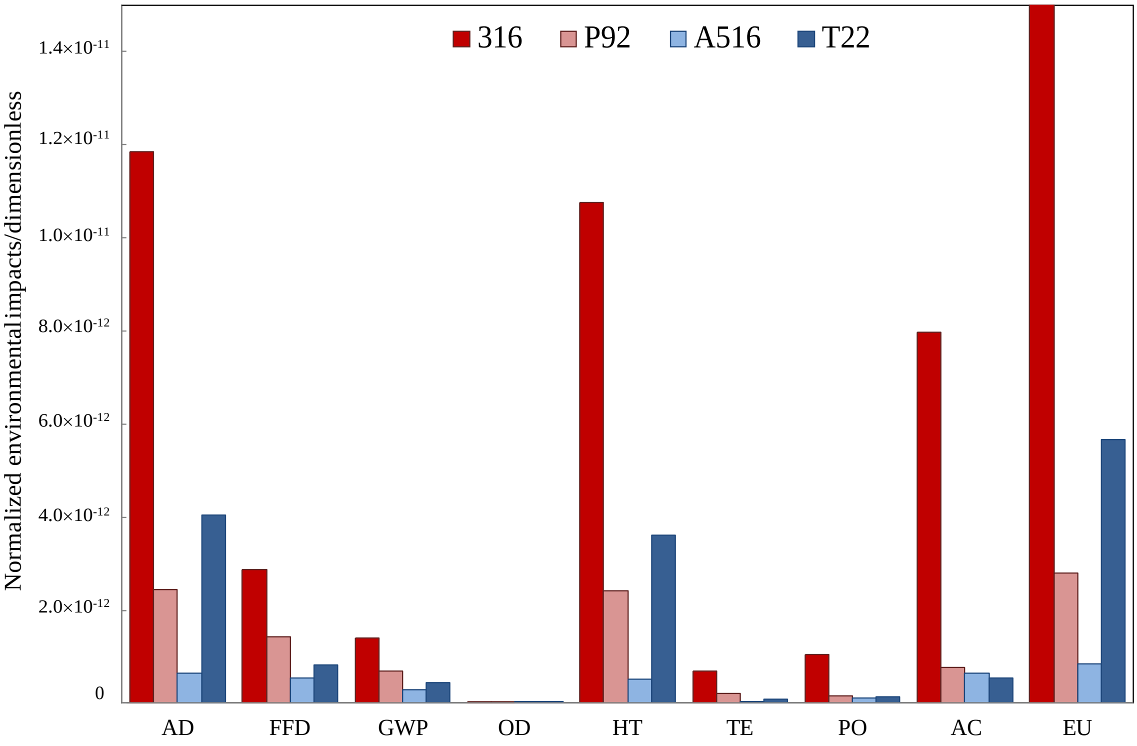

Fig. 3 Comparison of environmental impact categories in their normalized values for 1 kg 316, P92, A516 and T22 steels with CML-IA baseline V3.01/EU25/Normalization

molybdenum, as well as 53%–95% (516 and T22, respectively) of the impact on abiotic depletion. The contribution of molybdenum corresponds to its composition, since 316 steel contains by far the largest Mo (2.14 wt.%, see Table 1) and this involves the highest impact results.

On one hand, eutrophication, abiotic depletion and human toxicity got the highest normalization values (see Fig. 3). Eutrophication represents the environmental damages caused by an excess of macronutrients in the environ- ment caused in turn by emissions of nutrients to air, water and soil. Depletion of abiotic resources is the category, which represents the extraction of fossil fuels and minerals. Human toxicity represents the effect of toxic substances on the human being. In this regard, over 50% of the impacts in these three categories discussed are attributed to foreground molybdenum. Otherwise, acidification is the only category where the A516 impacts are higher than those of T22 (see Fig. 2). As noted in Fig. 4, the nickel content assumes high significance at the contribution to acidification impact.

Global warming potential was obtained as 7.09 kg CO_{2eq} per kg of 316 steel, whereas the result in global warming potential for the P92 steel case was 3.46 kg CO_{2eq} per kg of P92 steel. Therefore, this implies a possibility of 51% CO_2 emissions reduction if the P92 ferritic steel is used instead of 316 austenitic steel in those parts of the CSP plant operated at high temperatures. The low temperature steel study cases showed that a decrease of around 31% can be accomplished when the A516 steel is chosen instead of T22 steel. Compar- ing the highest (316 steel) with the lowest (A516 steel) CO_2 values, it is possible to notice a 79% emission reduction.

In future investigations, it might be possible to evaluate the differences between CSP plants built in these different steels and to know which steel actually contributes to the overall life cycle impact of CSP systems. However, this research study has been conducted in order to evaluate the early stage since there are no existing full scale plants with the alternative materials (T22, P92) to the conventional ones (A516, 316). This study highlights the possible short- comings of incorporating these steel and helps the material decision-making process.

In order to validate the LCA model, an uncertainty analysis was conducted. Figure 5 shows the calculations regarding the high temperature steels and the low temperature steels. One thousand calculations were run in the compara- tive uncertainty study. The results revealed that the model presents uncertainty in terrestrial ecotoxicity. In the high temperature cases, P92 steel obtained lower environmental impacts than 316 steel in all calculations for all the impact categories except terrestrial ecotoxicity. Regarding the low temperature steels, T22 steel presented result higher than 156 steel in all calculations for all impact categories except acidification, photochemical oxidation and terrestrial

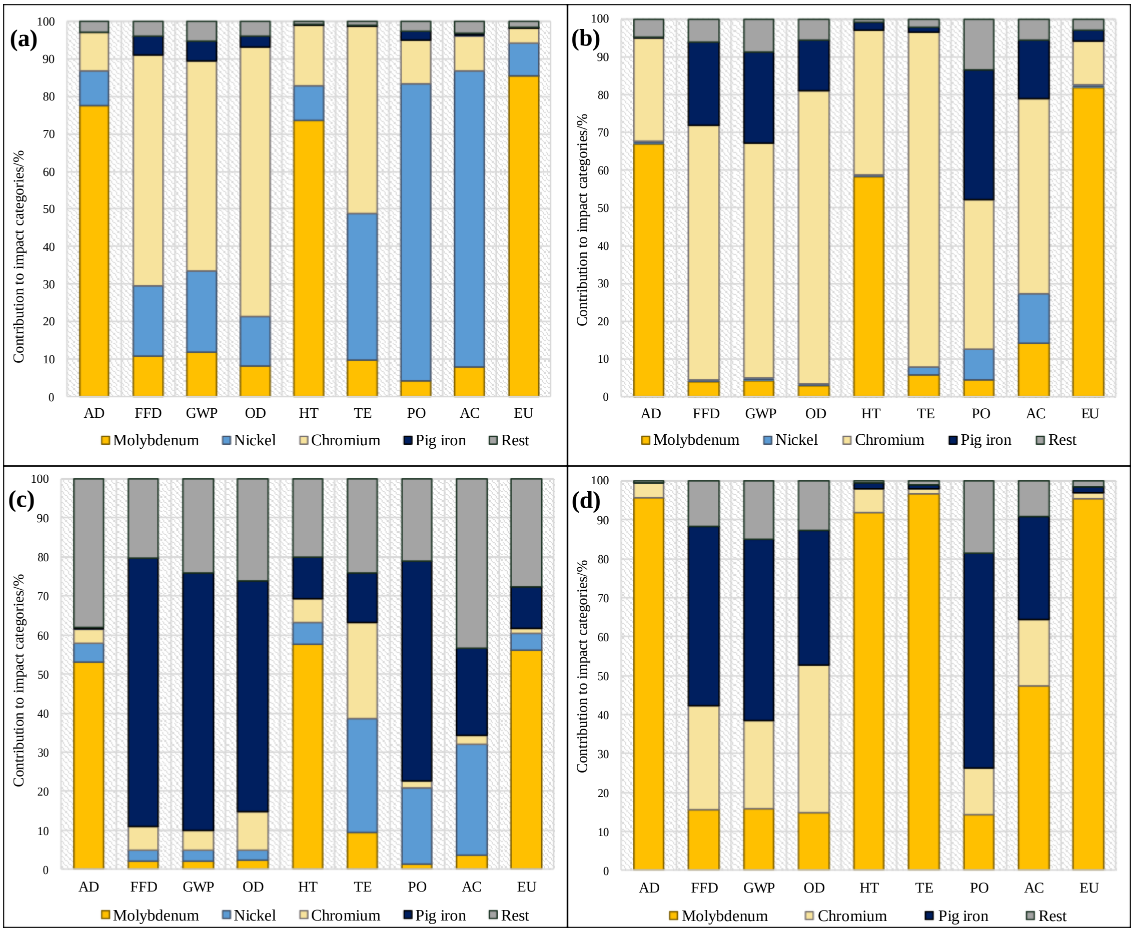

Fig. 4 Characterization of contribution to environmental impacts of main compounds in steel with CML-IA baseline method. **a** 316 steel; **b** P92 steel; **c** A516 steel; **d** T22 steel

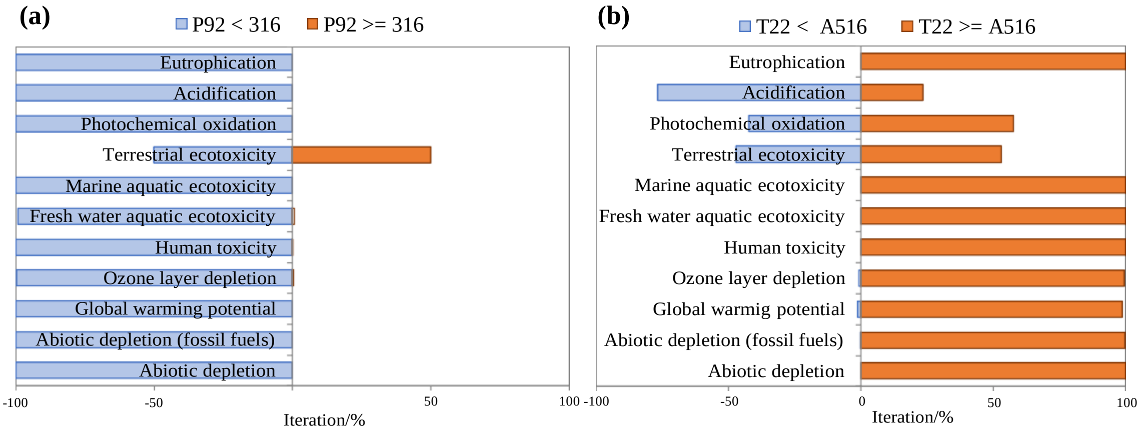

Fig. 5 Uncertainty analysis using Monte Carlo distribution. **a** High temperature steels P92 and 316; **b** low temperature steels T22 and A516

ecotoxicity. Hence, it is pretty likely that the environmental impacts of P92 steel are lower than those of 316 steel in all categories except terrestrial ecotoxicity. Likewise, the environmental impacts of T22 steel are lower than those of A516 steel in all categories except terrestrial ecotoxicity, acidification and terrestrial ecotoxicity.

4 Conclusions

This study is carried out to compare the environmental impacts of four types of steel. Two of them (A516 and T22 steels) are technically suitable for low temperature in CSP applications and the other two (316 and P92 steels) for high temperature in CSP applications.

The main contribution to most impact categories of the four steel assessed was the molybdenum. It was shown that utilizing a lower Mo content steel (A516 steel) instead of the highest (316 steel) resulted in more than 5 kg CO_2 emissions reduction per 1 kg of steel produced. Therefore, to reduce the environmental impacts, steels with lower Mo content should be adopted

Considering the complete LCAs, A516 steel was the most environmentally friendly and 316 steel performed the worst. The results showed the environmental adequacy of the conventional choice of carbon steel A516 against the low chromium content steel T22 in low temperature appli- cation. In the high temperature study cases, ferritic steel (P92) obtained better environmental results than austenitic steel (316). This finding made the ferritic steels to become the most efficient in high temperature applications, with the possibility of competing with the other systems, such as the austenitic steels, being not only as good as austenitic steels in terms of corrosion resistance and cheaper, but also with a better environmental behavior.

The study is limited to steel as substrate since these steels could be coated. A further study could assess the long-term effects of the steels in the operation phase and evaluate the consequences of some coatings over them. Notwithstanding these limitations, the generalizability of these results can easily be replicated in other industry or application.

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