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Comparative environmental assessment of two materials suited to centraltower CSP technology

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ABSTRACT

Compatibility of containment materials with molten salt thermal storage media is a significant technical chal- lenge for Concentrating Solar Power plants. Metal alloys in contact with molten salt must have a specific be- havior, mechanical properties and resistance to degradation processes that allow them to operate at tempera- tures above 500 °C, being both respectful to the environment.

Firstly, this study presents two types of specific materials to operate at raised temperatures in Concentrating Solar Power plants, particularly the central tower technology. The materials are AISI 347H stainless steel and the Ni-based alloy HRSA INCONEL 617. Then, a Life Cycle Assessment shows the influence and contribution to different impact categories from the elements that compose both metals, demonstrating that materials that provide better mechanical properties could have environmental shortcomings.

This paper aims to contribute to an improved understanding of the environmental implications of these materials and which is the best choice in terms of sustainability. The results showed better environmental be- havior in the AISI 347H case against INCONEL 617.

1. Introduction

In response to global economic growth, energy consumption has been increased. And the emissions of this circumstance have substantially contributed to the worldwide problem so called Global Warming (McGlade and Ekins, 2015). In this regard, renewables are clean and inexhaustible energy sources and the best option to address the CO_2 emission reduction. In recent years, International Renewable Energy Agency (IRENA) statistics showed (IEA, 2013) the exponential increase in clean energies generation. As an example of this, the power installed showed a 20.8% net growth from 2012 to 2013. Among renewables, solar energy is the most abundant resource and its use is the most promising solution to achieve this goal (Yan, 2015). Furthermore, among solar technologies, Concentrating Solar Power (CSP) is becoming an increasingly important electricity source. CSP capacity worldwide has grown to around 5 GW, much of this capacity installed in the last decade (Gauché et al., 2017). The most representative CSP developments are the parabolic trough collector (Daabo et al., 2016) and central tower receiver (Salomé et al., 2013). Both technologies can incorporate Thermal Energy Storage (TES) composed by nitrate molten salts. TES allow the continuous operation for the plant in nocturnal cycles or when there is not solar radiation available and this is the main advantage of CSP in comparison to other renewables.

One of the main concerns in CSP plant design is the material working conditions. Materials operating under high temperatures conditions are usually alloys steels. The combination of different factors such as the material composition, their life cycle, availability and the economic are essential for the viability of the plant. (Turchi et al., 2015). On one hand, the materials used in central tower CSP plants in contact with molten nitrate salts are low alloy carbon steels ($T \leq 400$ °C), Cr-Mo stainless steels with Cr content up to 9% ($T \leq 500$ °C), Cr or Cr-Ni stainless steels with alloys such as Mo, Nb, Ti ($T \leq 570$ °C) and Ni- base alloys such INCONEL or HASTELOY type ($T \leq 650$ °C) (Bauer et al. 2013). On the other hand, the majority of TES fluids are alkali nitrate molten salts. These molten salts are in contact with its metallic containing materials. This contact could cause corrosion phenomena in which the molten salts are the electrolyte (El Gharbi et al. 2011; De Miguel et al. 2016). Subsequently, the impurities contained in the industrial alkali nitrate molten salts (around 0.3 wt% chlorides) increase these corrosion processes between molten salts and steels Fabrizi, 2006.

Corrosion phenomena is one cause of the shortening materials life time. Therefore, corrosion phenomena in CSP is becoming an important issue and many authors studied the corrosion resistance of several metals in contact with molten salts. In the solar tower development Solar Two Plant in Daggett, (California), the A516 low-alloy carbon steel is used in those parts which are in contact with molten salts and which operate in low temperatures (240 °C), such as the cold molten salt tank. And those parts in contact with molten salt which operate at high temperatures (565 °C) are composed by an austenitic stainless steel (AISI 304 type, with 18% Cr and 8% Ni content). In this case, corrosion by cracking was observed in those pipes which were in contact with nitrate molten salt at high temperatures (Goods et al., 1994). García-Martín et al., 2017 evaluated the corrosion resistance of the austenitic stainless steels AISI 304 and AISI 316 and the results showed good behavior up to 550 °C Likewise, oxides layers were observed in the AISI 316 stainless steel receptor tubes (Moore et al., 2000). A thermo-resistant alloy Ni-based (HRSA INCONEL 625) also was evaluated and it was observed the formation of adherent oxides thin layers (Bradshaw and Goods, 2001). Moreover, Tzvetkoff and Gencheva, 2003 studied different Ni alloy types in contact to nitrate molten salts and the results showed dissolution processes of passivation.

In summary, scientific literature on steels and alloys in CSP plants showed the following issues:

- Possibility of using carbon steels in systems operating at temperatures up to 300 °C, such as pipes and low temperature molten salts storage tanks.
- High Cr-contain steels may be used in systems operating at temperatures close to 570 °C, such as pipes and high temperature molten salts storage tanks.
- It is advisable to use Ni base alloys in systems where temperatures are close to 650 °C such as the receiver or steam exchanger pipes.

Thus, among the different steels and alloys, there are some for specific application within the requirements CSP plants. So, when the operating conditions are not severe it is possible to use low-alloy carbon steels; which are low-cost materials. On the other hand, for those systems exposed to aggressive physic-chemical conditions, it is necessary to use materials which avoid the corrosion phenomena.

Taking into consideration the above-mentioned aspects and other authors recommendations (Moore et al., 2000 and Zavoico, 2001), this work focused on the environmental behavior of the well-known austenitic stainless steel AISI 347H type and the High Resistant Super Alloy (HRSA) INCONEL 617, in addition both alloys are suitable to be part of the central tower CSP plant systems in contact with high temperature molten salt nitrates. These materials were mainly developed to avoid corrosion phenomena in contact with nitrate molten salts (Bradshaw et al., 2002) providing high resistance and protection against corrosion phenomena at high temperatures (Yang et al. 2006).

In CSP developments, the environmental damages were identified mainly in the materials used in the large-scale projects power plant design. In fact, the material with the highest impact was steel followed by molten salt and synthetic oil (Ehtiwesh et al.,2016). It follows that the environmental impacts can be minimized with an appropriate material choice.

There are studies related to environmental assessment through the Life Cycle Assessment (LCA) techniques in CSP technology (Viebahn et al., 2009 and Lechón et al., 2008). However, the life cycle inventories of these works are addressed evaluating in a general way without specifying which steel grades are being assessed or which alloys are involved in every plant systems. Furthermore, the physic-chemical properties of different steels in contact with nitrate molten salts have been also studied (Moore et al., 2010). However, no evidence had been found in literature about the environmental behavior of INCONEL 617 or AISI 347H materials.

INCONEL 617 and AISI 347H steel are advanced materials because its technical properties improve the conventional ones used in CSP plants (Bradshaw et al., 2002) but their environmental behaviors have not been studied yet. For this reason, this study aims to give an environmental assessment for these two materials.

A detailed study of environmental aspects for steels and alloys used in plants with central tower CSP technology was necessary to cover the lack of these kind of works. To this end, this paper aimed to know which materials present better environmental performance. To address this, an evaluation is carried out using the LCA techniques. In this comparative LCA we examined the contribution of the chemicals components involved in each material to the final impact results. The results introduce the environmental aspect into the material choice as a new aspect as important as the technical issues in the CSP plant design.

2. Methodology

Life Cycle Assessment (LCA) is a widely recognized and accepted method. It is considered an appropriate technique in the analysis of environmental aspects in energy technologies (Davidsson et al., 2012) and the most complete tool to determinate all material impacts. Thus, to get firm conclusions on the environmental impact for both materials a comparative LCA was done.

The environmental assessment was carried out in accordance with the international standards ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b) which involve four steps:

1. Goal and scope.
2. Life Cycle Inventory.
3. Life Cycle Impact Assessment.
4. Interpretation.

2.1. Goal and scope

In this stage, the description of the system, the evaluation method used and the purpose of the study must be defined.

The objective of this LCA was to compare the environmental impacts of two alloys which are suitable in central tower CSP technology. The main purpose was to determinate and quantify the incidence of the main impact categories. This fact allows deciding which material presents better environmental behavior. In addition, the hot spots of each alloy were identified highlighting the material components with the greatest impact on the environment.

The intended audience is the scientific community, with the purpose of increasing awareness about the importance of selecting material that protects the environment. Moreover, environmental assessment using the LCA technique will identify of solutions to make the choice respectful to the environment. The functional unit taken as reference in the study was 1 kg of material. Then, 1 kg of INCONEL 617 was evaluated against 1 kg of AISI 347H steel.

The main stages in life cycle steel are the followings. (i) Production: This includes the complete production of stainless steel, from raw materials. (ii) Manu- facturing: In this step, stainless steel is finished. (iii) Use stage. And, (iv)

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Recycling stage: The end of life steel is to be recycled or sent to landfill.

This paper evaluates the impacts from the raw material extraction to the production of primary metal.

The scope of this LCA is a cradle to gate approach, which consist in an assessment from the raw material extraction and production to the factory gate. The limitations of this study are those specific to the cradle to gate approach which do not consider stages such as use phase or waste treatment and final disposal. But, this approach is justified because Cradle to Gate perspective is appropriate in the material evaluations (Guinée, 2002) and by the fact of CSP technology is a relatively immature technology compared with other renewables (Gauché et al., 2017). An then no data about next stage of the power plant life cycle (such as dismantling stage) has been reported. We launched this study as a tool to choose a suitable material in the new potential CSP developments from the environmental point of view. This is the first step towards this kind of studies because CSP technology integration pathways highlight some areas that need to be resolved and one of this is the environment.

LCA is carried out within the environmental impact system boundaries. The calculations corresponding to the impact categories involved in the study were carried out using the SimaPro 8.0® software since it is a very recognized software (Herrmann and Moltesen, 2015) and it analyzes the environmental performance of products and services following the ISO 14040/14044 (ISO, 2006a, b) recommendations.

This paper follows the ReCiPe Midpoint H in its V1.09 version. ReCiPe Midpoint method is a database containing characterization factors for Life Cycle Impact Assessment (LCIA). It contains the characterization factors of all the basic characterization methods that are extensively explained in the LCA manual (Goedkoop et al., 2009). Among the different cultural perspectives expounded by Thompson et al., 1990 this study it was performed under a Hierarchist (H) perspective, because is a perspective that seeks scientific consensus and it is referenced to in the ISO standards on LCA. The Hierarchist perspective coincides with the view that impacts can be avoided with proper management (Goedkoop et al., 2009). Finally, midpoint approach has been chosen to the assessment since it looks at the impact earlier along the cause-effect chain.

2.2. *Life cycle inventory (LCI)*

In this stage, the input quantification required to produce the functional unit is considered. It takes into consideration the extraction and production of raw materials, as well as the distribution of the final product. Emissions to the environment are also considered such as air, water or soil, and environmental costs such as water and land use.

Technical characteristics of the materials to be analyzed are described below:

2.2.1. *AISI 347H*

This material is a high chromium-content austenitic stainless steel. Table 1 shows its weight (wt%) chemical composition. The wt% carbon-content improves the steel in terms of creep properties at high temperatures. The presence of Nb prevents carbides precipitation and thus the intergranular corrosion. This steel is especially suited for elements operating under repeated cycles. It can be used in permanent operation with temperatures between 430 °C and 880 °C, the maximum working temperature is 900 °C. Furthermore, this steel is highly resistant to corrosion at elevated temperatures and presents optimal mechanical properties due to their stabilization by Nb (Mudali et al., 2005).

Table 1
AISI 347H steel composition in weight percentage, wt%.

	C	Mn	P	S	Si	Ni	Cr	Nb	N	Ta
wt%	0.06	2.0	0.045	0.030	1.0	10.00	18.00	0.48	0.02	0.5

2.2.2. *High resistant super alloy (HRSA) INCONEL 617*

This material is a solid solution in Cr-Ni-Co-Mo. INCONEL 617 provides high resistance in high temperature processes. This material is highly resistant in many oxidizing and reducing atmospheres due to its high wt% Cr and Ni content. The wt% Al-Cr combination gets resistance to oxidation at elevated temperatures and both Co and Mo contribute to solid solution strengthening. The chemical composition for this Superalloy is detailed in Table 2. The combination of high mechanical strength and oxidation above 980 °C temperatures, makes this alloy a suitable material for CSP plants components that operate in extreme conditions, such as nitrate molten salt at elevated temperature. Finally, with respect to HRSA INCONEL 617 corrosion resistance, it has very good oxidation resistance and carburization at elevated temperatures due to its high wt% Ni, Cr and Al. Moreover, the wt% Mo adds good behavior in humid environments and prolongs the superalloy life (Huijbregts et al., 2003).

Knowing their physic-chemical properties we needed to model these two materials in a LCI way to introduce all their features in SimaPro software. Thus, several assumptions were made to model the AISI 347H austenitic stainless steel and the thermoresistant superalloy HRSA INCONEL 617.

Ecoinvent is a highly recognized database (Weidema et al., 2013) and in this paper its third version was used. Ecoinvent 3 contains several metal and steel processes but they are neither AISI 347H nor HRSA INCONEL 617.

Stainless steel allows 100% recycling and Basson, 2014 estimated that at least 70% of stainless steel is recycled at its end of life (as iron scrap). Likewise, analyzing the Ecoinvent 3 steel processes it is possible to realize that the steel Ecoinvent database modeled processes contain a balanced between iron scrap, pig iron and the alloys weight composition. In this way, this study follow the Ecoinvent assumptions. Thus, we took an Ecoinvent 3 steel process (in concrete the chromium steel 18/8) and adapted to the AISI 347H weight composition (see Table 1). The Ecoinvent process chosen involves all upstream production. This process produce primary steel and included transports of hot metal and other input materials to converter, steel making process and casting and that dataset is related to plants in the European Union (from 2001 to 2013) with mainly converter technology.

In the HRSA INCONEL 617 study case the same assumptions were made, the main difference in this case is that HRSA INCONEL 617 is a nickel-based alloy and then the%wt Ni is higher than any steel. Table 2 show the HRSA INCONEL 617 wt% chemical composition.

All the above mentioned assumption meant that we assume the energy, water, the furnace process and its processes (e.g. dust) and the emission to air and water from the Ecoinvent database steel process and changed the chemical composition to the specific of the materials under study (detailed in Tables 1 and 2).

Tables 3 and 4 shows the life cycle inventories (LCI) considered in this paper. Table 3 for the AISI 347H and Table 4 for the HRSA INCONEL 617. In these tables, it is possible to notice the inputs and outputs referred to the functional unit (1kg of material). It is necessary water, chemicals (according with weight composition), iron scrap and pig iron, a portion of a converter (noticed as unit p in these inventories), those products of the converter (dolomite, quicklime, oxygen, inert waste), natural gas, coke and electricity, to produce the material. Likewise, its associated outputs are the emissions to air and water. All of these is what is expressed in Tables 3 and 4 and they constitute the LCI which were comparatively assessed.

2.3. *Life cycle impact assessment*

In this stage, a wide range of environmental impact categories were obtained, such as global warming, human toxicity, metal depletion, etc.

According international standard ISO 14040 (ISO, 2006a) there are four stages in Environmental Impact assessment:

Table 2
HRSA INCONEL 617 composition in weight percentage, wt%.

	C	Mn	P	S	Co	Mo	Si	Ni	Cu	Cr	B	Ti	Al
wt%	0.08	0.5	0.015	0.015	12.0	9.0	0.50	44.5	0.50	22.00	0.006	0.60	0.90

Table 3
Austenitic AISI 347 stainless steel Life Cycle Inventory.

Products		
Steel_AISI347H	1	kg
Resources		
Water	0.004520848	m^3
Materials/fuels		
Dolomite	0.00275	kg
Silicon, metallurgical grade	10	g
Sulfur	0.3	g
Phosphorus,	0.45	g
Manganese	20	g
Carbon black	0.6	g
Nickel, 99.5%	100	g
Nitrogen	0.2	g
Chromium	180	g
Thallium	5	g
Niobium	4.8	g
Oxygen, liquid	0.07145	kg
Blast oxygen furnace converter	1.33E-11	p
Iron scrap, sorted, pressed	0.5	kg
Pig iron	0.17865	kg
Dust, alloyed electric arc furnace steel	−0.0010625	kg
Quicklime, in pieces, loose	0.0425	kg
Inert waste, for final disposal	−0.0029	kg
Basic oxygen furnace waste	−0.032077	kg
Natural gas, high pressure	9.62E-04	m^3
Electricity/heat		
Coke	0.00025	MJ
Electricity, medium voltage	0.021944	kWh
Emissions to air		
Copper	2.50E-08	kg
Nitrogen oxides	1.25E-05	kg
Particulates, < 2.5 μm	4.75E-05	kg
Water/m^3	0.002531675	m^3
Carbon dioxide, fossil	0.0756	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	3.05E-14	kg
PAH, polycyclic aromatic hydrocarbons	1.20E-10	kg
Chromium	1.85E-07	kg
Manganese	6.05E-07	kg
Carbon monoxide, fossil	0.00473	kg
Lead	5.15E-07	kg
Emissions to water		
Water	0.001989173	m^3

Table 4
HRSA INCONEL 617 Life Cycle Inventory.

Products		
HRSA INCONEL 617	1	kg
Materials/fuels		
Boron	0.06	g
Tungsten	0	g
Titanium	6	g
Electric arc furnace converter	4.00E-11	p
Anode, for aluminium electrolysis	0.003	kg
Oxygen, liquid	0.0507	kg
Inert waste, for final disposal	−0.005	kg
Refractory, basic, packed	0.0135	kg
Pig iron	93.84	g
Slag, unalloyed electric arc furnace steel	−0.0768	kg
Aluminium, primary	9	g
Chromium	220	g
Copper	5	g
Silicon	5	g
Molybdenum	90	g
Cobalt	120	g
Sulfur	0.15	g
Phosphorus	0.15	g
Manganese	5	g
Carbon black	0.8	g
Nickel, 99.5%	445	g
Dust, alloyed electric arc furnace steel	−0.0051	kg
Quicklime	0.055	kg
Hard coal	0.014	kg
Natural gas, high pressure	0.025	m^3
Electricity/heat		
Electricity, medium voltage	0.425000	kWh
Emissions to air		
Cadmium	3.65E-08	kg
Mercury	2.24E-06	kg
Copper	2.30E-07	kg
Lead	1.81E-06	kg
Benzene, hexachloro-	2.00E-08	kg
Benzene	2.28E-06	kg
Chromium	1.25E-06	kg
Nitrogen oxides	0.00018	kg
Polychlorinated biphenyls	2.32E-08	kg
Particulates, < 2.5 μm	0.000166	kg
Hydrocarbons, aromatic	7.70E-05	kg
Sulfur dioxide	7.70E-05	kg
Particulates, > 10 μm	5.86E-05	kg
Hydrogen chloride	5.20E-06	kg
Particulates, > 2.5 μm, and < 10 μm	0.000166	kg
Carbon monoxide, fossil	0.00232	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	4.54E-12	kg
PAH, polycyclic aromatic hydrocarbons	3.72E-08	kg
Zinc	2.29E-05	kg
Hydrogen fluoride	2.35E-06	kg
Nickel	7.00E-07	kg

- *Classification:* In this stage, substances are classified according to whether they are likely to generate a certain impact on environment.
- *Characterization:* It is obtained by summing the product of masses for each substance and a factor that reflects their contribution to environmental impact and which is known as impact factor. Every impact category are calculated and summarized within their corresponding units.

The equation for every impact category is given by Eq. (1):

$$IMP_j = \sum_i k_{i,j} * LCI_{e,i} \quad (1)$$

where,

IMP_j: j impact category.
i, j: Damage Coefficient associated with the component i and impact j.
$LCI_{e,i}$: Life Cycle Inventory entry (component amount i).

Characterization quantifies the impact of the functional unit in each impact category. Damage coefficients (also so-called characterization factors) for every inventory substance constitute the impact method. As we described in Section 2.1, this assessment was done by means of ReCiPe Midpoint (Goedkoop et al., 2009) which is the database containing characterization factors for Life Cycle Impact Assessment (LCIA) and it was implemented in SimaPro software.

- *Normalization*: Once the impact has been quantified (characterization), in the normalization stage the impact category indicator results to be compared by a reference (or normal) value. This mean that the impact category is divided by the reference. A commonly used reference is the average yearly environmental load in a country or continent, divided by the number of inhabitants.

According ISO standards (ISO, 2006a, b), normalization is not mandatory but the environmental impact characterization is presented in their units and one way to make interpreting easier is to normalize them: dividing it by a reference. Thus, normalization gets dimensionless results.

These reference factors are available in SimaPro for the Netherlands (in the period 1997–1998), for Western Europe (in 1995) and the world (in 1990, in 1995 and in 2000), for the European Union (EU, the 25 countries comprising it in 2006) and finally, the EU 25 + 3 factors, which means the 25 European Union initial countries complemented by Iceland, Norway and Switzerland. The normalization of this paper was carried out by using the European Union (EU) factors (PRé Sustainability, 2016).

- *Weighting*: Impact categories are mixed to generate a single score. This part is not mandatory and is neither well recognized by the international standards (ISO, 2006b) nor the scientific community (Pizzol et al., 2016).

ISO standards require classification and characterization as mandatory steps and normalization and weighting as optional. Therefore, the environmental impact assessment consists in classification and characterization. Normalization is considered optional for a simplified LCA, but is recommended for detailed one (Frischknecht et al., 2007). In this paper, classification, characterization and normalization was done. And following the ISO standards (ISO, 2006b) recommendations, we did not carried out the weighting phase.

2.4. Interpretation

Through this step the results assessment obtained from the individualized evaluation of the environmental impact categories is carried out. An LCA comparative between different materials allows obtaining results that will lead the best material choice (Martinez-Blanco et al., 2015).

3. Results and discussion

3.1. AISI 347H stainless steel LCA

Life Cycle Assessment for AISI 347H stainless steel was doing using the ReCiPe Midpoint method. The inventory collected every input (raw materials, fuels, electricity, heat; from nature and from technosphere) and output (air emission, water emission and soil emission) of the manufacturing steel process for functional unit, 1 kg. Moreover, the database chosen was Ecoinvent 3. The LCA process was done following the steps according to the ISO 14040 and ISO 14044 standards (ISO, 2006a, b). At this respect, a thorough analysis of the main contributions to the total environmental impact was performed. In this sense, the inventory is classified and then characterized and normalized.

The characterization values are shown in Table 5. In this table, it is possible to distinguish the 12 impact categories assessed. These data results can be identified by their corresponding units in every impact category. In order to make interpreting easier the characterization values were normalized. In this regard, Fig. 2 shows the normalization results (dimensionless) in the AISI 347 study case. In the AISI 347H stainless steel normalization it is possible to identify the impact categories with the highest and lowest contributions to deteriorate the environment. Metal depletion, which characterization value is 14.15 kg Fe_{eq}, is the worst category because it is the highest value in

Table 5
Characterization results of 1 kg AISI 347H using ReCiPe Midpoint (H).

Impact category	Unit	Total
Climate change	kg CO_2 eq	6.733
Ozone depletion	kg CFC-11 eq	4.31E-07
Human toxicity	kg 1,4-DB eq	10.186
Photochemical oxidant formation	kg NMVOC	0.038
Particulate matter formation	kg PM10 eq	0.046
Ionising radiation	kBq U^{235} eq	1.520
Agricultural land occupation	m^2a	0.234
Urban land occupation	m^2a	0.091
Natural land transformation	m^2	0.001
Water depletion	m^3	254.459
Metal depletion	kg Fe eq	14.155
Fossil depletion	kg oil eq	1.709

normalization, as it could be appreciated in Fig. 2, in approximately balanced contribution, Mn, Ni and Cr are the responsible for this impact category. Metal depletion is following by Human toxicity in which is the Ni the most incident element.

In Natural Land Transformation impact category, the higher contribution to the impact are the Cr contribution followed by Ni. In Particulate matter formation category, the main contributors are also Cr and Ni. Regarding Fossil Depletion category, Fig. 2 show that this impact is mainly due to the chromium. Likewise, the major contribution in the Climate change impact category is due to the Cr. In fact, if an overall vision of the impacts is done, it is possible to appreciate the largest contribution to whole AISI 347H impact is due to Ni and Cr. Moreover, Fig. 2 showed that agricultural land occupational, ozone depletion, ionising radiation or water depletion are negligible in comparison with the rest of impacts assessed.

Finally, Fig. 2 showed that Metal depletion is the most relevant impact category. Thus, this study considered important to do an extensive assessment of the metal depletion category. In this sense, Fig. 3 show their network. This research follows the cut-off criterion to represent all relevant environmental impacts. In particular, flows of impacts less than the cut-off value have been excluded of the Fig. 3 representation. Those LCI elements did not appear in network is because their environmental relevance is not a concern. However, the network indicates those elements with greater influence on the final environmental impact. In this study case, Cr is the element that has a higher contribution (45.7%) this means that 45.7% of the complete metal depletion impact is due to the Cr content (0,18 kg). Furthermore, the upstream Cr impact is mainly due to the chromite. Other important flows were those from Mn and Ni. In the Mn case, the flows showed that 25.2% of whole metal depletion impact is due Mn. Likewise, the upstream of Mn showed that the impact from Mn is due to Ferromanganese and Manganese concentrate. Moreover, it is possible to see how 0.1 kg (the amount of Ni in the 1 kg Functional Unit assessed) is responsible of 27.4% of whole metal depletion impact. In summary, the main contributors to the worst impact category were Cr, Mn and Ni.

3.2. HRSA INCONEL 617 superalloy LCA

Similar to AISI 347H, the case study HRSA INCONEL 617 was analyzed to determinate the main contributions of the different elements considered in the total environmental impact. In this regard, HRSA INCONEL 617 superalloy LCA was carried out according to the same method, (ReCiPe Midpoint H) and the same data base (Ecoinvent 3).

Table 6 shows the HRSA INCONEL 617 impact categories characterization. And Fig. 4 showed their normalization values. The results showed that the most representative impact categories are Human Toxicity, Metal Depletion, Natural Land Transformation and Particulate matter formation. In fact, Human Toxicity category reach 419 kg.1.4-DB_{equiv} characterization value. Fig. 4 showed that molybdenum (Mo) is

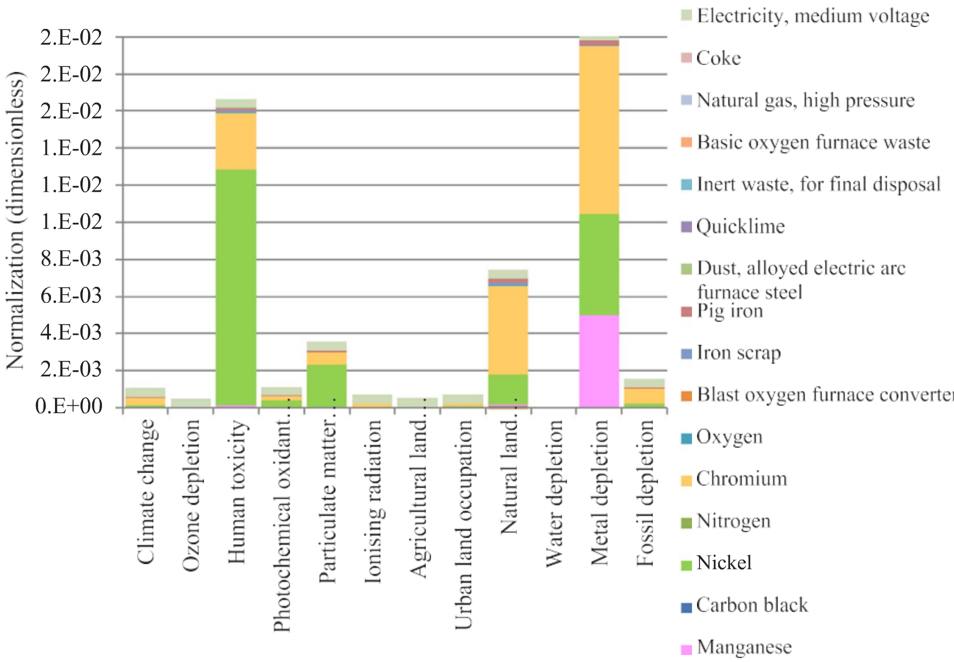

Fig. 2. Analyzing 1 kg AISI 347H steel; Method: ReCiPe Midpoint H. Normalization.

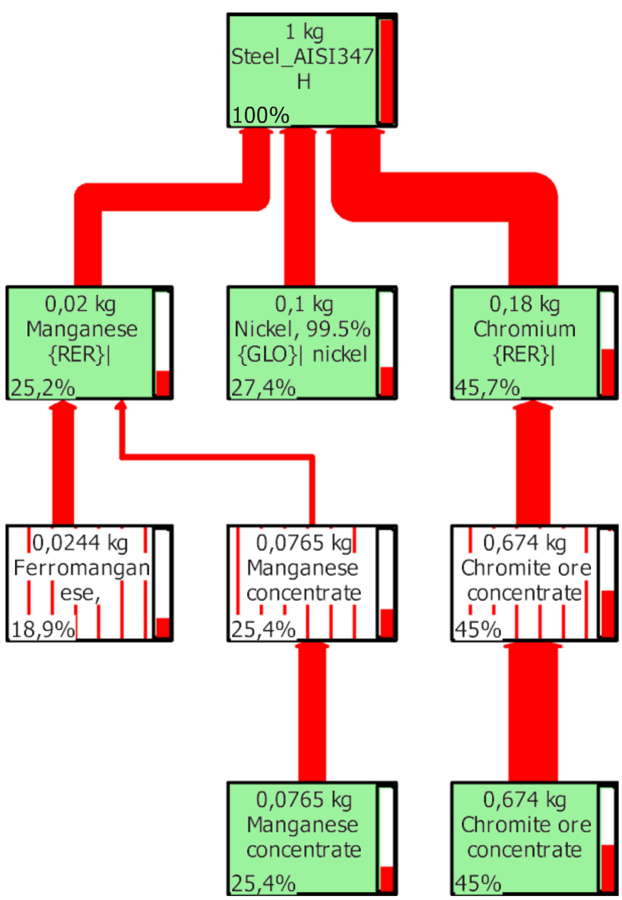

Fig. 3. Metal Depletion (kg Fe eq) impact category characterization network. AISI 347H stainless steel. ReCiPe Midpoint H. Cut-off value: 13%.

the main reason for the high Human Toxicity value. In the case of the Metal depletion category, the highest incidence is due to Mo and Ni and well below the Cr. In case of Natural Land Transformation, the component that causes higher impact is Mo again. Following the steps doing in the 347H study case, we wanted to deeply assess the most harmful

Table 6
Characterization results of 1 kg HRSA INCONEL 617 using ReCiPe Midpoint (H).

Impact category	Unit	Total
Climate change	kg CO_2 $_{eq}$	16.743
Ozone depletion	kg CFC-11 $_{eq}$	9.40E-07
Human toxicity	kg 1,4-DB $_{eq}$	419.390
Photochemical oxidant formation	kg NMVOC	0.259
Particulate matter formation	kg PM10 $_{eq}$	0.416
Ionising radiation	kBq U^{235} $_{eq}$	2.987
Agricultural land occupation	m^2a	0.783
Urban land occupation	m^2a	0.949
Natural land transformation	m^2	0.0053
Water depletion	m^3	506.106
Metal depletion	kg Fe $_{eq}$	106.367
Fossil depletion	kg oil $_{eq}$	4.181

category. At this respect, Fig. 5 shows the Human Toxicity category contribution network, for a cut-off of 5.74% of environmental damage. This means that impacts below this cut-off value are not showed in the network. Fig. 5 show the contribution of the Ni to the final human toxicity impact. This is a very representative result because a big amount of wt% Ni content in the functional unit (0445 kg of Ni in 1 kg of 3.2 HRSA INCONEL 617) only provokes 6.16% of the worst impact category (Human Toxicity). However, the amount of 0.09 kg of Mo in the LCI are the responsible of 92.2% of the human toxicity impact. With this result is it possible to notice the harmful feature of Mo. If the human toxicity network is assessed, is It possible to notice that the upstream damage of the Mo is due to the molybdenite production.

Besides the specifics LCA of both materials, a comparative LCA were also included in this evaluation. In this regard, Fig. 6 represents the characterization values in% of environmental damage. These results reveal that environmental benefits can be obtained by avoiding 347H use because the AISI 347H Steel gets lower values of impacts in every category assessed. Fig. 7 shows the normalization of the comparative LCA. In this figure, it is possible to notice that human toxicity, metal depletion, natural land transformation are the main environmental problems in both materials assessed and how to other environmental problems such as ozone depletion or climate change are not representatives in an environmental point of view.

In the comparative LCA it is possible to notice the main impacted categories. This is mainly due to the following factors:

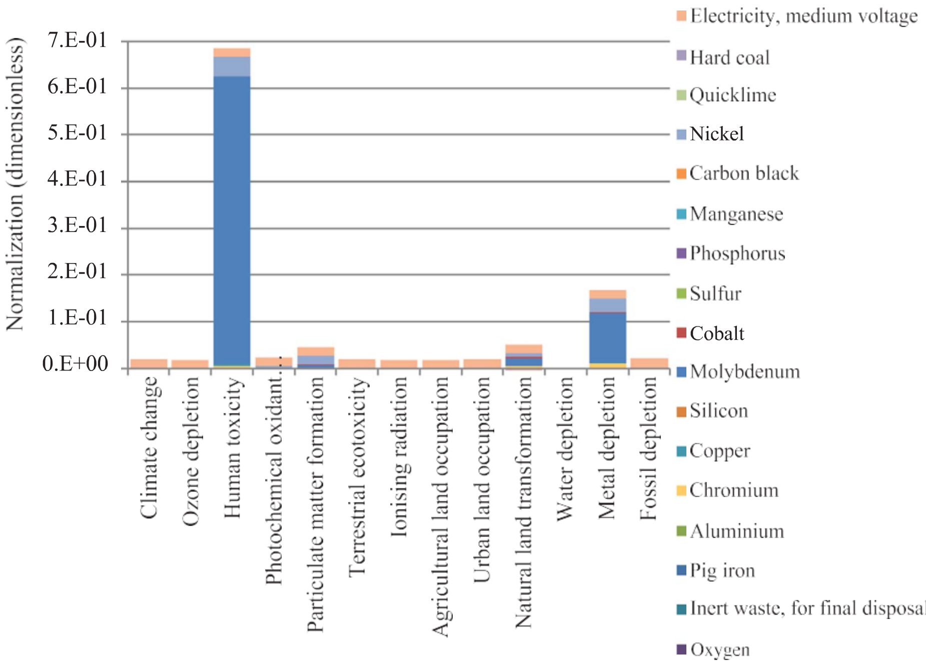

Fig. 4. Analyzing 1 kg HRSA INCONEL 617; Method: ReCiPe Midpoint H. Normalization.

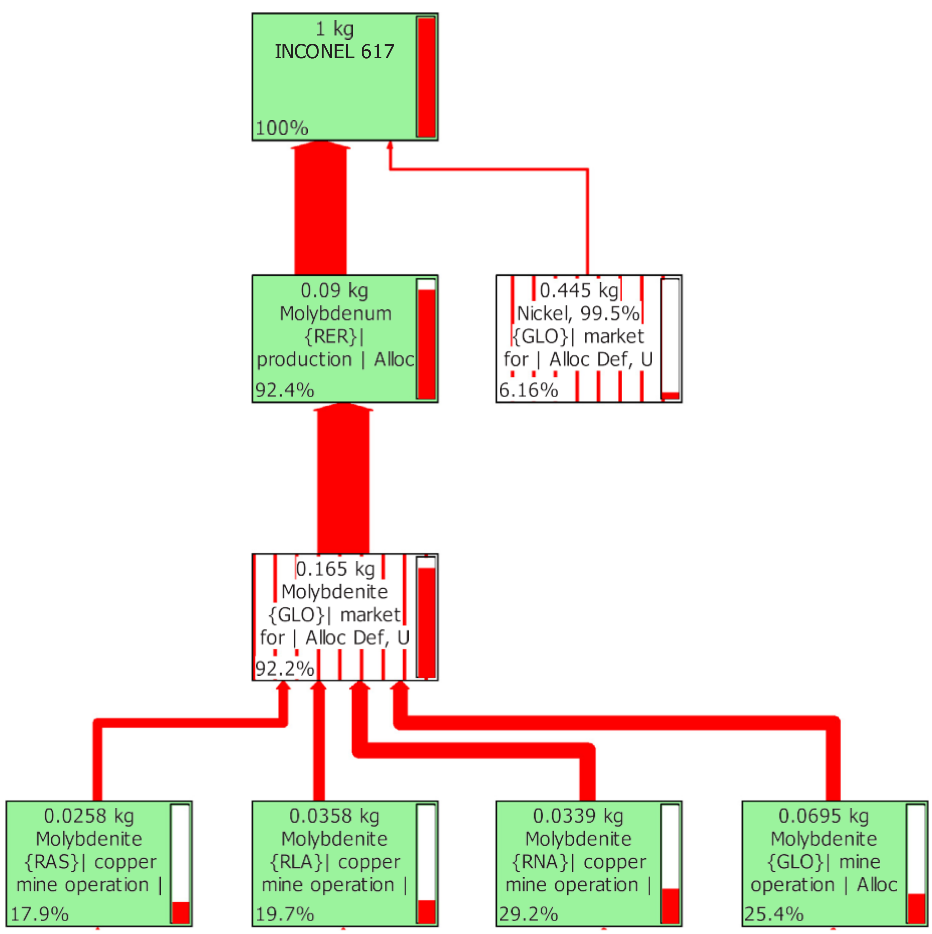

Fig. 5. Human toxicity (kg 1,4-DB eq) impact category characterization network. HRSA INCONEL 617. ReCiPe Midpoint H. Cut-off value: 5,7%.

- *Human Toxicity impact category:* This is an impact category corresponding to emission of substances or particles that can cause diseases in human health. The high values for this category of impact are due to the contribution of Ni and Mo, by different processes for their production, the market and chrome production.

- *Metal Depletion impact category:* Metal Depletion impact category, is mainly due to mineral extraction. Minerals involved in obtaining major metals and causing the increase of values in this impact category are Molybdenite, and Pentlandite, Pyrrhotite and Chromite, of which Mo is obtained, Ni and Cr.

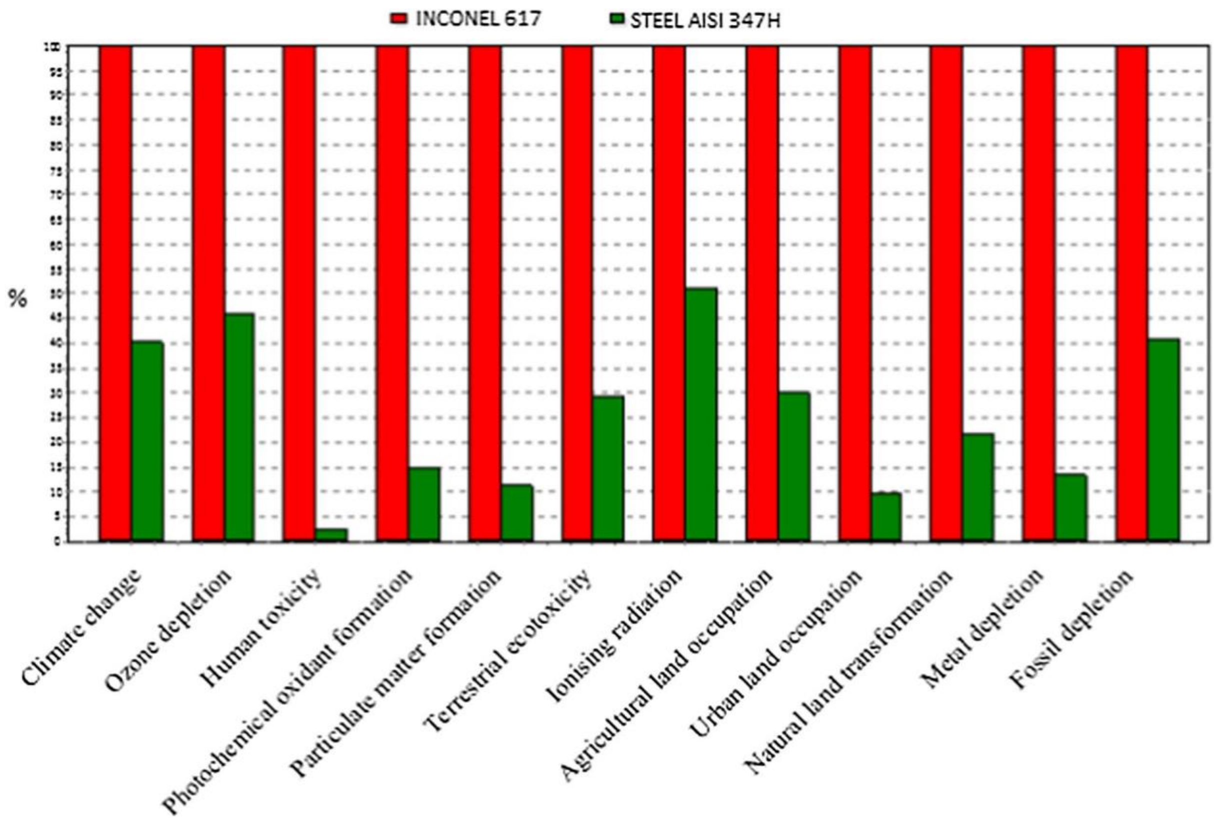

Fig. 6. Comparing 1 kg HRSA INCONEL 617 to 1 kg Stainless Steel AISI 347H; Method: ReCiPe Midpoint (H). Characterization. [% of environmental impact].

- *Natural Land Transformation impact category:* Mining activity for mineral extraction causes disruption of the soil so that the waste generated in this activity cause soil impoverishment and hence the vital development of different species. The contribution at this impact category in this study is due to Cr, Ni and Mo.
- *Particulate Matter Formation impact category:* The primary responsibility for contribution is extraction processes and obtaining Ni and Cr production, in the case of AISI 347H and less influence of Mo, in the case of HRSA INCONEL 617.

4. Conclusions

Currently, the materials choice for CSP plants aim to minimize the degradation effects suffered by the fact of working at raised temperatures in the presence of molten salts. The addition of different alloying allows the improvement of the physic-chemical properties, but can impact negatively on the environmental aspects. Then, it is necessary to work towards the development of new materials that minimize the environmental impacts in CSP plants.

This study compares superalloy HRSA INCONEL 617, 1 kg. vs. AISI 347H stainless steel 1 kg. by ReCiPe Midpoint H LCA method, under the same conditions. At this respect, impact categories classified from major

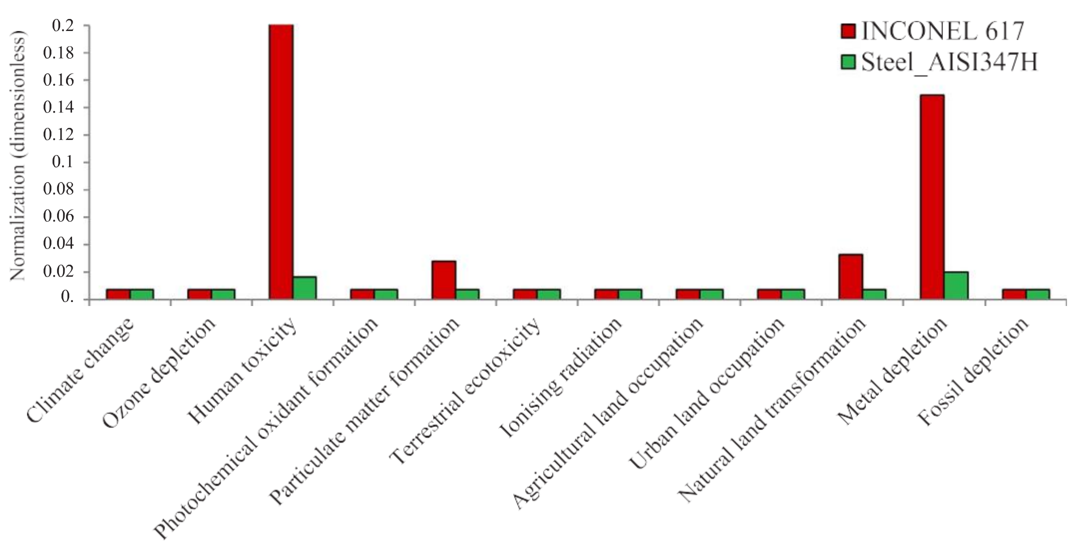

Fig. 7. Comparing 1 kg HRSA INCONEL 617 to 1 kg Stainless Steel AISI 347H; Method: ReCiPe Midpoint (H). Normalization. [dimensionless].

to minor environmental damage were: Metal Depletion, Human Toxicity, Natural Land Transformation and Particulate Matter Formation.

Ni, Cr, Mo and Mn are alloys which improve technical material properties. But, the results showed a great incidence of these alloys in the most affected impact categories. LCA networks showed higher incidence in the processes involved in obtaining them.

The final results showed that AISI 347H stainless steel reduced the environmental impacts compared to those obtained from HRSA INCONEL 617. This is an important reason in the material choice when the central tower plant is being designed.

The values in every single impact category are considerably higher in the case of HRSA INCONEL 617 vs. AISI 347H stainless steel. As it was noticed in the single LCA of each metal, Mo is the main problem in main impact categories.

Comparing to AISI 347H steel case, HRSA INCONEL 617 gets much higher values in normalization (dimensionless) for Human Toxicity and Metal Depletion impact categories.

Besides the good mechanical and corrosion resistant properties of HRSA INCONEL 617, the comparative LCA proves the better environmental behavior of AISI 347H stainless steel. Then, AISI 347H stainless steels is environmentally friendly compared to Ni- base superalloys. Therefore, and taking consideration the above mentioned issues, the LCA technique allows for the detection of environmental impacts and is a good decision-making tool for the material choice in the CSP plants.

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