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Life Cycle Assessment of the Fluids Used in a Concentrated Solar Power Plant

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Abstract. In the present work, the environmental damage of two types of molten salts and synthetic oil has been evaluated with the aim of deciding whether the use of molten salts is more suitable than synthetic oil from an environmental point of view. To this end Life Cycle Assessment has been used, since it offers numerous advantages in the assessment of aspects associated with the development of a product and its potential impact throughout the life of a given product from raw material acquisition, processing, manufacturing, use and finally its disposal. According to the results, the replacement of the VP-1 like thermal oil by molten salts is absolutely recommended from an environmental perspective, since the environmental impact of molten salts appear to be reduced in comparison to Therminol®VP-1. Thus, direct systems, in which thermal storage and heat transfer fluid are unified using molten salts, emerge to improve the power cycle performance, these being a good option not only from the known technical point of view, but also from the environmental point of view. Life Cycle Assessment seems to be a suitable and necessary methodology to quantify the environmental impacts of fluids, materials, and O&M in CSP plants.

Keywords: LCA; Molten salt; Solar Salt; Hitec; Therminol®VP-1; CSP

INTRODUCTION

Scientific and commercial developments worldwide have proven the technology viability of using concentrated solar energy for the production of electricity at a large scale. The final scope is the reduction of Greenhouse gas emissions and of the dependence on fossil fuels for energy production, coherently with The United Nations Climate Change Conference (COP21) targets and in order to mitigate Global Warming phenomenon which is becoming alarming [1]. However, and despite its renewable nature, solar power also generates environmental impacts that need to be identified, quantified and evaluated. Various authors have evaluated the environmental impact of CSP [2-4], Life Cycle Assessment (LCA) being the most used methodology. LCA is a suitable technique for assessing numerous aspects associated with the development of a product and its potential impact throughout the life of a given product from raw material acquisition, processing, manufacturing, use and finally its disposal [5].

One of the main aspects under study is the substitution of the Therminol®VP-1 thermal oil used as Heat Transfer Fluid (HTF) by molten salts, which are currently used as Thermal Energy Storage (TES) mediums in various commercial plants. CSP tend to improve their efficiency to get better Levelized Cost of Energy (LCOE) [6]. In this regard, the use of molten salts gains thermal efficiency because its working temperature range is higher and wider than that of others fluids [7-8].

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Molten salt as HTF both transfer heat to power cycle and store heat in a TES tank without additional heat exchanger. The technical viability of these direct systems has been proved in the parabolic trough Archimede plant [9] and in the tower Solar Two project [10]. In addition, Therminol®VP-1 like thermal oil has some constraints such as fire hazards, limited working temperature and environmental contamination in case of leaks [8].

At this respect, and regarding the environmental impact, an evaluation of the impact of this substitution would be of great interest. Thus, this investigation was performed to evaluate the feasibility of using molten salt simultaneously both as HTF and TES, always from an environmental point of view. This means to address the environmental benefits of molten salts against VP-1 thermal oil. In a CSP plant, thermal energy is stored by means of vast molten salt tanks. However, the HTF mass trough the collectors' system is much lower than the amount of molten salt storage. In fact, there is a study that collects the inventory of several CSP plants [11]. This work revealed that the used of thermal oil as HTF barely represents 7% wt. of the amount of molten salt used as TES. On this basis, the present article is referred to the fluids as HTF, assuming that the storage system is always composed by molten salts. In the conventional indirect systems, there are two fluids: thermal oil for HTF principles and molten salt as TES. However, molten salt direct systems get the unification of their HTF and TES being both the same fluid.

Regarding the conventional systems, a previous study gathered the inventory of material and energy flows required for the construction and operation of some solar thermal power plants in Spain [11]. Instead, in relation to CSP direct systems the maturity of the technology is already in industrial phase for tower systems but still in demonstration phase for parabolic troughs [12]. The main developments regarding direct systems are Archimede project [9] in parabolic and Solar Two and Solar Tres [13] in tower systems. A recent study [14] quantified the amount of molten salt required in a direct system, but it did not distinguish the amount of product allocated to TES and HTF purpose.

In the light of the above, the aim of this work is to determine, evaluate and quantify the environmental impacts of the three fluids currently used in the commercial parabolic-trough CSP plants, and also evaluate the improvement that the substitution of Therminol®VP-1 by molten salts would imply from an environmental point of view.

EXPERIMENTAL

The LCA was conducted according to standard methods ISO 14040:2006 [15] and ISO 14044: 2006 [16]. According to these standards, LCA includes various phases of study: (1) the definition of the goal and scope —which defines the aim and the functional unit; (2) inventory analysis—which lists raw materials, emissions of pollutants into air, water and soil, solid wastes and consumption of resources per functional unit; (3) impact assessment —which assesses the environmental impact of the inventory inputs and outputs throughout the life cycle; and (4) interpretation of results (see Fig. 1).

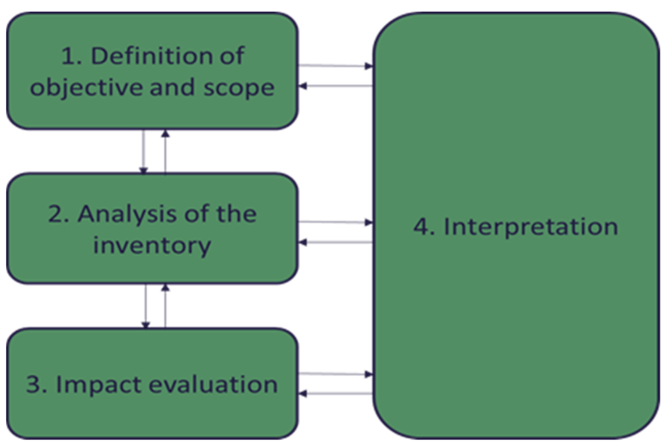

FIGURE 1. LCA phases according to the standard ISO 14040:2006.

Every CSP plant implement their performance model input defining the system's design parameters. Two plants that produce the same electricity per year might use different masses of HTF depending on the technology. Initially it was considered 1GWh as Functional Unit. That is why a further statistical analysis should have been conducted to get the relationship between 1kg of HTF and 1GWh produced. Unfortunately, there are not enough reports with every

HTF quantity in every CSP plant to perform this statistical study, since CSP is a relative new technology and direct systems are still being developed. Therefore, and knowing that there is approximately a total capacity of ~6 GWe worldwide [12], the authors consider that there is a lack of studies to conduct an appropriate statistic relationship between HTF and 1GWh produced. However, with a unitary kg mass-based Functional Unit the impacts result scalable. Furthermore, it is challenging to investigate the contribution of every material component to the whole impact in order to develop new fluids, which is one of the key factor of CSP industry [13] and LCA eco-efficiency principles [17]. In addition, if the environmental damage is assessed in this way, it would be easier quantify the environmental damages of a leak. By the fact of setting the amount %wt of the leak, it will be possible to know their environmental impacts until the moment before the leak occurred

In view of the foregoing, one kg of each fluid (binary solar salt, Hitec ® solar salt and Therminol®VP-1 oil) has been chosen as Functional Unit. A research work based on 1kg of each HTF is considered to produce a general and scalable model. The system boundary is a Cradle to gate approach. In the Life Cycle Inventory (LCI) phase the quantity of material used should be measured and identified. Table 1 shows the LCI based on the weight composition of the fluids. Data for each one have been taken from some processes included in Ecoinvent 3 database [18].

The impact evaluation phase is composed by mandatory and optional elements. According to ISO 14040, mandatory elements are classification and characterization. As optional element, normalization is recommended for detailed LCA.

LCA calculations were accomplished by using the SimaPro 8 software and CML Impact Assessment (CML-IA) baseline methodology. CML-IA classifies and then characterizes the environmental impacts. This method applies characterization factors recognized in the LCA Handbook [19]. CML-IA baseline also contains normalization values. The study included the following impact categories: abiotic depletion (kg Sb_{eq}), abiotic depletion of fossil fuels (MJ), global warming potential (kg CO_2eq), ozone layer depletion (kg CFC-11_{eq}), human toxicity (kg 1,4-DB_{eq}), terrestrial ecotoxicity (kg 1,4-DB_{eq}), photochemical oxidation (kg C_2H_4 eq), acidification (kg SO_{2eq}) and eutrophication (kg PO_{4eq}). According ISO 14040/14044 standards, 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 referenced values. When normalization is done, the environmental impacts gets dimensionless. The normalization of this paper was carried out by using the European Union (EU) factors [20].

TABLE 1. LCI components. 1kg of fluid as Functional Unit.

[kg]	Sodium nitrate	Potassium nitrate	Sodium nitrite	Diphenyloxide	Biphenyl
Binary	0.6	0.4	-	-	-
Hitec ®	0.07	0.53	0.4		
Therminol®VP-1	-	-	-	0.735	0.265

RESULTS AND DISCUSSION

Figure 2 shows a comparison of the three fluids studied regarding their normalized values. These values are obtained through the relation between the characterized values reached by the fluids under study and the global values in each category. SimaPro 8 implements several CML-IA normalization factors. The EU25 (the 25 countries comprising Europe in 2006) normalization factors were chosen to carry out this study.

It was observed that Therminol®VP-1 reached the highest values in all the impact categories. All these categories were classified in water impact categories, social impact categories, and energy impact categories, the latter appearing to be the most attractive and interesting in CSP technology.

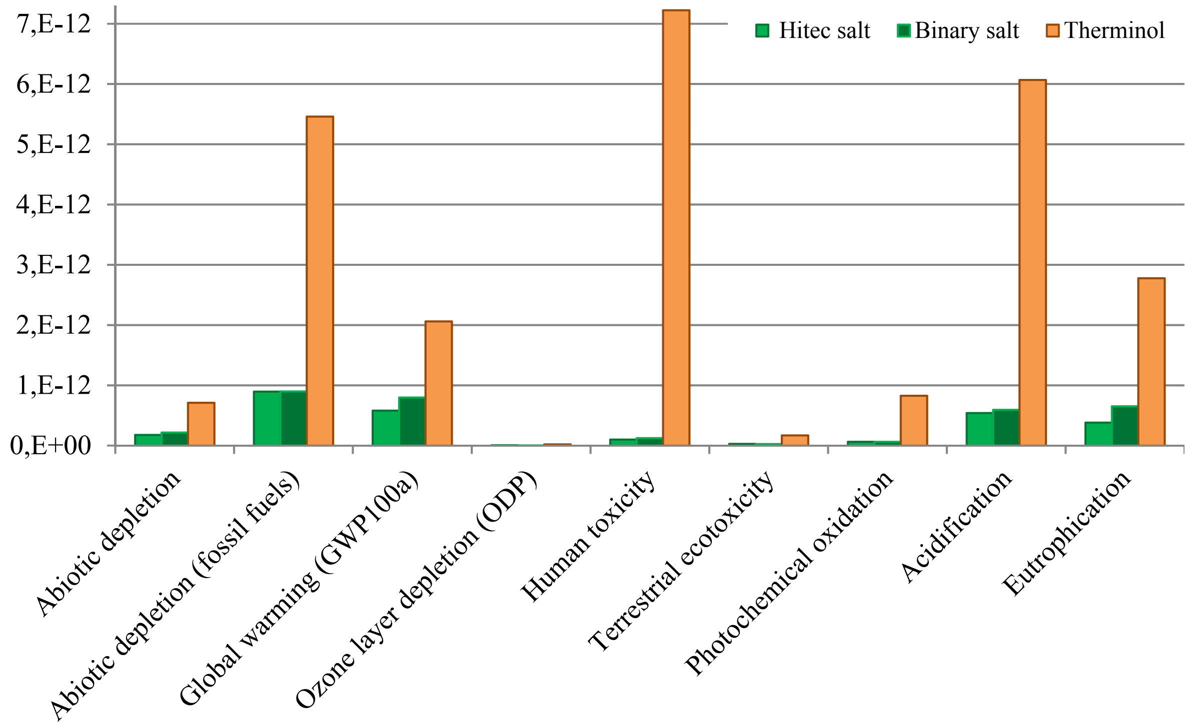

FIGURE 2. Comparison of 1 kg of binary salt', 1 kg 'Hitec salt' and 1 kg 'Therminol'® VP1; Method: CML-IA baseline V3.01 / EU25 / Normalization [dimensionless].

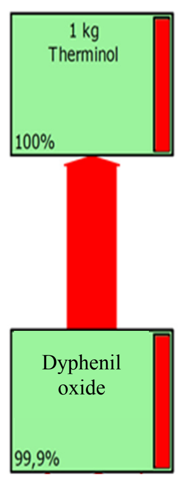

FIGURE 3. Impact category network of Human Toxicity category in Therminol®VP-1.

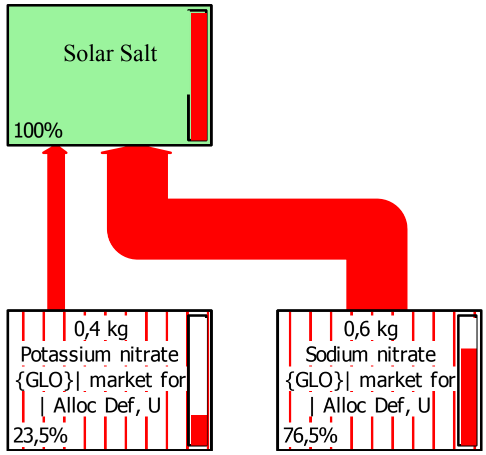

FIGURE 4. Impact category network of Abiotic Depletion (fossil fuels) in Binary Solar Salt.

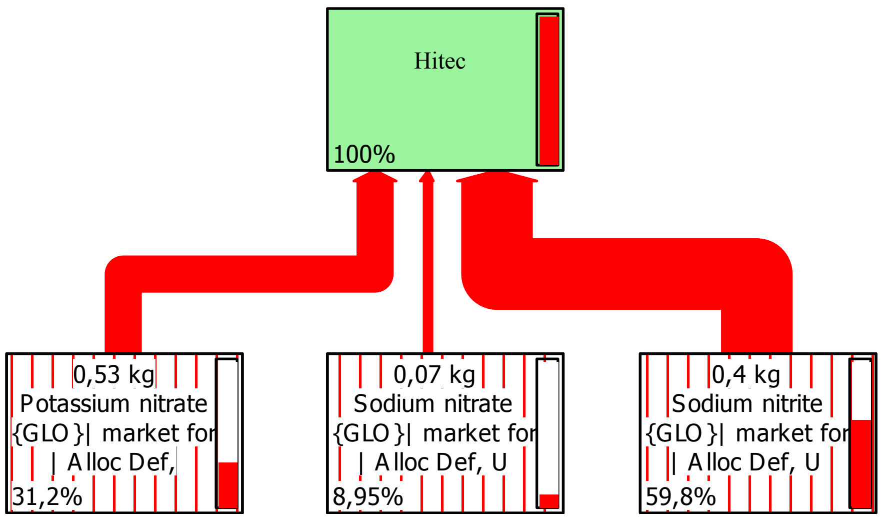

FIGURE 5. Impact category network of Human Toxicity category in Abiotic Depletion (fossil fuels) in Hitec® Solar Salt.

According to a reported work based on the study of an energetic analysis of CSP plants combined with LCA [21], VP1 synthetic oil showed a significant energetic demand (a contribution of 19%). In this regard, Ehtiwesh et al. [21] pointed out that in the synthetic oil case, the resources of the non-renewables categories such as fossil and nuclear present the largest demands (values above 99%), correlating the environmental problems of VP1 to the problems caused by non-renewable plants.

According to the results, the present work proves Therminol®VP-1 provokes serious environmental problems, both in energy impact categories, water impact categories and social impact categories. Human Toxicity is the main problem of this fluid, this reaching 56.01 kg 1.4-DB_{eq}, where the 99.9% is caused directly by the diphenyl oxide, which one of the components of Therminol®VP-1 (see Fig. 3). On the other hand, the environmental impact of an indirect CSP plant using Therminol®VP-1 as HTF and Solar Salt as TES (Thermal Energy Storage) fluid was compared to the environmental impact of a direct CSP plant using Hitec salt as HTF and TES fluid. According to the obtained results, a direct CSP plant using Hitec salt is more environmentally friendly than an indirect CSP plant, not only due to the use of Therminol®VP-1 as HTF, but also to the use of Solar Salt as TES fluid.

Abiotic depletion is the category, which rise higher impacts in the molten salts study cases. Figure 4 shows how 76.5% of the Binary solar salt impact is caused by sodium nitrate and 23.5% potassium nitrate. That is, in 28.27 MJ of abiotic depletion (fossil fuels), 21.63 MJ are direct cause of sodium nitrate and 6.64 MJ by potassium nitrate. In the

Binary study case, the most harmful component is the sodium nitrate. Hitec solar salt network (figure 5) shows that sodium nitrate is the lowest contributor, to the damage closely related to the low weight percentage of it in the salt composition, which is 7%. In this case, the abiotic depletion (fossil fuels) is the most dramatic impact category followed by climate change. Ozone layer depletion is the category with a better behavior in terms on sustainability followed by terrestrial ecotoxicity. By diminishing as much as possible of the most harmful component ($NaNO_3$ goes from 60 wt% in the binary solar salt to 7 wt% in the Hitec®), maximizing the most environmentally friendly component (KNO_3 goes from 40 wt% in the binary solar salt to 53 wt% in the Hitec®) and adding a new component to improve the physic-chemical properties, 40 wt% $NaNO_2$, it is possible to get better environmental behavior.

CONCLUSIONS

The main focus of this study has been the comparison of three HTF used in CSP plants from the LCA point of view, considering its life cycle. This study is the first step towards a new research line to assess the environmental performance using the LCA methodology. According with both technical and environmental analysis the feasibility of the appropriate material will be complete.

The results showed greatest impacts for the Therminol®VP-1 oil in comparison to Hitec® and Binary molten salts. Considering the complete LCA, the Hitec® has shown better environmental behavior than the binary solar salt. Hitec showed that the dematerialization in the content of the most harmful component (sodium nitrate) results in a global environmental improvement of a complete molten salt.

In the case of Therminol®VP-1, it is possible to conclude that most of the impact came from In the case of Therminol®VP-1, a significant of the percentage relatively important composition (26.5 wt% Biphenyl) contribution, does not have a great contribution to the impacts, most of them coming from Diphenyloxide. Then, the biphenyl environmental properties cause less damage than the Diphenyloxide, being the Biphenyl contribution despicable.

The Life Cycle Assessment performed over the Therminol®VP-1 like thermal oil currently used as heat transfer fluid (HTF) in Parabolic Trough CSP technology (Therminol®VP-1) and also over the two commercial molten salt mixtures (Solar Salt and Hitec) concludes that the replacement of the Therminol®VP-1 like thermal oil by molten salts is absolutely recommended from an environmental perspective, since the environmental impact of molten salts appear to be reduced in comparison to Therminol®VP-1. LCA is a necessary analysis to quantify the environmental impacts of fluids, materials, and O&M in CSP plants.

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