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Life Cycle Assessment of heat transfer fluids in parabolic troughconcentrating solar power technology

E. Batuecas[a,*], C. Mayo[a], R. Díaz[b], F.J. Pérez[a]

[a] Surface Engineering and Nanostructured Materials Research Group, Complutense University of Madrid, Complutense Avenue s/n, 28040 Madrid, Spain
[b] Open University of Madrid, UDIMA, Faculty of Technical Sciences and Engineering, Road A-6, 15, exit 36, 28400 Collado Villalba, Madrid, Spain

ABSTRACT

The majority of parabolic trough concentrating solar power plants consist of an indirect system where the heat transfer fluid (typically synthetic oil) exchanges energy with a secondary circuit which is connected to the power cycle. Synthetic oil has a technical limitation by the maximum operating temperature. This results in the search for new fluids. On the other hand, with the aim of having energy when there is no sun shining, it has increased the use of thermal storage. Thermal energy storage systems are composed of molten salts and presents higher operating temperatures than synthetic oil. Thus, direct systems, in which thermal storage and heat transfer fluid are unified and normally molten salts, emerge to improve the power cycle performance. To determine the future potential of direct systems, this paper evaluates the environmental damage of two types of molten salts and synthetic oil in order to decide whether the use of salts is better than synthetic oil, from an environmental point of view by using the Life Cycle Assessment (LCA) techniques. LCA results showed greater impacts in the syntheticoil case than the molten salts

1. Introduction

According to International Energy Agency's projections, energy demand will be increased by one third, and energy-related CO_2 emission will rise by 20% until 2040 [1].

This is a context with urgent need to decarbonize [2] the current energy mix. Renewables are the big winners in the race to meet energy demand growth [3].

Concentrating solar power (CSP) presents huge potential for the large-scale deployment of clean renewable energy [4–6].

With a growing demand to develop and improve upon the sustainable utilization of renewable energies in general and CSP in particular, different designs and replacements to effectively store and transform solar power have been submitted [7].

The parabolic trough collectors' system is currently the most developed and implemented worldwide CSP technology [8]. It constitutes more than 80% [9] of plants under operation and construction.

In these systems, sun thermal energy is transmitted to a heat transfer fluid (HTF). Solar radiation is concentrated. Then, HTF exchanges energy with a secondary circuit which is connected to the power cycle. Also, in CSP plans it is possible to incorporate a Thermal Energy Storage (TES) system. TES technology solves the time mismatch between solar energy supply and electricity demand, which provides a distinct advantage to CSP plants compared to other renewable energies [9].

The maturity of molten salt storage technology has promoted that over 80% capacity under construction has incorporated energy storage [9]. However new materials are needed for the expected worldwide deployment in CSP plants and they should include not only technical and economical criterion, but also ecological performances [10].

The compromise between thermal efficiency and economy makes CSP thermal storage using molten salts the most competitive option [11,12]. Also, molten salts TES improve the Levelized Cost of Energy (LCOE) [13].

Desirable properties of HTF and TES fluid are low melting temperature and / or high maximum operating temperature, high thermal conductivity and density appropriate, good thermal stability, low vapor pressures, corrosion resistance against the containment material and low cost [14].

Nowadays, several different types of HTFs are used in commercial CSP plants. They are steam, air, thermal oils and molten salts [14–17]. However, all of these materials have many disadvantages as HTFs. The purpose of getting higher operating temperatures for improving the Rankine cycle efficiency, results in developments for new materials beyond synthetic oils and other configuration of plants. It is here where the molten salts acquire relevance as heat transfer fluids.

The HTF is expected to not only transfer heat as a media in the CSP system, but also directly store heat in a TES tank without additional heat exchanger [18]. This are the so-called direct systems.

The parabolic trough CSP plant can be classified in direct system or indirect system.

Direct system works simultaneously with the same fluid as HTF and TES, these do not require a physical separation between the heat transfer fluid and storage. Instead, in indirect systems TES and HTF are different fluids, connecting by a heat exchanger. It means HTF operating in the solar field transfers its energy through a heat exchanger to TES medium, molten salts.

The most commonly used HTF technique in parabolic trough CSP plants is the indirect system. In this system, thermal oil such as Therminol® [19], is physically separated from the TES fluid by a heat exchanger. Historically, thermal oil has been used as HTF in parabolic trough due to their affordable price, low vapor pressure, good thermal stability, and long lifetime. But three main constraints associated with them: (a) environmental contamination in case of leaks, the ground affected by a leak has to be decontaminated; (b)fire hazards, the fire point is usually below the solar field working temperaturas (c) limited working temperature, thermal oils currently available at affordable prices have a maximum working temperature of 393 °C, which limits the temperature of the superheated steam delivered to the parabolic collectors system to about 385–390 °C; this limitation jeopardizes the overall plant efficiency [17].

Then, thermal oils are not the perfect working fluid for parabolic trough collectors, because they have some important constraints [17]. Selecting the appropriate heat transfer fluid and storage medium is a key technological issue for the future success of CSP technology [20].

This paper is focused in molten salts and how they can replace the synthetic oil to improve the environmental behavior of the system.

The organic oil may be replaced by an inorganic fluid such as molten salt. Inorganic fluids have upper temperature limits in the range of 465 °C to 600 °C, allowing an improvement in efficiency of the Rankine cycle to values of from 0.40 to 0.43 [21]. Furthermore, direct systems avoid the need for intermediate heat exchangers [22].

Nowadays, the technical progress consists of developing molten salts as replacement of conventional synthetic oils.

Molten salts are the most promising HTF candidate in parabolic trough CSP systems [20,23–25] because of high thermal stability temperatures and properties [26–28] also for its wide availability, material compatibility and safety and environmental health properties [29]. If there is a leak, it remains as a thick solid film that can be easily recovered and reused, thus avoiding the high decontamination costs associated with oil leakages on ground and nitrates used in molten salts have been traditionally used by farmers as fertilizer [17].

Molten salt can reach temperatures of around 600 °C, depending on its composition. This is the main property in the feasibility of direct systems for removing synthetic oil. It is therefore essential to develop fluids that can withstand high temperatures without degrading.

Some mixtures containing Li-and other additives have also been researched and patented for future development [30–32]. But, nitrates and nitrites are not only cheaper, but also much less corrosive than fluorides or chlorides.

The disadvantages of molten salts are: they solidify at temperatures above synthetic oil. This requires installing heating systems to prevent solidification of salts in the various sections of pipe in the solar field, for times when the field is inactive or has a low ambient temperature but Therminol® has the maximum operating temperature fixed at 393 °C [33]. This fact effectively sets a limit of efficiency of the Rankine cycle of about 0.375 [34]. While it is true that molten salts require appropriate temperatures and this implies the cost of electric heating equipment monitoring in all molten salt pipes, the advantages outweigh the disadvantages. Molten salts (binary and Hitec®) are cheaper than synthetic oil and both of them improve the maximum operating temperature point. For instance, Hitec® can withstand temperatures up to 593 °C without losing its properties. Molten salts have got high heat capacity, high density, high thermal and chemical stability, low vapor pressure, no harmful effects, satisfactory physical properties and a lower unit cost. These allow further improvement in thermal efficiency for solar thermal power plants, increasing the Rankine Cycle efficiency by increasing the operating temperature [35].

In theory, the use of molten salt in direct application of heat transfer fluids could be constrained due to their high freezing temperature points. But in practice, it exist mixtures such as the Hitec®, and others [36] (for instance 50–80 wt% KNO_3, 0–25 wt% $LiNO_3$ and 10–45 wt% $Ca(NO_3)_2$) in which its melting point is near 100 °C [35]. This is an improvement respect to the common mixture binary molten salt.

The indirect system's viability has been widely proved. For instance, in Andasol CSP plants [36] and many others. Sixty-three parabolic trough CSP plants were fully operational during mid-2015 and sixty-one of these plants were using thermal oil as HTF [17].

On the other hand, direct system's viability has been proved in Italy in the Archimede project which consists in a 5 MW parabolic trough CSP plant [37–39] and in California in the tower CSP Solar Two project [36]. Also, simulation models of molten salt parabolic trough plant have been developed [40,41]. F. Zaversky et al. [42] modeled parabolic trough solar collectors that use molten salt as heat transfer fluid, instead of the conventional thermal oil and they concluded that Rankine performance was improved using molten salt as HTF, instead of thermal oil.

Furthermore, Abengoa Solar studies the feasibility cost and performance of a parabolic trough plant with 6 h molten salt storage [43]. Their results show how the molten salt work as HTF can reduce the storage cost up to 43.2%, the solar field cost up to 14.8% and the LCOE up to 14.5%. These results are always related to an indirect CSP plant with Therminol® HTF. Replacing the thermal oil with the molten salt as the operating fluid in the collector system, allows a higher temperature outlet of solar field, which means greater efficiency in the power block improving Rankine cycle and the energy storage cost.

There are some studies in the field of Life Cycle Assessment (LCA) in solar thermal energy [44–46] Viebahn et al. [44] publish the LCA inventory of several Spanish CSP plants. Lechón et al. [45] carried out environmental impact assessments of the electricity produced in a two CSP plants: a 17 MW central tower and a 50 MW parabolic trough. Ehtiwesh et al. [46] asses the environmental impact and cost, in terms of exergy for the entire life cycle of a CSP plant. Recently a review has been published [47].

The physico-chemical properties of HTF have also been studied [35], [48–54]. However, regarding LCA in HTF no data is found reported in the literature.

For all of the above-mentioned reason, it is necessary to study in more detail the environmental aspects of HTF in the CSP plants. The first step towards discovering whether the HTF being molten salts have got a correct ecological performance or not, is to evaluate it with a complete LCA.

The aim of this work was to determinate the environmental behavior of Binary Molten Salt, Hitec® Solar Salt and Therminol® oil. The LCA will compare three these different fluids. The results are useful to select the optimal HTF.

2. Methodology

LCA provides a structured analysis of inputs and outputs at each stage of the life cycle for products and services; it is a specific elaboration of a generic environmental evaluation framework [55].

The environmental assessment was conducted following the ISO 14040 [56] and 14044 [57] standards. According to the methodology described by international standards, the LCA is divided into the following phases: (1) goal and scope definition, (2) inventory analysis, (3) environmental impact assessment, and (4) interpretation.

2.1. Goal and scope definition

The goal for this LCA was to compare the environmental impacts of three heat transfer fluid used in parabolic trough concentrating solar power technology to determine and quantify the main environmental contributors and which of them is worst in terms on sustainability.

Determining these impacts may deliberate on the convenience for using molten salt as HTF instead of synthetic oil, always from an environmental point of view. The study of the overall environmental impacts allows the two types of molten salt to be evaluated with respect to the synthetic oil.

In addition, the hotspots of each fluid were identified highlighting components with larger impacts over the environment.

The LCA will be used as a tool in order to identify solutions for making the most environmentally respectful choice. The functional unit selected was 1 kg of material. System boundary set a cradle-to-gate perspective which is appropriate in the material assessments [58].

2.2. Inventory analysis

The data inventory stage involves the input quantification required to produce the functional unit.

In the present study, the following assumptions were made. For modeling Therminol®, Binary Molten Salt and Hitec® salt, it has taken place and is included in Ecoinvent 3 [59] data base, modifying and adapting them to the specific compositions of needed materials. The components came from Ecoinvent 3 data base processes therefore are associated with all upstream subprocesses production. Thus, this system boundary takes into account the energy and material inputs, and environmental outputs from, all the cradle-to-gate processes associated with the manufacturing of these heat transfer fluids.

In the present study the attributional approach has been applied by the delimitation of the system, i.e. the inventory system represents the processes actually affected as recommended by B. Weidema [60].

On the other hand, category indicators can take different approaches, oriented to the problem, in that case they are denominated midpoint, and oriented to the damage caused in ecosystems, resources and humans, then it is called the endpoint. When the midpoint approach, complexity is reduced and results are better communicated, these values are more accepted in the scientific community [61]. That is why the CML-IA (Impact Assessment) baseline with midpoint indicators has been selected. The version used was V3.01. Then CML-IA baseline V3.01 is the completed name of the method.

Materials to be analyzed are:

- The Binary Solar Salt, an alkali metal nitrate mixture which is composed of 40 wt% KNO3 60 wt% $NaNO_3$ [60]. Table 1 [34,38,62] shows the properties of this mixture. It melts at 220 °C and is thermally stable until around 600 °C, offering high density, low vapor pressure, moderate heat capacity, low chemical reactivity and low cost [63]. Furthermore, Table 1 shows the properties of Therminol and Hitec® Solar Salt.
- The ternary mixture Hitec® Solar Salt is composed of 40 wt% $NaNO_2$, 7 wt% $NaNO_3$ and 53 wt% KNO_3, and it comes from the research carried out by Kalichevsky [64]. But it is G. Picard [65] who developed it completely for its application in energy storage, obtaining a melting point of 142 °C and a heat capacity value of 1560 J / Kg K, offering high density and moderate heat capacity.
- Therminol® is the trade name of the thermal oil to be tested in this paper. It is an organic and synthetic oil. This fluid is a eutectic mixture of biphenyl and diphenyl oxide, both molecules derived from benzene. Its freezing point is lower than that of each of the separate components: it is 12 °C.

The functional unit was 1 kg of HTF, then the inventory was the quantities of every component in each kg of functional unit. Table 2 shows the needed quantities for producing 1 kg of each material. It is based on the weight composition of Therminol, Binary and Hitec® Solar salts.

2.3. Environmental impact assessment

According to the ISO 14044 [57] there are four stages in the environmental impact assessment:

Classification: The stage where the substances which are going to cause damage in every potential impact are decided.

Characterization: Previously classified substances are assigned each impact factor and the results are getting in the units of each impact category. Characterization follows the expression done where impact factor changes in each substance. (Eq. (2.1)):

$$IMP_j = \sum_i k_{i,j} * LCI_{e,i} \tag{2.1}$$

IMP_j : j impact category k_i,

j: Coefficient of damage associated with the component i and impact j

$LCI_{e,i}$: Life Cycle Inventory entry.

Normalization: Defined as calculating the magnitude of category indicator results relative to reference information.

Table 1
Properties of two different molten salts and Therminol®.

Fluid	Melting point [°C]	Maximum operating temperature [°C]	Cost [$/kg]	Properties at 300 °C		
				Density [kg/m³]	Dinanic viscosity [mPa.s]	Heat capacity [J/kg]
Binary Solar Salt	220	600	0.49	1899	3.26	1495
Hitec® Solar Salt	142	593	0.93	1640	3.16	1560
Therminol®	13	393	3.96	784	0.41	2360

Table 2
LCA Inventory. Amount of inputs materials for 1 kg output of functional unit.

	Sodium nitrate [kg]	Potassium nitrate [kg]	Sodium nitrite [kg]	Diphenyloxide [kg]	Biphenyl [kg]
Binary molten salt	0.6	0.4			
Hitec® molten salt	0.07	0.530	0.4		
Therminol®				0.735	0.265

For each baseline indicator, normalization scores are calculated for reference situations. Normalization factors are available for the Netherlands (1997–1998), Western Europe (1995) and the world (1990, 1995 and 2000) [66], the European Union (the 25 countries comprising it in 2006, EU25) and the European Union complemented with Iceland, Norway and Switzerland in 2000, EU25 + 3, 2000).

In this paper normalization factors (1/N) are showed in Table 3 and the EU25 factors were chosen. Eq. (2.2) shows how these factors work. Normalized results are dimensionless.

$$\text{Normaliced impact category} = \text{Charactericed impact cathegory} * \left(\frac{1}{N}\right) \quad (2.2)$$

Weighting: Defined as converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices [57].

The ISO standards dictate classification and characterization as mandatory and normalization and weighting ad optional. Therefore, the environmental impact assessment consists of the accomplishment of a classification and a characterization of the impacts; Normalization is regarded as optional for simplified LCA, but is recommended for detailed LCA [67]. But, the scientific community [68–70] discourages weighting. In fact, ISO 14044 [57] considers weighting not scientifically based.

In order to do the LCA, a method is chosen; in this case it was CML baseline. In addition, to perform the calculations, Simapro software was the tool used.

LCA calculations were accomplished by using software SimaPro version 8.0.2. The CML baseline methodology [71] was used with normalization but without weighting, and included 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}) impact categories.

CML-IA is a database that contains characterization factors for life cycle impact assessment (LCIA). It contains the characterization factors for all baseline characterization methods mentioned in the Handbook on LCA [71]. The last update for this method was done in August 2016.

3. Results and discussion

As its name suggests, the binary solar salt is composed of two components, potassium nitrate, 40 wt%, and sodium nitrate, 60 wt%. To analyze the relative contributions of its two components their environmental impacts were characterized.

The characterization (Table 4) and normalization (Table 5, Fig. 1) for binary solar salt shows that having a composition of 40 wt% potassium nitrate, does not imply a contribution to the impacts with the same proportion. In fact, the impact amount corresponding in the potassium nitrate case stays below the 30% line. The greatest contributions to the impact categories are due to sodium nitrate. It is clearly evident in terrestrial ecotoxicity, photochemical oxidation and human toxicity categories, in which around 80% of the impact that occurs is due to sodium nitrate.

The binary salt normalization is represented in Fig. 2. Normalization shows the impact categories involves further environmental degradation. The most environmentally damaging situation occurs in the abiotic depletion (fossil fuels) category followed, then global warming potential. It is followed by acidification and eutrophication. Sodium nitrate always contributes with superiority. The most environmentally friendly categories are ozone depletion and terrestrial ecotoxicity.

In summary, the binary solar salt has the wider environmental problems in abiotic depletion (fossil fuels) and climate change, its main agent being sodium nitrate.

It shows how 76.5% of the 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.

The second impact category in binary solar salt is global warming. 73.4% of global warming in binary solar salt is caused by sodium nitrate and 26.6% because of potassium nitrate.

Solar salt Hitec® characterization and normalization provides results to be analyzed. They are shown in Tables 4, 5 and in Fig. 2. The characterization is observed for all impacts that sodium nitrate is the lowest contributor, 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.

In the binary solar salt, the sodium nitrate compound suggests greater impacts compared to potassium nitrate. In Hitec® solar salt case the potassium nitrate and sodium nitrite are those which have a higher contribution, meaning that a decrease in the concentration of sodium nitrate, reduces its contribution to impact. In the Hitec® solar salt the sodium nitrate is reduced to 7%, achieving with this a global reduction in all categories. Not being disturbed due to the increase of 40–53% of potassium nitrate in the composition and the addition of 40% sodium nitrite.

Global Warming is the second impact category in LCA for Hitec® salt in which it is possible to determinate that sodium nitrate contributes to 48.5% of global warming potential produced by 1 kg of Hitec® salt. Then, 11.8% is caused by sodium nitrate and 39.7% by the sodium nitrite.

Hitec® case is a good example of ecoefficiency in comparison to the binary solar salt. 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. Therefore, these results show a comprehensive discussion of lightweighting benefits.

Tables 4, 5 and Fig. 3 show the characterization and normalization

Table 3
EU25 normalization factors (1/N).

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

Table 4
Results. Characterization of 1 kg of each material.

Impact category	Unit	Binary molten salt	Hitec ® molten salt	Therminol®
Abiotic depletion	kg Sb_{eq}	1.83E-05	1.49E-05	6.02E-05
Abiotic depletion of fossil fuels	MJ	28.272006	28.18709	171.66413
Global warming potential (GWP100)	kg CO_{2eq}	4.0068605	2.9141476	10.349689
Ozone layer depletion	kg CFC-11_{eq}	1.04E-07	2.75E-07	1.78E-06
Human toxicity	kg 1,4-DB_{eq}	0.94681959	0.77783552	56.010517
Terrestrial ecotoxicity	kg 1,4-DB_{eq}	0.00117808	0.00136373	0.00814478
Photochemical oxidation	kg C_2H_{4eq}	0.00052763	0.00052233	0.0069965
Acidification	kg SO_{2eq}	0.01672546	0.01519623	0.17089745
Eutrophication	kg PO_{4eq}	0.0085963	0.00501582	0.03662807

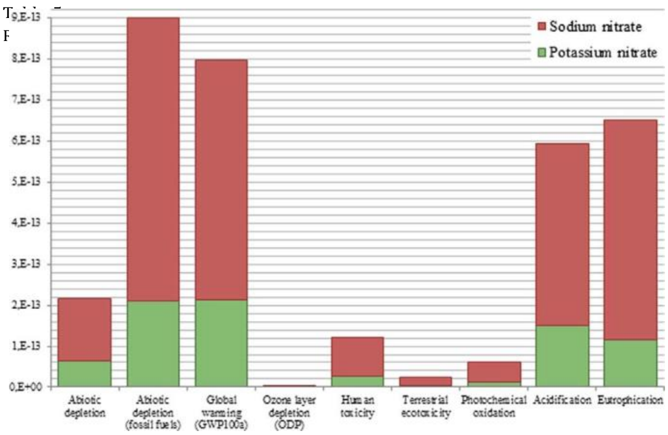

Fig. 1. Analyzing 1 kg Binary salt; Method: CML-IA baseline V3.01/EU25/ Normalization.

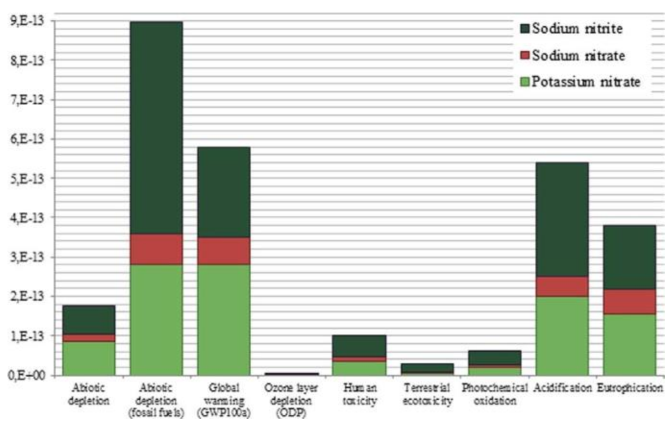

Fig. 2. Analyzing 1 kg Hitec® salt; Method: CML-IA baseline V3.01/EU25/ Normalization.

results for Therminol® LCA.

In Therminol® 1 kg LCA, the human toxicity impact category has been the main impact with negative consequences on the environment getting 56.01 kg 1.4-DB_{eq}, in which 99.9% are direct cause of Diphenyl oxide. Thus, the contribution of Biphenyl to the most controversial impact of the LCA is less than 0.056 kg 1.4-DB_{eq}. Acidification impact category is the second category, and its characterization shows a flow to 98.2% of the impact coming from Diphenyloxide. Then, in the 0.17089745 SO_2 kg_{eq} associated with 1 kg of Therminol®, only 3.07 E-03 are due to Biphenyl.

Figs. 4 and 5 show the characterization and normalization respectively, for comparative LCA study for three materials. In the characterization (Fig. 4), it is possible to see how the Therminol® gets the

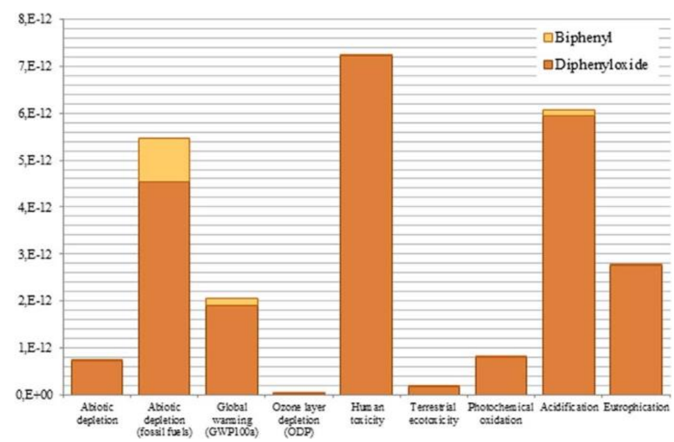

Fig. 3. Analyzing 1 kg 'Therminol®'; Method: CML-IA baseline V3.01/EU25/ Normalization.

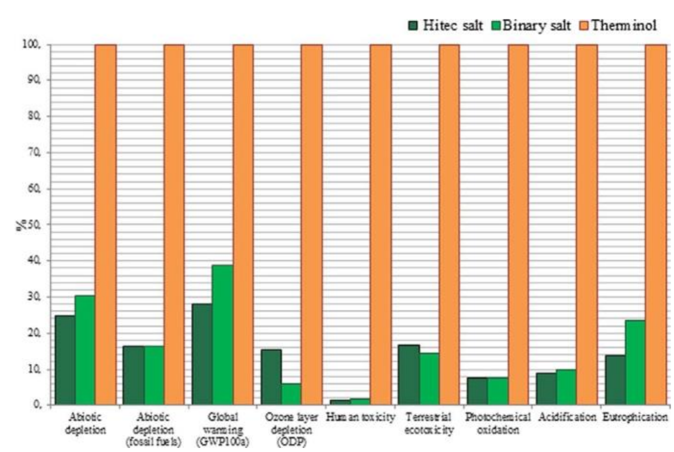

Fig. 4. Comparing 1 kg 'Binary salt', 1 kg Hitec® salt' and 1 kg 'Therminol®'; Method: CML-IA baseline V3.01/EU25/Characterization.

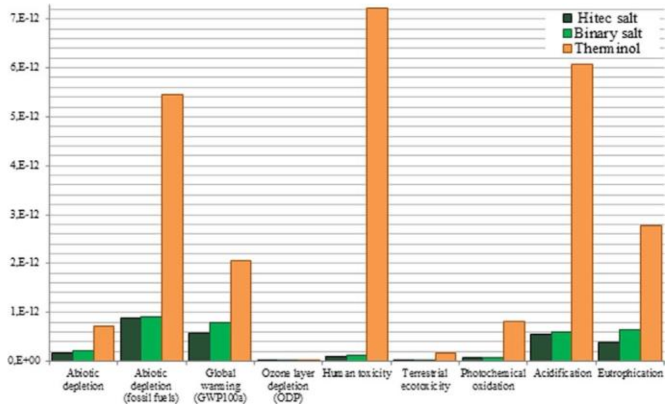

Fig. 5. Comparing 1 kg binary salt, 1 kg Hitec® salt and 1 kg Therminol®; Method: CML-IA baseline V3.01/EU25/Normalization.

highest values in every impact category. The amounts of 8 of 9 impacts analyzed are three times higher in Therminol® oil compared to the salts. The normalization of the impacts shows that in molten salts every impact category is lower than in Therminol® which means that molten salt is more environmentally friendly compared to Therminol®. It is possible to appreciate that Hitec® salt is the most environmentally friendly. In ozone layer depletion characterization, it is seen that the contribution of binary salt is lower than Hitec®. This is the only category in which binary salt results are worse than Hitec® but then in normalization (Fig. 5) it is possible to see how this category is the less impacting.

4. Conclusions

The goal of this study was to evaluate the environmental impacts of two molten salts and a synthetic oil using LCA techniques. This article intends to contribute to understanding of the importance of making a materials choice not only based on physic-chemical properties but also on its sustainability criteria.

The results presented here highlighted the greatest impacts for the synthetic oil in comparison to Hitec® and Binary molten salts. Furthermore, Hitec® presents significant improvements over the binary solar salt.

One of the applications of LCA is eco-efficiency pursuit. Hitec® solar salt is an example of eco-efficiency. By reducing the content in the most harmful component it is possible to get global improvements in the HTF molten salt.

In the case of Therminol®, 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.

A comparison of environmental impacts was made with CML methodology. Every Therminol® impact category shows the highest environmental impacts of all HTF studied.

Therefore, analyzing unit processes is it possible to determinate that HTF used in indirect systems are less sustainable than direct systems. It is possible to conclude that the synthetic oil is harmful in all categories, and then the option of direct system will be more favorable to environment protection.

The most environmentally friendly fluid assessed was Hitec® salt. The choice based on environmental criteria is a direct system with Hitec® molten salt as HTF and TES fluid at the same time.

Technically [37–41] it was demonstrated the possibility of using molten salt as HTF and thus eliminating the heat exchanger thereby reducing losses associated with it, but it was important know if this was environmentally friendly or not. A complete LCA was necessary to determinate it. Consequently, this work is a new step forward by introducing the sustainability parameter as important as the physic-chemicals in the materials election in parabolic trough CSP plants.

References

[1] International Energy Agency (IEA), WorldEnergy Outlook, OECD/IEA, Paris, 2013, 2013.
[2] P. Denholm, J.C. King, C.F. Kutcher, P.P. Wilson, Decarbonizing the electric sector: combining renewable and nuclear energy using thermal storage, Energy Policy 44 (2012) 301–311.
[3] International Energy Agency (IEA), WorldEnergy Outlook 2016. OECD/IEA, Paris, 2016.
[4] X.L. Wei, Q. Peng, J. Ding, X.X. Yang, J.P. Yang, B. Long, Theoretical study on thermal stability of molten salt for solar thermal power, Appl. Therm. Eng. 54 (2013) 140–144.
[5] A. Soléa, L. Miró, C. Barrenechea, I. Martorell, L.F. Cabeza, Corrosion of metals and salt hydrates used for thermochemical energy storage, Renew. Energy 75 (2015) 519–523.
[6] K.H. Solangi, M.R. Islamb, R. Saidur, N.A. Rahimb, H. Fayaz, A review on global solar energy policy, Renew. Sustain. Energy Rev. 15 (4) (2011) 2149–2163.
[7] L. Sikos, J. Klemeš, Reliability, availability and maintenance optimization of heat exchanger networks, Appl. Therm. Eng. 30 (1) (2010) 63–69.
[8] L. Zhang, M.C. Yang, Y.Z. Zhu, H.J. Chen, Numerical study and optimization of mirror gap effect on wind load on parabolic trough solar collector, Energy Proc. 69 (2015) 233–241.
[9] M. Liu, N.S. Tay, S. Bell, M. Belusko, R. Jacob, G. Will, F. Bruno, Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies, Renew, Sustain. Energy Rev. 53 (2016) 1411–1432.
[10] Y. Lalau, X. Py, A. Meffre, R. Olives, Comparative LCA Between Current and Alternative Waste-Based TES for CSP, Waste Biomass-. Valor 7 (2016) 1509–1519.
[11] R. Serrano-López, J. Fradera, S. Cuesta-López, Molten salts database for energy applications, Chem. Eng. Process.: Process.Intensif. 73 (2013) 87–102.
[12] N.P. Siegel, Thermal energy storage for solar power production, Wiley Interdiscip. Rev: Energy Environ. 1 (2012) 119–131.
[13] C. Parrado, A. Marzo, E. Fuentealba, A.G. Fernández, 2050 LCOE improvement using new molten salts for thermal energy storage in CSP plants, Renew. Sustain. Energy Rev. 57 (2016) 505–514.
[14] K. Vignarooban, X. Xu, A. Arvay, K. Hsu, A.M. Kannan, Heat transfer fluids for concentrating solar power systems–A review, Appl. Energy 146 (2015) 383–396.
[15] J. Pacio, T. Wetzel, Assessment of liquid metal technology status and research paths for their use as efficient heat transfer fluids in solar central receiver systems, Sol. Energy 93 (2013) 11–22.
[16] Y. Tian, C.Y. Zhao, A review of solar collectors and thermal energy storage in solar thermal applications, Appl. Energy 104 (2013) 538–553.
[17] E. Zarza Moya, Innovative working fluids for parabolic trough collectors, in: Advances in Concentrating Solar Thermal Research and Technology, Woodhead Publishing Series inEnergy, pp. 75–106, 2017. ⟨http://dx.doi.org/10.1016/B978-0-08-100516-3.00005-8⟩.
[18] X. Xua, K. Vignaroobanc, B. Xud, K. Hsua, A.M. Kannana, Prospects and problems of concentrating solar power technologies for power generation in the desert regions, Renew, Sustain. Energy Rev. 53 (2016) 1106–1131.
[19] R. Cable, D. Blake, B. Kelly, D. Kearny, H. Price, P. Nava, N. Potrovitza, Overview on use of a Molten Salt HTF in a Trough Solar Field, NREL/PR-550-40028. ⟨http://www.nrel.gov/docs/fy03osti/40028.pdf⟩.
[20] Yu-Ting Wu, Shan-Wei Liu, Ya-Xuan Xiong, Chong-Fang Ma, Yu-Long Ding, Experimental study on the heat transfer characteristics of a low melting point salt in a parabolic trough solar collector system, Appl. Therm. Eng. 89 (2015) 748–754.
[21] A. Maccari, Innovative Heat Transfer Concepts in Concentrating Solar Fields, ENEA Solar Thermodynamic Energy. ⟨http://ec.europa.eu/energy/res/events/doc/maccari_enea.pdf⟩.
[22] J. Stekli, L. Irwin, R. Pitchumani, Technical challenges and opportunities for concentrating solar power with thermal energy storage, J. Therm. Sci. Eng. Appl. 5 (2013) 021011.
[23] T.C. Paul, A.K.M.M. Morshed, E.B. Fox, A.E. Visser, N.J. Bridges, J.A. Khan, Thermal performance of ionic liquids for solar thermal applications, Exp. Therm. Fluid Sci. 59 (2014) 88–95.
[24] D.M. Blake, L. Moens, M.J. Hale, H. Price, D. Kearney, U. Herrmann, New heat transfer and storage fluids for parabolic trough solar thermal electric plants, in: Proceedings of the 11th SolarPACES International Symposium On concentrating Solar Power and Chemical Energy Technologies, Zurich, Switzerland, September 4–6, 2002.
[25] R. Ferri, A. Cammi, D. Mazzei, Molten salt mixture properties in RELAP5 code for thermodynamic solar applications, Int. J. Therm. Sci. 47 (2008) 1676–1687.
[26] Q. Peng, X. Wei, J. Ding, J. Yang, X. Yang, High-temperature thermal stability of molten salt materials, Int. J. Energy Res. 32 (2008) 1164–1174.
[27] J.I. Ortega, J.I. Burgaleta, F.M. Tellez, Central receiver system solar power plant using molten salt as heat transfer fluid, J. Sol. Eng. – Trans. ASME 130 (2008) 0245011–0245016.
[28] A. Giglioa, A. Lanzinia, P. Leonea, M.M. Rodríguez García, E. Zarza Moya, Direct steam generation in parabolic-trough collectors: a review about the technology and a thermo-economic analysis of a hybrid system, Renew. Sustain. Energy Rev. 74 (2017) 453–473.
[29] L. Moens, D.M. Blake, D.L. Rudnicki, M.J. Hale, Advanced thermal storage fluids for solar parabolic trough systems, J. Sol. Energy Eng. 125 (2003) 112–116.
[30] J.C. Gomez, High-Temperature Phase Change Materials (PCM) Candidates for Thermal Energy Storage (TES) Applications, NREL 303-275-3000. ⟨http://www.

nrel.gov/docs/fy11osti/51446.pdf⟩.
[31] Y. Li, Y. Zhang, M. Li, D. Zhang, Testing method of phase change temperature and heat of inorganic high temperature phase change materials, Exp. Therm. Fluid Sci. 44 (2013) 697–707.
[32] A.G. Fernández, S. Ushakb, H. Galleguillosb, F.J. Pérez, Development of new molten salts with LiNO3 and Ca(NO3)2 for energy storage in CSP plants, Appl. Energy 119 (2014) 131–140.
[33] M. Liu, W. Saman, F. Bruno, Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems, Renew. Sustain. Energy Rev. 16 (2012) 2118–2132.
[34] D. Kearney, U. Herrmann, P. Nava, B. Kelly, R. Mahoney, J. Pacheco, H. Price, Assessment of a molten salt heat transfer fluid in a parabolic trough solar field, J. Sol. Energy Eng. 125 (2003) 170–176.
[35] C.Y. Zhao, Z.G. Wu, Thermal property characterization of a low melting-temperature ternary nitrate salt mixture for thermal energy storage systems, Sol. Energy Mater. Sol. Cells 95 (2011) 3341–3346.
[36] S. Sau, N. Corsaro, T. Crescenti, C. Dottavi, R. Liberatore, S. Licoccia, V. Russo, P. Tarquino, A.C. Tizzoni, Techno-economic comparison between CSP plants presenting two different heat transfer fluids, Appl. Energy 168 (2016) 96–109.
[37] A. Maccari, D. Bissi, G. Casubolo, F. Guerrini, L. Lucatello, G. Luna, A. Rivaben, E. Savoldi, S. Tamano, M. Zuanella, Archimede Solar Energy molten salt parabolic trough demo plant: a step ahead towards the new frontiers of CSP, Energy Procedia 69 (2015) 1643–1651.
[38] D. Kearney, U. Herrmann, P. Nava, B. Kelly, R. Mahoney, J. Pacheco, R. Cable, D. Blake, H. Price, N. Potrovitza, Overview on use of a molten salt HTF in a Trough solar field, NREL (2003), ⟨http://www.nrel.gov/docs/fy03osti/40028.pdf⟩.
[39] M. Liu, W. Saman, F. Bruno, Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems, Renew. Sustain. Energy Rev. 16 (2012) 2118–2132.
[40] M. Falchettaa, A.G. Rossib, Dynamic simulation of the operation of a molten salt parabolic trough plant, comprising draining procedures, Energy Procedia 49 (2014) 1328–1339.
[41] F. Matino, A. Maccari, Molten salt receivers operated on parabolic trough demo plant and in laboratory conditions, Energy Procedia 69 (2015) 481–486.
[42] F. Zaversky, R. Medina, J. García-Barberena, Marcelino Sánchez, D. Astrain, Object-oriented modeling for the transient performance simulation of parabolic trough collectors using molten salt as heat transfer fluid, Sol. Energy Rev. 95 (2013) 192–215.
[43] D. Grogan, Development of Molten-Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants-Public Final Technical Report, No. DOE/08GO18038 Abengoa Solar, ⟨https://www.osti.gov/scitech/servlets/purl/1090096⟩, 2013.
[44] P. Viebahn, S. Kronshage, Y. Lechon, Deliverable n 12.2-RS Ia. Final report on technical data, costs, and life cycle inventories of solar thermal power plants. New Energy Externalities Developments for Sustainability (NEEDS). ⟨http://www.needs-project.org/2009/Deliverables/RS1a%20D12.2%20Final%20report%20concentrating%20solar%20thermal%20power%20plants.pdf⟩ (accessed 21 April 2017).
[45] Y. Lechón, C. de la Rúa, R. Sáez, Life cycle environmental impacts of electricity production by solarthermal power plants in Spain, J. Sol. Energy Eng. 130 (2) (2008) 021012.
[46] I.A. Ehtiwesh, M.C. Coelho, A.C. Sousa, Exergetic and environmental life cycle assessment analysis of concentrated solar power plants, Renew. Sustain. Energy Rev. 56 (2016) 145–155.
[47] D. Chr. Lamnatou, Chemisana, concentrating solar systems: life cycle assessment (LCA) and environmental issues, Renew. Sustain. Energy Rev. 78 (2017) 916–932.
[48] A.G. Fernández, H. Galleguillos, E. Fuentealba, F.J. Pérez, Corrosion of stainless steels and low-Cr steel in molten Ca(NO3)2–NaNO3–KNO3 eutectic salt for direct energy storage in CSP plants, Sol. Energy Mater. Sol. Cells 141 (2015) 7–13.
[49] A.G. Fernández, M. Cortes, E. Fuentealba, F.J. Pérez, Corrosion properties of a ternary nitrate/nitrite molten salt in concentrated solar technology, Renew. Energy 80 (2015) 177–183.
[50] M.T. de Miguel, V. Encinas-Sánchez, M.I. Lasanta, G. García-Martín, F.J. Pérez, Corrosion resistance of HR3C to a carbonate molten salt for energy storage applications in CSP plants, Sol. Energy Mater. Sol. Cells 157 (2016) 966–997.
[51] A.G. Fernández, F.J. Pérez, Improvement of the corrosion properties in ternary molten nitrate salts for direct energy storage in CSP plants, Sol. Energy 134 (2016) 468–478.
[52] G. García-Martín, M.I. Lasanta, V. Encinas-Sánchez, M.T. de Miguel, F.J. Pérez, Evaluation of corrosion resistance of A516 Steel in a molten nitrate salt mixture using a pilot plant facility for application in CSP plants, Sol. Energy Mater. Sol. Cells 161 (2017) 226–231.
[53] M. Muraleedharana, H. Singhb, S. Suresha, M. Udayakumara, Directly absorbing Therminol-Al2O3 nano heat transfer fluid for linear solar concentrating collectors, Sol. Energy 137 (2016) 134–142.
[54] Weiguo Xua, Shuyan Wangb, Guodong Liua, Qinghong Zhanga, Muhammad Hassana, Huilin Lua, Experimental and numerical investigation on heat transfer of Therminol heat transfer fluid in an internally four-head ribbed tube, Int. J. Therm. Sci. 116 (2017) 32–44.
[55] A. Tukker, Life cycle assessment as a tool in environmental impact assessment, Environ. Impact Assess. Rev. 20 (2000) 435–456.
[56] ISO 14040 Environmental Management – Life Cycle Assessment - Principles and Framework, 2006.
[57] ISO 14044 Environmental Management – Life Cycle Assessment – Requirements and Guidelines, 2006.
[58] J. Martínez-Blanco, A. Inaba, M. Finkbeiner, Scoping organizational LCA—challenges and solutions, Int. J. Life Cycle Assess. 20 (2015) 829–841.
[59] B.P. Weidema, C. Bauer, R. Hischier, C. Mutel, T. Nemecek, J. Reinhard, G. Wernet, The Ecoinvent database: Overview and methodology, Data quality guideline for the Ecoinvent database version 3, ⟨http://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf⟩.
[60] B.P. Weidema, Market information in life cycle assessment, No. 863. Miljøprojekt, ⟨http://lca-net.com/files/Market-information-in-life-cycle-assessment.pdf⟩.
[61] J. Bare, TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0, Clean. Techn. Environ. Policy 13 (2011) 687–696.
[62] Therminol 55. Heat Transfer Fluid by Eastman. ⟨https://www.therminol.com/products/Therminol-55⟩ (accessed 10 November 2016), 2016.
[63] S. Pintaldi, C. Perfumo, S. Sethuvenkatraman, S. White, G. Rosengarten, A review thermal energy storage technologies and control approaches for solar cooling, Renew. Sustain. Energy Rev. 41 (2015) 975–995.
[64] V.A. Kalichevsky, J.W. Payne, R. Frederick, Treatment of heat transfer salts, US Pattent Office 2375759 A. ⟨http://www.google.com.na/patents/US2375759⟩.
[65] G. Picard, T. Flament, B. Tremillon, P. Saint-Paul, Process for stabilizing a mixture of molten alkali metal nitrates and alkali metal nitrites usable particularly as a heat transfer fluid and stabilized mixture thus obtained, U.S. Patent Office 4559993 A, ⟨https://patents.google.com/patent/US4559993A⟩, 1985.
[66] M.A.J. Huijbregts, L. Breedveld, G. Huppes, A. de Koning, L. Van Oers, S. Suh, Normalisation figures for environmental life-cycle assessment: the Netherlands (1997/1998), Western Europe (1995) and the world (1990 and 1995), J. Clean. Prod. 11 (2003) 737–748.
[67] PRé, various authors, SimaPro database manual methods library. PRé, Reported version 2.9, ⟨https://www.pre-sustainability.com/download/DatabaseManualMethods.pdf⟩, 2016.
[68] W.P. Schmidt, J. Sullivan, The value debate: weighting of life cycle assessments in a global context: global diversity exists and has to be valued, Int. J. Life Cycle Assess. 7 (2002) (250-250).
[69] W.P. Schmidt, J. Sullivan, Weighting in life cycle assessments in a global context, Int. J. Life Cycle Assess. 7 (2002) 5–10.
[70] M. Pizzol, A. Laurent, S. Sala, B. Weidema, F. Verones, C. Koffler, Normalisation and weighting in life cycle assessment: quo vadis? Int. J. Life Cycle Assess. (2016) 1–14.
[71] J.B. Guinée, Handbook on life cycle assessment operational guide to the ISO standards, Int. J. Life Cycle Assess. 7 (2002), pp. 311–313.