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

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A B S T R A C T

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 synthetic oil 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

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Nomenclature

CSP	Concentrating solar power
HTF	Heat transfer fluid
TES	Thermal Energy Storage
LCOE	Levelized Cost of Energy
LCA	Life Cycle Assessment
kg Sb_{eq}	Abiotic depletion
MJ	Abiotic depletion of fossil fuels
kg CO_{2eq}	Global warming potential (GWP100)
kg $CFC\text{-}11_{eq}$	Ozone layer depletion
kg $1,4\text{-}DB_{eq}$	Human toxicity
kg $1,4\text{-}DB_{eq}$	Terrestrial ecotoxicity
kg C_2H_{4eq}	Photochemical oxidation
kg SO_{2eq}	Acidification
kg PO_{4eq}	Eutrophication

Subscripts

eq	Equivalent

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].