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Embodied energy and cost of high temperature thermal energy storage systems for use with concentrated solar power plants

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HIGHLIGHTS

- Environmental impact and CAPEX of novel high temperature TES systems is presented.
- Three systems were studied; EPCM, PCM coil-in-tank and liquid sodium.
- The embodied energy and CAPEX are compared to other high temperature TES systems.
- The systems have energy payback periods of 1, 1.6 and 38.6 months, respectively.
- The EPCM system had the lowest CAPEX estimate of $11.2/kWh_t$.

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ABSTRACT

The intermittency of renewable energy systems remains one of the major hurdles preventing a large scale uptake of these technologies and concentrated solar power (CSP) systems are no different. However, CSP has the benefit of being able to store excess heat using thermal energy storage (TES). For the uptake of CSP with TES it must be demonstrated that the technology is both economically as well as environmentally feasible. This paper aims to investigate the economic and environmental impact of several TES options that are available for CSP systems. The investigated systems include an encapsulated phase change material (PCM) system, a coil-in-tank PCM system and a liquid sodium TES system. The economic impact in the current study refers to the capital cost (CAPEX) of each system including the tank, storage material, encapsulation cost (if applicable) and allowances for construction and engineering. The environmental impact of each system is accounted by calculating the embodied energy of each of the system components. Each storage system will be required to store a comparable amount of energy so that reliable conclusions can be drawn. The results from this analysis conclude that the encapsulated PCM (EPCM) and coil-in-tank system represent an embodied energy of roughly one third of the corresponding state-of-the-art two-tank molten salt system.

Furthermore, the EPCM and coil-in-tank systems result in CAPEX reductions of 50% and 25% over the current state-of-the-art two-tank molten salt system. The liquid sodium system was found to result in higher embodied energy and CAPEX than any previously studied TES system. Finally, the advantages and disadvantages of each system was discussed and compared to previous literature.

1. Introduction

1.1. Background

The field of high temperature thermal energy storage (TES) has steadily been growing with several successful demonstrations showing the benefit of TES as a storage method for high temperature concentrated solar power (CSP), however the cost and environmental impacts of these system is largely unknown,

Abbreviations: PCM, phase change material; TES, thermal energy storage; CSP, concentrated solar power; CAPEX, Capital Expenditure; EPCM, encapsulated phase change material.

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Nomenclature

Abbreviation

CSP	concentrated solar power
PCM	phase change material
EPCM	encapsulated phase change material
LCA	life cycle analysis
s-CO_2	supercritical carbon dioxide
HTF	heat transfer fluid
NTU	number of transfer units
TESS	thermal energy storage system
TES	thermal energy storage
CAPEX	Capital Expenditure
CO_2/$CO_{2\text{-e}}$	carbon dioxide/carbon dioxide equivalent
GWP	global warming potential
LCOE	levelised cost of electricity
CFD	computational fluid dynamics
SAM	system advisor model
BOS	balance of system

Symbol

ρ	density [kg/m^3]
Δh_f	enthalpy of fusion [kJ/kg]
$	US dollars [USD]
C_{SHELL}	cost factor- shell material [$/kg]
C_{TUBE}	cost factor- tubing material [$/kg]
$\eta_{power\ cycle}$	efficiency of power cycle [%]
cp	heat capacity [kJ/kg K]
T	temperature [°C]
C_{FM}	cost factor- filler material [$/kg]
C_{HTF}	cost factor- heat transfer fluid [$/kg]
Q_{cap}	discharge capacity [MWh$_t$]
$Days_{op}$	operational days [–]

unpublished or overlooked. Previous attempts at quantifying the embodied energy or carbon footprint of phase change material (PCM) TES have been performed by Oró et al. [1], Anisur et al. [2], Lopez-Sabiron et al. [3] and Miró et al. [4]. Anisur et al. [2] found that about 3.43% of CO_2 emissions by 2020 could be reduced through the application of PCM in building and solar thermal power systems. Further savings could be achieved if PCMs could be used in other applications such as thermal comfort of vehicles, transport refrigeration, engine cold start or waste heat management. Lopez-Sabiron et al. [3] investigated the potential of PCMs as a storage option for recovering waste heat for downstream applications, thereby reducing the amount of fossil fuel needed for heat generation. The life cycle analysis (LCA) and global warming potential (GWP100) methodology were used to identify the best cases, considering the environmental benefits that each case can generate. It was found that in general PCMs achieve an environmental benefit as the reduction in fossil fuel use is enough to balance the energy consumed in the production of the PCM. However, they noted that the selection of the PCM greatly influences the environmental benefit. This sentiment is echoed by Miró et al. [4] who investigated the embodied energy of three high temperature TES options. The studied options were high temperature concrete slabs, a two-tank molten salt system and a PCM system. From the analysis it was shown that the high temperature concrete system had the lowest embodied energy. As the liquid molten salt and PCM were nitrate-based the embodied energy of these systems was large. The results from Miró et al. [4] are found to be similar to that of previous research by Oró et al. [1] using the same methodology. Oró et al. [1] found that the solid TES system corresponded to the lowest LCA impact across all three of the main factors; namely eco system quality, human health and resources. The molten salt system was found to have the largest impact on human health and resources due to the materials used in the molten salt. The PCM studied by Oró et al. [1] was also found to have a high impact on human health and resources but was less than the molten salt system due to a lower material inventory. In the current study an environmental and economic analysis has been performed on several promising methods of high temperature TES.

The embodied energy methodology has been selected as the environmental evaluation tool due to its versatility and ability to easily compare systems. This type of evaluation allows materials with large embodied energy values to be replaced by more favourable materials while still at the design phase, saving time and money. The embodied energy methodology can be defined as an energy accounting process investigating the energy used through the entire production chain. However, the main issue with this type of methodology is the lack of agreement on the system boundary: some of them consider the transport from the industry to the application, while others consider the disposal of the material or the percentage of recycled material in the production process. In the current study the embodied energy data has been taken from sources with known system boundaries so that a direct comparison can be made.

The current method of storage for large scale CSP plants is the two-tank system utilising molten salt. While this method of storage has been successful in current plants, if CSP is to be economically competitive in the future the cost must be reduced. Furthermore, it has been shown that the two-tank molten salt storage method suffers from a significantly high environmental and health impact [1,4], reducing the environmental savings of the overall system. To achieve economical competiveness and a reduction in environmental impacts a new generation of CSP plants (and TES systems) must be realised. To increase the cost competiveness of future CSP plants they must be able to operate at higher temperatures to increase the turbine efficiency. The current operating limit of solar salt is 565 °C, which is well below the predicted temperature of 600–700 °C required in future s-CO_2 Brayton cycles. If storage is to be coupled to the new generation of turbines it must be able to supply heat above 600 °C. Furthermore, the cost of the storage system must be reduced to $AU25/kWh$_t$ in order to reduce the levelised cost of electricity (LCOE) of the CSP plant to 12c/kWh [5].

Current two-tank molten salt storage systems are unable to achieve these targets so new methods of storage must be investigated. To this end PCMs or liquid metals are seen as a promising solution. PCMs are materials that can store/release a large amount of heat as they undergo a change of phase. The high energy density of these materials allows the storage volume and therefore the storage cost to be reduced. However, the main issue with current PCMs is their inherent low thermal conductivity. This low thermal conductivity leads to long charge/discharge times, which is undesirable for power generation. To increase the thermal conductivity, the PCM can either be encapsulated or placed in a coil-in-tank arrangement. Alternatively, liquid metals, principally liquid sodium, have an inherently high thermal conductivity and high temperature stability which could allow them to be a suitable high temperature sensible energy storage option if the safety issues associated with them can be curtailed. To identify the potential