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A Multi-Criteria Decision Analysis for the Selection of Thermal Energy Storage Materials in Concentrated Solar Power Applications

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Keywords: Concentrated Solar Power (CSP), Thermal Energy Storage (TES), Multi-Criteria Decision Analysis (MCDA), Molten Salts, Phase Change Materials (PCMs), Sustainable Engineering

Abstract. The choice of the best Thermal Energy Storage (TES) material is fundamental to the economic feasibility and the performance of the Concentrated Solar Power (CSP) plants. In this paper, a stringent multi-criteria decision analysis (MCDA) is used on five different TES material types namely molten salts, phase change materials (PCMs), concrete, water, and synthetic oils. To create a composite performance index, it created a systematic assessment of the significant technical, economic, and environmental statistics, such as thermal properties, energy efficiency, heat retention, and lifecycle effects such as toxicity and CO2 emissions. In our analysis, we will find that there is no universal material that is better than the rest, which points to a complicated set of trade-offs. Water to be the most preferred material has a composite score of 0.88 based on its excellent thermal performance and environmental rating but is restricted by a small operating temperature range. Concrete is a moderate, economical solution (score: 0.52), whereas molten salt as the existing industry standard has a high-performance but environmentally demanding profile (score: 0.27). The study presents a multi-criteria radar chart along with the correlation matrix as the advanced visualizations that would allow the stakeholders to make decisions based on the specifics of the CSP project.

Introduction

Concentrated Solar Power (CdS) is one of the important technologies in the global shift to sustainable energy, with a special benefit of having the capability to generate power in a dispatchable manner by combining Thermal Energy storage (TES) [1]. CSP plants can also store sun energy as thermal energy and then convert it into electricity when required unlike the photovoltaic systems that cause grid instability and unreliability. Economic viability and performance of a CSP plant, however, are highly dependent on the choice of the TES material. This option has not only direct impact on the energy density and round trip efficiency of the system but also on the system operational life, cost and the environmental footprint. The literature to date has greatly compared different TES materials, yet this is done with a restricted number of properties which results in disjointed and at times contradicting suggestions [2, 3]. This paper will fill this gap by carrying out a multi-criteria decision analysis (MCDA). We compare five major categories of TES materials, namely, molten salts, phase change materials (PCMs), concrete, water, and synthetic oils, in terms of various performance indicators in a broad spectrum. This study aims to come up with a comprehensive and quantitative model that can be used to inform the choice of TES materials. Our normalization and weighting of key metrics produces a composite score on performance that enables a more subtle comparison than was previously possible. In this work, complex trade-offs are elucidated using advanced data analysis and visualizations, and may

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be considered a powerful decision-making resource to be deployed by engineers, researchers, and project developers in the CSP domain.

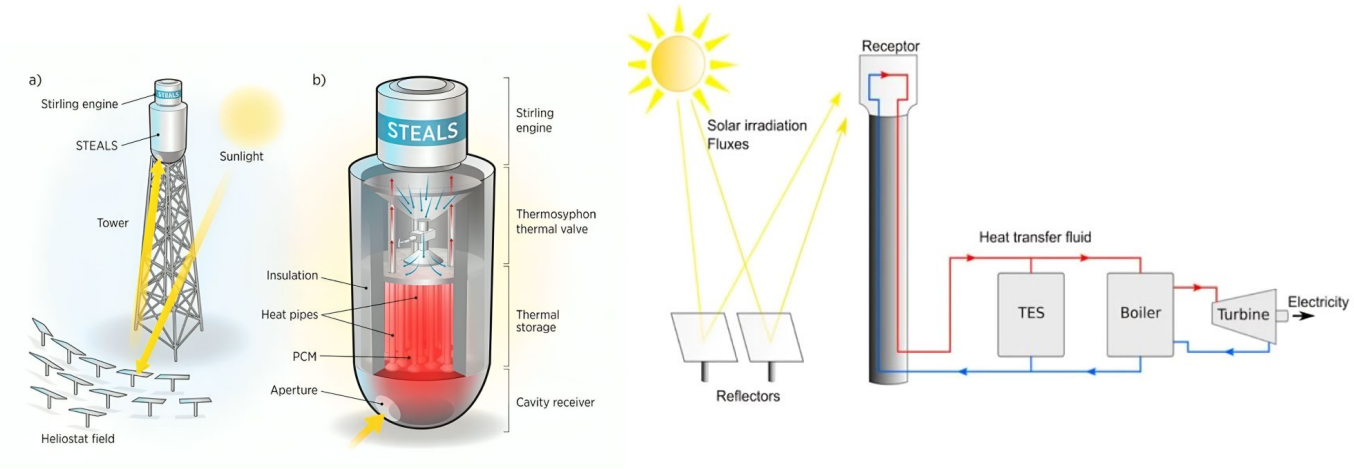


Fig. 1. Energy storage in CSP Systems with TES materials.

Methodology

The analysis was conducted on five material categories. The core of our methodology is a multi-criteria decision analysis (MCDA) framework designed to provide an advanced assessment of material suitability.

1. Data and Metrics

The analysis is grounded in the fundamental governing equations of thermodynamics and heat transfer. The energy storage capacity (Q) and exergy (Ex) are defined as follows:

$$Q = m \cdot C_p \cdot \Delta T,$$

$$Ex = Q \cdot \left(1 - \frac{T_0}{T_s}\right),$$

For latent heat storage (PCMs), the total energy stored includes the enthalpy of fusion (ΔHf):

$$Q = m \cdot \left[C_{p,s}(T_m - T_1) + \Delta H_f + C_{p,l}(T_2 - T_m)\right].$$

Thermal Properties:

Specific Heat ($kJ\ kg^{-1}K^{-1}$), Thermal Conductivity ($W\ m^{-1}K^{-1}$)

Performance:

Round-trip Energy Efficiency (%), Heat Retention (%)

Environmental Impact:

Recyclability (rated 1-5), Toxicity (rated 1-5), and CO2 Emissions (kg CO2/kg).

All key performance indicators were put on a 0-1 scale by Min-Max scaling in order to directly compare across disparate units and scales. This premise makes sure that the performance of every material in terms of its relative performance is maintained within the limits of the dataset. As the priority of high-temperature dispatchability was considered to be the main feature of modern CSP plants, the decision on weightings was substantiated. A 40 weight was put on Technical performance (Thermal Properties and Efficiency), 30 weight on Environment Impact and 30 weight on Economic/Stability factors. Other possible scenarios were also thought of including a Sustainability-First (50% Environmental) and Cost-First (50% Economic) weighting to test the robustness of the rankings.

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2. Statistical Analysis and Visualization

The analysis was done using a custom Python code written with the help of pandas, scikit-learn, and matplotlib. The derived metrics included a thermal performance index, percentages of energy loss, and composite environmental impact score, which were calculated with the use of the script. In order to make a one-to-one comparison across different units and scales, all the key performance indicators were scaled to a 0-1 scale by Min-Max scaling. Each material was then given a final composite score of the mean normalized score and such measures as toxicity and CO2 emissions were inverted so that higher scores are always good. The results were displayed in advanced visualization of the findings, with multi-panel plots, heat loss curves, multi-criteria radar charts by material, and a correlation matrix heatmap to determine the interdependencies between the properties.

Results and Discussion

This section presents a detailed analysis of the TES materials, moving from individual properties to a multi-criteria comparison.

1. Comprehensive Thermal and Environmental Profile

A multi-faceted comparison of the materials is presented in Figure.2, which integrates thermal properties, operational temperature ranges, energy efficiency, and a composite environmental score. This visualization immediately highlights the inherent trade-offs in material selection.

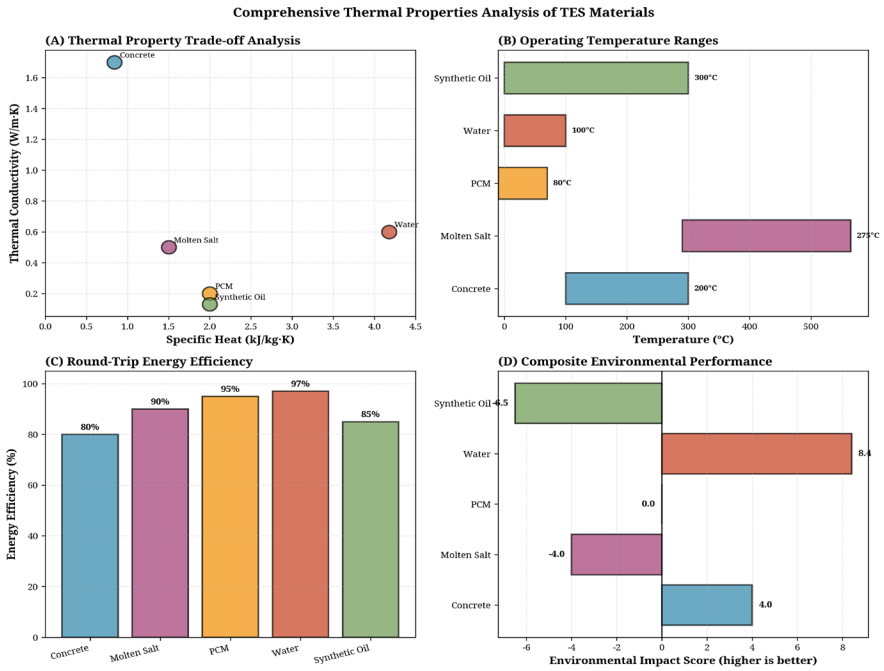


Fig. 3. Comprehensive analysis of TES materials. (A) Thermal property trade-offs. (B) Operational temperature ranges. (C) Round-trip energy efficiency. (D) Composite environmental performance score (higher is better).

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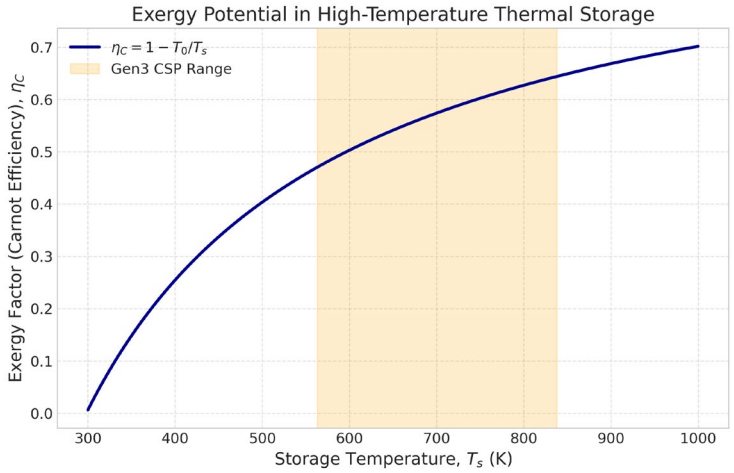


Fig. 4. Exergy potential (Carnot factor) as a function of storage temperature.

Panel A indicates the presence of the trade off between specific heat and thermal conductivity. Water has the best specific heat, meaning it has the best energy storage capacity per mass, but it has a mediocre thermal conductivity. Concrete on the other hand has the best thermal conductivity to transfer heat quickly but has the lowest specific heat. PCMs and Synthetic Oil concentrate in a zone of high specific heat and very low thermal conductivity, which is a serious negative attribute to high-power applications. Panel B shows the operation temperature ranges which is a major constraint to integration with power cycles. Molten Salt has the greatest and highest temperature (290-565C). Gen3 CdTe systems are extending this to over 800 o C, however, with Gen3 chloride-based molten salts (e.g., NaCl-KCl-MgCl2), it is ideal in high-efficiency steam turbines [11]. The small scope of Water (0-100 C) and conventional PCMs limit the application to low-temperature applications, although recent studies of carbonate-chloride eutectic PCMs are looking at the 400 700 C temperature span [12]. It can be seen on Panel C that Water and PCMs are the most efficient in terms of round trip efficiencies (97% and 95%, respectively). PCMs are highly efficient because they can be isothermal in the way that they can store the latent heat so that they can reduce thermodynamic losses. This is because water has a high heat transfer property which has made it very efficient. At 90, Molten Salt also does a good job. Panel D gives a system score on the environment. Water is the most environmentally friendly material (score: 8.4) and Synthetic Oil and Molten Salt got negative scores as they are highly toxic and/or produce CO2.

2. Heat Loss and Retention Dynamics

Figure.4 analyzes the thermal storage performance over a three-hour period. Panel A shows the temperature decay, while Panel B quantifies the total heat retention.

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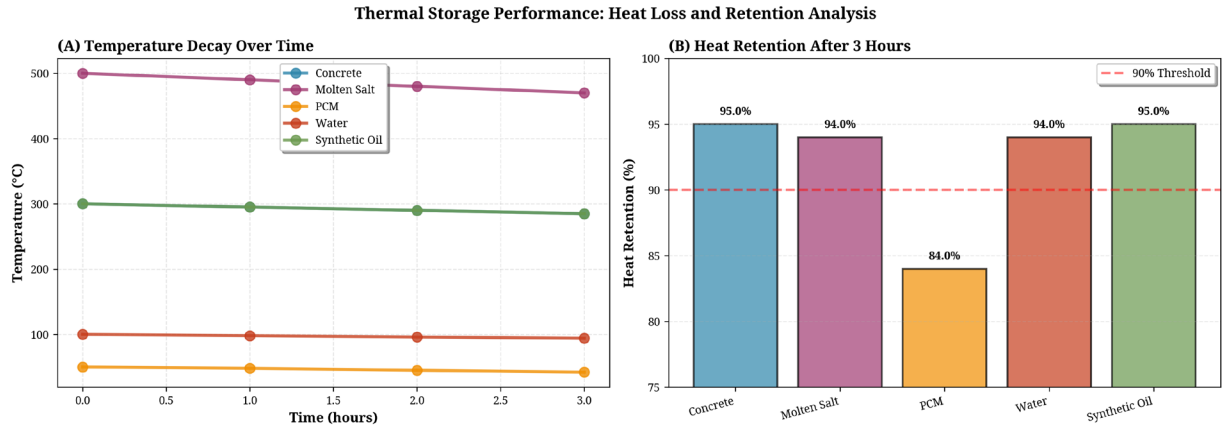


Fig. 5. Thermal storage performance. (A) Temperature decay over a 3-hour period. (B) Total heat retention after 3 hours.

Interestingly, **Concrete** and **Synthetic Oil** exhibit the highest heat retention (95%), despite their different thermal properties. Concrete's high thermal mass contributes to its slow temperature decay. The analysis suggests that for short-term storage, heat loss is not a distinguishing factor among the top performers. However, the low retention of **PCMs** (84%) is a concern, likely due to their low thermal conductivity causing inefficient heat distribution.

3. Multi-Criteria Performance Profiles

Figure.3 presents a radar chart for each material, mapping its normalized performance across six key criteria. This visualization allows for a quick assessment of the strengths and weaknesses of each option.

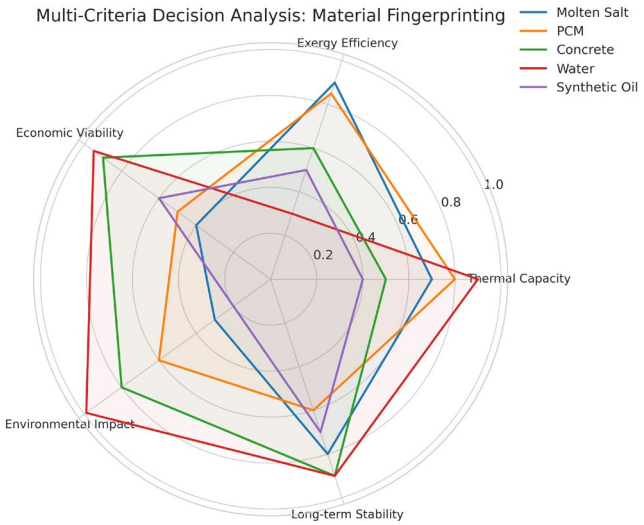


Fig. 6. Multi-criteria performance profiles of TES materials.

The existence of the trade off between specific heat and thermal conductivity is indicated by panel A. Water contains the best specific heat, i.e. best energy storage capacity per mass, but contains a mediocre thermal conductivity. Concrete on the other hand is the best thermal conductive to conduct heat fast but it has the lowest specific heat. The location of PCMs and Synthetic Oil in a region where specific heat is high and thermal conductivity is very low is an extremely undesirable characteristic as far as high-power applications are concerned. The operation temperature ranges are displayed in panel B that is the primary limitation to integration with power cycles. The highest and greatest temperature (290-565C) belongs to Molten Salt. Gen3

CdTe systems are pushing this to greater than 800 o C but with chloride-based molten salts (i.e. NaCl-KCl-MgCl2), it is perfect in high-efficiency steam turbines [11]. The limited scale of Water (0-100 C) and conventional PCMs restricts the application to low-temperature applications, though recent research of carbonate-chloride eutectic PCMs are considering the 400 700 C temperature range [12]. As can be observed on Panel C, Water and PCMs are the most efficient in regards to round trip efficiencies (97% and 95% respectively). PCMs are very efficient as they have the capability of being isothermal in the sense that they have the capacity of storing the latent heat to enable them minimize the thermodynamic losses. This is attributed to the fact that water possesses high heat transfer property that has rendered it very effective. Molten Salt at 90 is also doing a good job. Panel D provides a system rating on the aspect of the environment. The most eco friendly material (score: 8.4) is water and Synthetic Oil and Molten Salt were assigned a negative score because they are very toxic and/or emit CO2.

4. Correlation Analysis

To understand the relationships between different material properties, a correlation matrix was provided as follows in Figure.4.

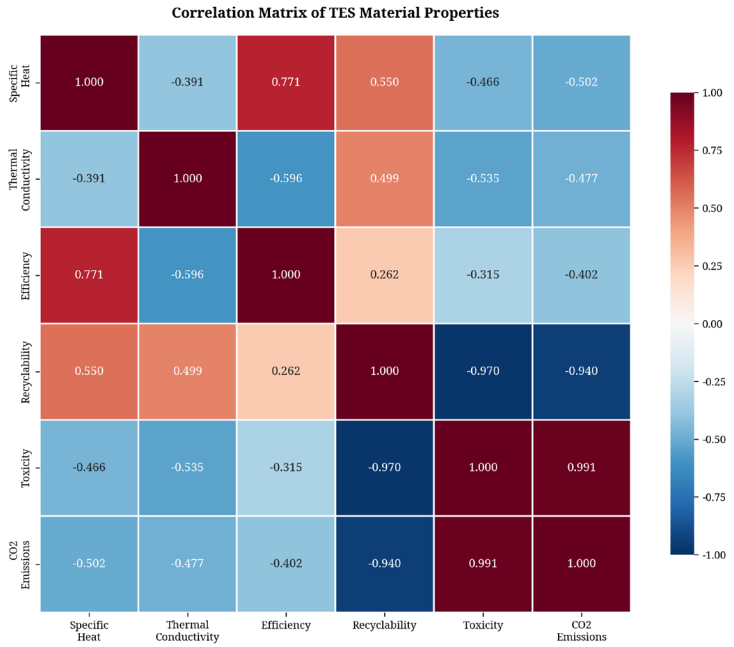


Fig. 7. Correlation matrix of TES material properties. Red indicates a positive correlation, and blue indicates a negative correlation.

There are a number of significant relationships to be noticed in the matrix. Toxicity and CO2 Emissions have a strong positive correlation (r = 0.991) indicating that a high carbon footprint of materials is also likely to contribute to their toxicity. Specific Heat (r = 0.771) and Thermal Conductivity (r = -0.596) have a positive and negative correlation with Efficiency respectively. This counter-intuitive observation needs further research but can be a result of a small sample (n=5). Statistical shortcomings Statistical limitations Statistical limits are sensitive to outliers, and the possibility of rank reversal in the case of the addition of new materials. These effects should be overcome in future studies by using larger datasets and hybrid MCDA approaches such as AHP-TOPSIS [15].

Conclusion

This paper has shown that a multi-criteria decision analysis framework can be very effective in choosing TES materials to be used in CSP applications. Incorporating a large pool of technical,

economic, and environmental measurements into a composite performance measure, we have offered a more comprehensive and detailed comparison compared to what exists in the literature. It can be seen that there is no universal solution; the best material to use is extremely dependent on the needs of a project. Our most important conclusions are that water has the best performance in our MCDA framework, but it can only be utilized in low-temperature processes. Concrete is a very balanced, economical and eco-friendly material that can be used in numerous applications. The existing industry standard, Molten Salt, has good performance at high temperatures although it presents serious environmental and safety issues. Lastly, PCMs are high-energy density coupled with high-efficiency systems that are impeded by low thermal conductivity. The visualizations and analysis presented in this paper represents a potent instrumentation in the possession of stakeholders as they are leaving the simplistic comparisons and making data-driven choices that will balance performance, cost, and sustainability.

Implications and Future Directions

The multi-criteria analysis given in this paper gives practical advice towards the design of CSP systems. In the case of dispatchable, high temperature generation, molten salt is the best option regardless of environmental constraints and its 290-565 C operating range is suitable to a high-efficiency Rankine cycle [2]. Concrete can be used for a balanced alternative with the same score (4.0) of excellent environmental performance, and 95% heat retention, thus being appropriate in constant discharge overnight. PCM is good in niche applications, where a high energy density and isothermal heat release is needed, but thermal improvement techniques are required to surpass its low conductivity (0.2 W/m 0.1 W/m K) [3]. This correlation is high between specific heat and efficiency ($r = 0.771$), indicating that there is need to conduct more research on high-capacity materials. Further efforts are needed on composite material with high thermal conductivity and high specific heat including nanofluids and nanocomposites. The high level of correlation between toxicity and CO2 emissions ($r = 0.991$) indicates the importance of comprehensive sustainability measurements. Also, long-term thermal cycling degradation mechanism research is essential to economic feasibility. Policymaking wise, low environmental material should be favored in areas that have strict policies, with economic analysis taking into consideration both CAPEX and OPEX trade-offs of material performance and lifecycle costs.

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