

New database of sustainable solid particle materials to perform a material-based design for a thermal energy storage in concentrating solar power

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ABSTRACT

Renewable energies have surged worldwide, aiming to mitigate greenhouse gas emissions and reduce dependence on fossil fuels. Concentrated solar power (CSP) with thermal energy storage (TES) emerges as a viable alternative to bridge the gap between renewable energy generation and consumption. However, existing CSP plants face a significant challenge in optimizing performance due to the operational temperature limitations of solar salt. While alternative materials, such as solid particles for sensible heat storage in solar towers exceeding 600 °C, have been proposed, the crucial aspect revolves around selecting a new alternative sustainable low-cost material for use as a TES media. This article investigates the optimization of CSP-TES systems by evaluating alternative sustainable low-cost materials sourced from several sectors such as the mining or metallurgical industry, municipal solid wastes, or demolition wastes. The materials, either used in their original form or formulated into aggregates for mortars, underwent thorough a property comparison focused on thermal, physical properties, and cost. With this data, a database was created using the Constructor software from ANSYS and integrated with the Selector software from the same company that provides instrumental for the creation of a comprehensive repository of sustainable materials, providing a database that serves as a practical reference guide for optimizing the selection of sustainable materials as TES in CSP plants. Then, a baseline could be established for selecting a sustainable material for a specific design, considering the properties of the materials. This methodology consists of redesigning and adapting the system according to the material, and it is known as the Materials-Based Design (MBD) process.

1. Introduction

With the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 [1], it has been clearly established that climate change is related and accelerated by human activity, mostly from fossil fuels used for energy purposes. Within this context, renewable energies have risen, all over the world, intending to reduce greenhouse gas emissions and the dependency on fossil fuels. Similarly, energy efficiency improvement is one of the most promoted subjects by the European Commission [2] through their energy efficiency directives. Energy technology interactions must be developed and deployed together between energy policies and the market. Integrated and connected electricity systems are key to transforming of the energy sector. In addition, energy systems integration and enhanced demand response will bring new opportunities

for optimization and increased efficiency in delivering services. In this scenario, thermal energy storage has been proposed as one of the promising side technologies to reduce energy consumption, match energy supply to energy demand, improve the energy efficiency of renewable energies and increase energy recovery by applying it to waste heat systems, all consequently reducing CO₂ emissions [3,4].

Thermosolar energy has been studied for more than a hundred years, and the first concentrating solar power (CSP) plant was built in 1968 in Italy by Professor Giovanni Francia. This plant could produce 1 MW of energy using superheated steam [4]. Since then, CSP plants have evolved and have been implemented in different countries. This work is focused on the high temperature concentrating solar towers, because they offer high conversion efficiency from thermal energy to electric energy and are highly scalable.

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Nowadays, most of the concentrating solar towers work with molten salts as the main Thermal Energy Storage (TES) and Heat Transfer Fluid (HTF) material. However, this material presents several drawbacks because of the corrosion and low reliability when reaching temperatures over 565 °C [5–7]. Therefore, innovation on selecting and developing new materials for CSP tower plants is one of the main goals to improve the actual commercial technology.

Research groups and enterprises are commonly focused on system design and afterwards, they search for the materials that best fit the specified boundary conditions of the designed system. However, there are several cases in which the number of available materials are limited and the system design must be done according to the available materials. Even if the available materials can be improved, there are a limited number of them. This happens in high temperature systems, where the temperature is highest and the materials that are available to operate in such conditions are the least stable.

Our case of study is the use of alternative-sustainable solid particle materials for sensible heat storage in solar towers for temperatures over 600 °C [8,9]. Solid particle materials have been proposed for enhancing concentrating solar power plants, but these materials can be potentially used for waste heat exploitation and solar heat industrial applications [10,11]. Some materials have been previously considered, such as silica sand, alumina powder, fly ash, silicon graphite, among others; nevertheless, an accurate materials selection process [12] has not been performed [9,13] to decide which is the best option. Despite this, key properties and parameters have been previously identified and measured for some of the considered materials, such as thermal conductivity or specific heat capacity [9,14], which can help in designing and implementing a selection procedure that leads to the material performing the best.

In the conventional engineering design process, the market need is initially translated into a working principle, defining both the requirements and constraints. The subsequent stages (conceptual design, embodiment design, and detailed design) ultimately lead to the product specification. However, materials behavior is often not considered until the later stages, possibly after concept evaluation and prototyping. Failure to incorporate materials and their properties early in the design process may result in selecting a material that exceeds some technical specifications but falls short in others. Alternatively, there may be another material that broadly meets all specifications, offering superior overall performance.

The materials selection approach starts from the requirements that the materials must meet to achieve an acceptable performance of the main design concept. To find a suitable material for a specific design, properties and key parameters interactions, manufacturing process energy, and environmental impacts must be evaluated to determine the relevance of each of them. Moreover, it could be necessary to go back to the design process several times adapting the layout, scale, or even the work principle according to the best materials available. This process of re-designing according to the material selection can be considered Materials-Based Design (MBD) process. This is the scenario of a packed-bed technology in a CSP plant, since there is a limited number of materials that could handle the target service temperature, that exceeds 600 °C in the new concept without solar salt. Parameters and properties of materials can have a big impact on the system performance and its durability. Several materials have been proposed for this application but there is a lack of information of their properties and parameters and the operation conditions, so an estimation of some of the properties will be considered according to the composition of the material.

Properties and parameters of a specific material can then determine changes in the CSP plant design. An example is the system storage capacity that changes according to thermal properties of storage material such as heat capacity, and to morphological conditions such as particle size distribution or particle shape. Therefore, this study is focused on developing a MBD focused on the main requirements for solid particles to be used as a TES material in high temperature CSP tower systems. Key

parameters and properties will be identified, finding their contribution to the different plant design stages.

2. Key parameters and properties

Based on previous research, the most significant parameters, and their target values to evaluate the possible materials to be used as solid particles in a TES system for CSP plants, are listed in Table 1. This table provides a technical and scientific basis for making a proper selection of the most appropriate candidate materials.

Several parts or stages can be identified in a CSP-TES plant. Each stage has an objective that must be enhanced to optimize the whole plant and involves several properties or parameters of the material that must be improved. In this case of study, the material properties in the TES tank will be addressed in Table 2 to optimize the performance of the packed bed.

3. New database of sustainable materials for TES

Potential sustainable solid particle materials for TES have been identified in the literature. These materials meet common characteristics, such as stability at high temperatures, high density, and low cost. All these candidates will be evaluated to maximize their best properties for high-temperature TES integration in a material selection study for a CSP-TES tank. To this end, a new database was created by Constructor software from Ansys Granta (Ansys GRANTA, ANSYS, Inc., Cambridge,

Table 1
Key properties and parameters of solid particle materials for CSP plants [11].

	Properties and parameters	Relevance	Desired value
Physical	Sphericity	Affectations on the HTF through the bed.	0.9
	Roundness	Affectations on the HTF through the bed.	0.9
	Solid density	Determines the energy density and have influence in the heat exchange process.	High
	Particle size distribution	Determine the bed void fraction and the average size of the particles. Important to prevent the sintering and agglomeration of the material, good heat transfer with a high contact area between the HTF and influence in the pressure drop of the HTF.	0.5–10 mm
Mechanical	Hardness	Determine the wear and mechanical degradation of the solid particle under thermal stress conditions.	High
	Yield strength		High
	Fracture toughness		High
Thermal	Specific heat capacity	Determines de energy density of the material.	High
	Thermal conductivity	The ability of the particles to absorb heat and to transfer it to the heat exchanger.	High
	Melting point	Melting point have a close relationship with sintering, which must be avoided.	Higher than 1500 °C
	Elongation	Determines the resistance of a material to sudden and large changes in temperature. Thermal shock can cause dynamic crack propagation producing fatigue in the material structure. Also, physical degradation can make the material more reactive.	High
Chemical	Thermal expansion coefficient		High
	Chemical composition	Determines chemical stability influence on the durability	Stable with temperature

Table 2
Stage objectives and material properties of the TES tank and the durability-related properties of the material.

	Stage	Main objectives	Properties and parameters involved
Thermal energy storage system	Store and release thermal energy	Increase amount of stored thermal energy, decrease thermal losses, avoid sintering, reduce void fraction in the bed to increase thermal exchange, and reduce material cost.	Specific heat, bulk and solid density, melting point or degradation temperature, particle size distribution, availability and cost.
	Thermo-mechanical stability	Improve durability of the particles and system materials.	Chemical composition, sphericity, roundness, melting point, particle size distribution, hardness, yield strength, fracture toughness, elongation, thermal expansion coefficient
Durability-related properties	Material compatibility	Avoid corrosion and wear. Ensure compatibility with the HTF.	Corrosion enhancement of system components.

UK, 2024).

The database includes various wastes and by-products from industries. Comprising 20 potential TES materials, classified into 5 main groups according to their origin, Fig. 1: (1) Demolition wastes (construction industry), (2) mining industry, (3) municipal solid wastes, (4) steelmaking industry, and finally, (5) other metal industries like aluminum and copper industry.

For each potential material, the selected information included in the database were density, maximum temperature service, specific heat capacity, thermal conductivity, and cost. All these data are presented in a range, from minimum to maximum value, see Fig. 2. These variables are critical to evaluating and selecting the best material candidates to be used as TES for CSP applications. Remarkably, most of the data was gathered from literature.

However, the thermal properties of certain materials were estimated

based on their chemical composition. The selected range spans from the compound's minimum to maximum values, weighted by the percentage of each element. The maximum temperature was determined by considering factors such as the maximum degradation temperature, onset of severe thermal decomposition, or melting point. The thermal properties of the chemical compounds were obtained from the Selector (Ansys) software database, as well as from the literature, as reported in Tables 3–7. These values may also vary depending on the composition of the waste produced, which is influenced by each new batch of material.

The thermal properties and chemical composition provided in the database are summarized in the following tables: Table 3 presents materials and properties from the construction industry, Table 4 from solid waste incinerators, Table 5 materials from the mining industry, Table 6 from the steelmaking industry, and Table 7 from other metal industries.

4. Materials based design approach for the TES system

During the design process of a complex system, to make the material selection it is essential to evaluate its performance in each of the tasks that it will perform in the final application. The optimization of this performance becomes an objective that depends on different properties and parameters of the material that can be grouped according to the objectives of each stage of the application, based on its specific needs.

When different material properties and parameters are combined to improve a specific objective, the performance of the material is determined by the material index [39]. Typically, these material indices are obtained after an initial screening and evaluate the performance of the candidate materials under the defined boundary conditions [40].

The materials-based design approach focuses on obtaining a material index through the existent methodology for material selection [12]. In the case under study (Fig. 3), the selection of the TES medium will be made for the TES tank with the objective of increasing thermal energy storage capacity and heat transfer. In this CSP tower system configuration, a conventional solar receiver using Solar Salt will be employed, and the same Solar Salt will serve as the HTF to transfer heat to the TES tank.

The objectives for the TES tank are included in Table 2: 1) Increment of the amount of thermal energy stored, which is related to the specific heat capacity and the density of the material, 2) Decrease of thermal losses, that have geometrical relations with the area and volume of the storage design, avoiding sintering of the particles that is related to the melting point of the material, and 3) reduction of void fraction of the bed to enhance thermal exchange with the HTF. The reduction of the void

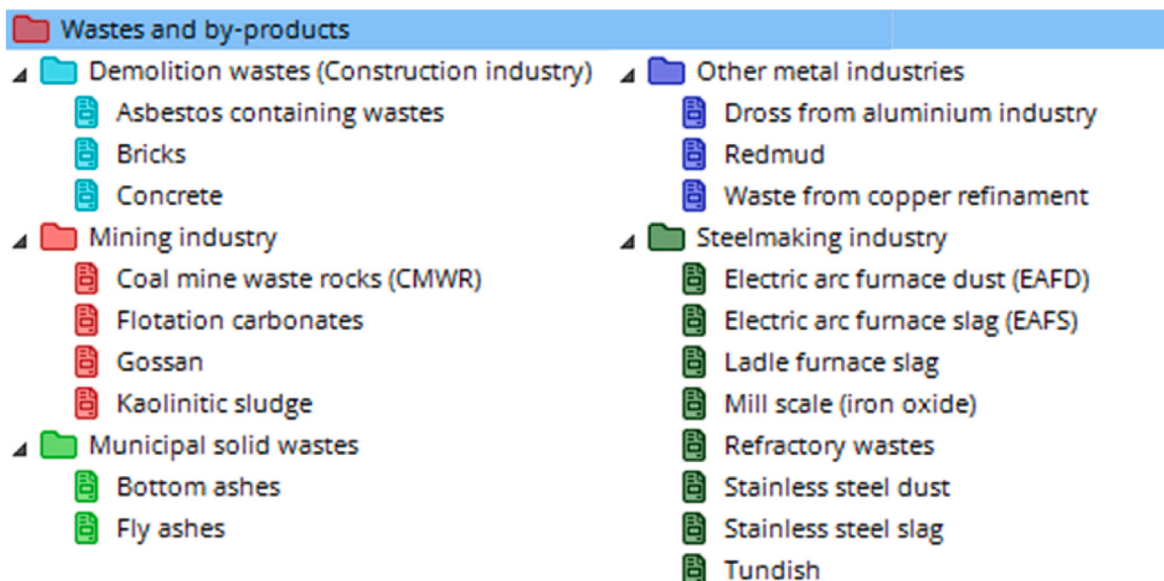


Fig. 1. Classification of wastes and by-products in the Sustainable Solid Particles Materials for Thermal Energy Storage database.

Electric arc furnace slag (EAFS)			
Steelmaking industry >			
Density	3,35e3	-	3,39e3 kg/m ³
Max temperature	1e3	-	1,2e3 °C
Specific heat capacity	0,99	-	1,07 J/g·°C
Thermal conductivity	0,53	-	0,64 W/m·°C
Cost	100	-	300 €/ton
Comments	Values can vary depending on composition.		

Fig. 2. Materials properties presented in the Sustainable Solid Particles Materials for Thermal Energy Storage database.

Notice that the average cost of these materials, factoring in the necessary pre-treatment or other preliminary adaptations, needs to be considered to estimate the material cost (C_m).

Table 3

Alternative sustainable materials from the construction industry (demolition wastes) intended for TES. *High temperature treatment needed to stabilize the waste.

Material	Composition	Specific heat capacity (kJ/kg·°C)	Density (kg/m ³)	Thermal conductivity (W/m·°C)	Max service temperature (°C)	Cost (€/ton)	Comments	Ref.
Asbestos containing wastes	O (32 wt%), Ca (21 wt%), Si (23 wt%), Fe-Mg-Al (13 wt%)	0.80–1.03	3000–3120	1.40–2.10	1500–1600	200–1000*	Requires a high-temperature pre-treatment to form a structure stable to thermal cycles.	[15]
Concrete	CaO (62 %), SiO ₂ (22 %), Al ₂ O ₃ (5 %), CaSO ₄ (4 %), Fe ₂ O ₃ (3 %), MgO (2 %), S (1 %), sand and gravel	0.85–1.17	2200–2400	1.25–1.50	400–600	5–15	Demolition wastes from urban projects: pre-treatment of the wastes needed.	[16]
Bricks	SiO ₂ (50 wt%), Al ₂ O ₃ (14 wt%), Fe ₂ O ₃ (5 wt%), CaO (4 %), MgO (13 wt%), K ₂ O (3 wt%)	0.70–1.07	1640–1780	0.35–0.70	1600–2000	1–2		[16]

Table 4

Alternative sustainable materials from municipal solid waste incinerators intended for TES. The values can vary depending on the composition of the ashes.

Material	Composition	Specific heat capacity (kJ/kg·°C)	Density (kg/m ³)	Thermal conductivity (W/m·°C)	Max service temperature (°C)	Cost (€/ton)	Comments	Ref.
Fly ashes	SiO ₂ , Al ₂ O ₃ , CaO	0.71–1.12	2900–2960	1.16–1.59	1000–1400	20–40	High volatile fractions are composed by gases from the combustion, and heavy metals.	[15, 17]
Bottom ashes	Al ₂ O ₃ , SiO ₂ , CaCO ₃ , CaO, Fe ₂ O ₃	0.71–1.12	2900–2960	1.16–1.59	1000–1400	20–40	Non-volatile incineration fraction: Mainly composed by ceramics (60 %), ferrous metals (20 %), non-ferrous metals (5 %), unburned organic matter (3 %)	[16, 17]

fraction of the bed is promoted by an appropriate particle size distribution (PSD) [41]. However, PSD will also lead to an increase on the pressure drop of the HTF. Therefore, it is important to achieve an equilibrium between these two factors to not compromise the operation.

Therefore, from the material perspective, to improve the thermal storage capacity, and thus reduce the rate of thermal losses, energy density should be maximized. Energy density is related to bulk density and specific heat of the material and to the temperature increase, which is a design parameter [12,42]. This can be observed in Equation (1):

$$\frac{Q}{V} = \rho C_p \Delta T \quad \text{Eq. 1}$$

where Q is the amount of stored heat (J), V is the volume (m³), ρ is the material bulk density (kg/m³), C_p is its heat capacity (J/kg K), and ΔT is the temperature difference between the lowest and highest operating temperatures.

Another objective in this stage is to store the maximum amount of energy at the lowest cost. This can be translated into Equation (2), where C is the cost of the material in €, and C_m is the cost in € of the material per unit mass.

$$\frac{Q}{C} = \frac{C_p}{C_m} \Delta T \quad \text{Eq. 2}$$

Table 8 includes the summarized information of boundary conditions for TES materials selection.

The two objectives expressed in Equation (3) and Equation (4), must be maximized or the inverse minimized. From each equation, a material index (M_1 and M_2) can be extracted, which only depends on the material properties and not on any structural, functional, or geometric parameter.

$$M_1 = \rho C_p \quad \text{Eq. 3}$$

Table 5

Alternative sustainable materials from the mining industry intended for TES. The values can vary depending on composition.

Material	Composition	Specific heat capacity (kJ/kg·°C)	Density (kg/m ³)	Thermal conductivity (W/m·°C)	Max service temperature (°C)	Cost (€/ton)	Comments	Ref.
Carbonate Flotation (CEF)	CaMg(CO ₃) ₂ , MgCO ₃ , Fe ₂ O ₃ (less content)	0.97–1.13	3340–3440	2–5	2000–2500	0.1–1	Low-grade magnesium carbonate that needs a pre-treatment in order to neutralize the compounds for high-temperature applications.	[18]
Gossan	SiO ₂ , Fe ₂ O ₃ , FeO ₂ H. Also, in less content (Plumbojarosite [PbFe ₃ (SO ₄)(AsO ₄)(OH) ₆], Potassium jarosite [KFe ₃ (SO ₄) ₂ (OH) ₆])	0.98–1.03	3720–3780	1–3	700–1500	0.1–1	Waste from copper ore extraction in the mining industry	[19, 20]
Coal mine waste rocks (CMWR)	SiO ₂ (50–60 %), Fe ₂ O ₃ (6–13 %), Al ₂ O ₃ (20–23 %)	0.79–0.81	2.49–3.25	7.45–11.5	800–1000	10–30	Waste produced during the coal mining and processing. Combination of many rocks that will need pre-treatment and adequacy.	[21, 22]
Kaolinitic sludge	SiO ₂ /Al ₂ O ₃ (60/30 %; 10 % other)	0.70–0.90	2850–2850	0.5–2.5	500–1800	50–100	Sludge obtained from the refining to obtain pure raw kaolin. Preparation of sludge will be needed.	[23]

Table 6

Alternative sustainable materials from the steelmaking industry intended for TES.

Material	Composition	Specific heat capacity (kJ/kg·°C)	Density (kg/m ³)	Thermal conductivity (W/m·°C)	Max service temperature (°C)	Cost (€/ton)	Comments	Ref.
Electric arc furnace dust (EAFD)	FeO (28.2 %) and ZnO (25.2 %) and other compounds of: Ca (5.1 %), Si (1.9 %), Pb (3.1 %), Cl (2.5 %) among others	1.1–1.2	3620–4930	0.5–1.5	1000–1200	20–50	Volatile dust produced during steel recycling. Mainly composed by Zn and Fe oxides and other heavy metals.	[20,24]
Electric arc furnace slag (EAFBS)	CaO (35 %), FeO(15 %), SiO ₂ (9 %),MgO (5 %), MnO (3 %), Al ₂ O ₃ (2 %)	0.99–1.07	3350–3390	0.53–0.64	1000–1200	100–300	Slag formed in electric arc furnace during steel recycling as a flotation slag in the melting tank.	[16,20, 25]
SS Slag (Stainless steel)	CaO, SiO ₂ , Al ₂ O ₃ , MgO, Cr (0,1–20 %), Ni (0,05–7%)	0.80–1.10	3350–3390	0.5–1	1000–1400	100–300	Slag obtained from stainless steel from different origins. The valorisation of this slag is mainly used for metal recuperation (Cr, Ni ...).	[25–27]
SS Dust (Stainless steel)	CaO, SiO ₂ , Al ₂ O ₃ , MgO, MnO, Na ₂ O, K ₂ O, P ₂ O ₅ , Fe ₂ O ₃ , Cr, Ti, Zn, Pb, Ni	0.70–1.20	3620–4930	0.5–1.5	1300–1400	20–50		[26]
Ladle furnace slag	CaO (58 %), SiO ₂ (17 %), Al ₂ O ₃ (12 %), MgO (10 %), SO ₃ (1 %)	0.5–1	3700–3720	0.5–1.5	1000–1200	100–500	Slag obtained from the production of raw steel in ladle furnaces.	[28]
Tundish	MgO (+60 %), Mg(OH) ₂ , CaO	1.03–1.14	3180–3410	0.64–0.85	1000–1200	50–150	Waste obtained from the furnace demolition of steelmaking process. Mainly composed by MgO and other impurities from steel.	[29,30]
Refractory wastes	40 % Al ₂ O ₃ /50 % SiO ₂ /MgO, ZrO ₂	0.70–1	2970–3280	1–2.5	1000–1200	50–150	Different wastes from refractory bricks origin.	[30]
Mill scale (iron oxide)	FeO, Fe ₂ O ₃ , Fe ₃ O ₄	0.70–1	5170–5740	0.5–1.5	500–550	50–150	Waste of iron oxide produced by the rolling mill in the steel hot rolling process.	[31]

$$M_2 = \frac{C_p}{C_m}$$

Eq. 4

The relation of the specific heat capacity and the density (M_1) and the specific heat capacity and the cost (M_2) are expressed in Figs. 4 and 5, respectively.

Then, the two first equations can be rewritten with their material index so they can be solved for stored heat (Q) and set them equal as presented in Equation (5) and Equation (6):

$$Q = V \Delta T M_1 = C \Delta T M_2$$

Eq. 5

$$M_1 = \frac{C}{V} M_2 \quad \frac{1}{M_2} = \frac{C}{V} \frac{1}{M_1}$$

Eq. 6

So, it is possible to obtain a relationship between M_1 and M_2 , that will represent a line of slope 1 in a graph of the inverse of M_2 vs the inverse of M_1 , positioned on an ordinate to the origin that depends on the cost-volume ratio of the storage system. For the same system volume, the cost will be higher the higher the position of the straight line. This representation can be calculated as expressed in Equation (7).

Table 7
Alternative sustainable materials from other metal industries intended for TES.

Material	Composition	Specific heat capacity (kJ/kg·°C)	Density (kg/m ³)	Thermal conductivity (W/m·°C)	Max service temperature (°C)	Cost (€/ton)	Comments	Ref.
Waste from copper refinement	SiO ₂ (32 %), FeO (43 %), Al ₂ O ₃ (2 %), CaO (1,5 %), MgO (0,8 %), CuO (0,6 %)	0.5–1	1870–1870	1–2	500–1000	1000–5000	Obtained from the copper manufacturing industries as a by-product in smelting process.	[32–34]
Dross from aluminium industry	Al metal 28–50 %, Al ₂ O ₃ (14 %), MgAl ₂ O ₄ (26 %) NaAl ₁₁ O ₁₇ (7 %), AlN (4 %)	0.63–0.75	2720–3310	1.16–2	500–1100	200–500	By-product generated during the production of aluminium through processes such as smelting and refining.	[35,36]
Red mud	Fe ₂ O ₃ (31–43 %), CaO (12 %), Al ₂ O ₃ (10 %), SiO ₂ (12 %), Na ₂ O (6 %), TiO ₂ (5,9 %)	1.03–1.31	3050–3630	0.77–0.83	600–900	20–50	By-product generated in the production of alumina through the Bayern process from bauxite ore.	[37,38]

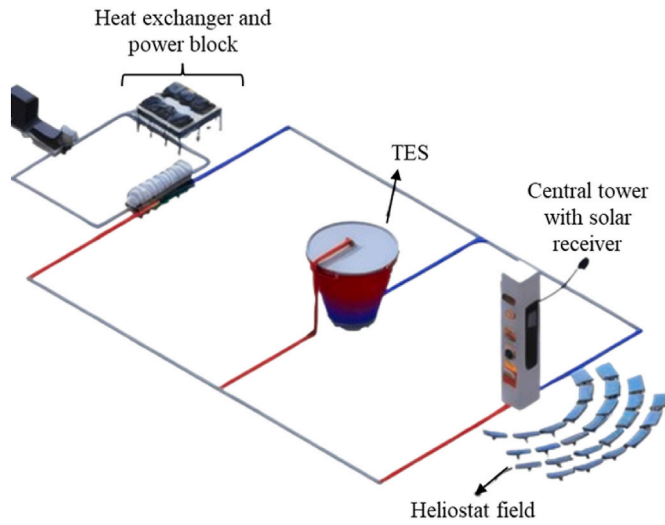


Fig. 3. Main parts of the CSP tower system configuration. A single-tank in a packed-bed configuration will be chosen for the evaluation.

Table 8
Boundary conditions for Material index definition in the TES stage.

STORAGE	Function	To store the thermal energy in the solid particles
	Constrains	Maximum service temperature higher than the highest operating temperature High energy density
	Objectives	Maximize the energy storage per unit volume and per unit of material cost
	Free variables	Material choice Dimensions

$$M_1 = C_p \cdot \rho \rightarrow \frac{1}{M_1} = \frac{1}{(\rho \cdot C_p)} \quad M_2 = \frac{C_p}{C_m} \rightarrow \frac{1}{M_2} = \frac{C_m}{C_p} \quad \frac{1}{M_2} \text{ vs } \frac{1}{M_1} \rightarrow \text{Slope 1} \quad \text{Eq. 7}$$

Fig. 6 shows both indexes for all the materials reported in section 3. For the same cost-volume ratio, material performing the best will be found closer to the origin of the graph.

After careful consideration of the optimal materials for the TES tank, with the primary objective being the amount of stored energy and minimizing heat losses, the expressions in Eq. (5) were rewritten in terms of each material index. This enables the estimation of the best candidate in terms of stored energy.

The amount of energy stored per unit volume and per unit cost can be then expressed as in Equation (8) and Equation (9):

$$Q_{\text{stored (vol)}} = \Delta T M_1 \quad \text{Eq. 8}$$

$$Q_{\text{stored (cost)}} = \Delta T M_2 \quad \text{Eq. 9}$$

As depicted in Fig. 6, the evaluation of both material indices within the considered materials and sectors reveals the best correlation between energy density and cost in materials originating from the mining industry, construction sector, and steelmaking sector. Among these, the mining industry shows greater potential, especially due to the low cost of its wastes. However, these materials are often tied to the production of a primary product, and the waste or by-products generated usually have a fluctuating price associated with the main production line, as well as subsequent treatment and environmental evaluation.

This variability is reflected in Table 9, where the energy stored per cost exhibits significant variations and uncertainty. Table 9 will highlight the best candidates based on both the higher amount of energy stored per volume and the higher energy stored per cost.

5. Material-based design approach for durability-related properties

In addition to the restrictions that the particulate material must meet directly related to the system (in which the main objective is the maximum amount of heat stored), there are other requirements, which we have called durability-related, that should be taken into account: throughout its life, the particulate material will undergo thousands of temperature cycles that will affect its thermomechanical stability and will be in contact with other materials with which the system is built, which we call material compatibility.

5.1. Thermo-mechanical stability

The temperature's influence on the material directly impacts its fracture resistance, encompassing factors such as chemical composition, agglomeration, sintering, melting point, and particle size distribution. Variations in temperature over time can induce changes in the initial chemical composition and structure of materials.

In solid particle materials, fractures result from three phenomena: collisions between particles, the rate of temperature change, and compression. Thermal shock and fatigue occur when there's a sudden temperature change in the particle surroundings, surpassing the material's strength. Additionally, crack initiation and propagation increase with each thermal charge/discharge cycle, requiring a study across multiple cycles [43] and various mean sizes of the same material.

The primary effect of thermal shock is the variation in the particle size distribution, influencing properties such as specific surface, thermal performance, and fluid-mechanic concerns involving the void fraction change and HTF pressure drop.

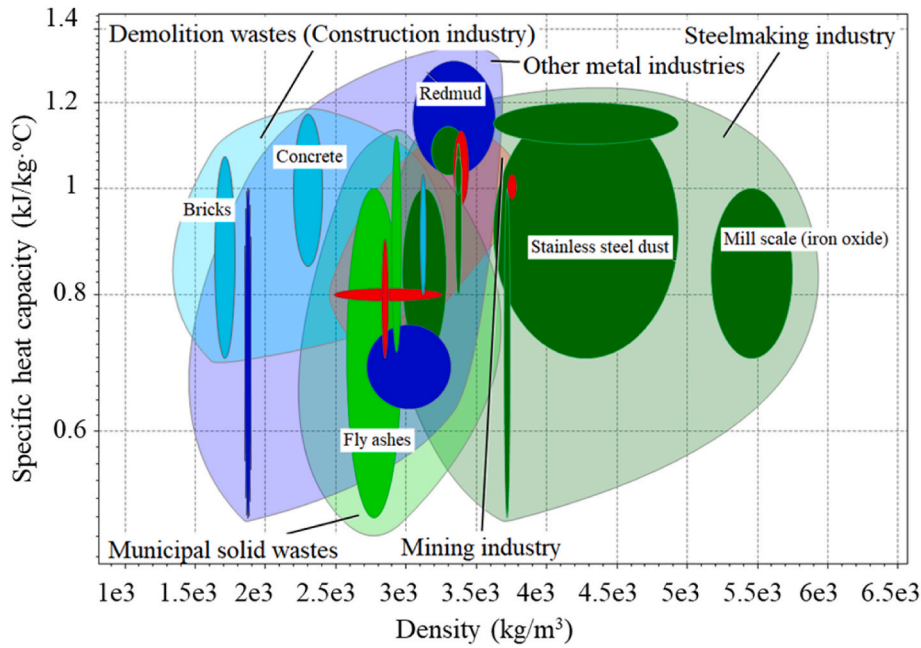


Fig. 4. Specific heat capacity vs density of the materials considered (M_1). Chart created with a database designed with ANSYS software.

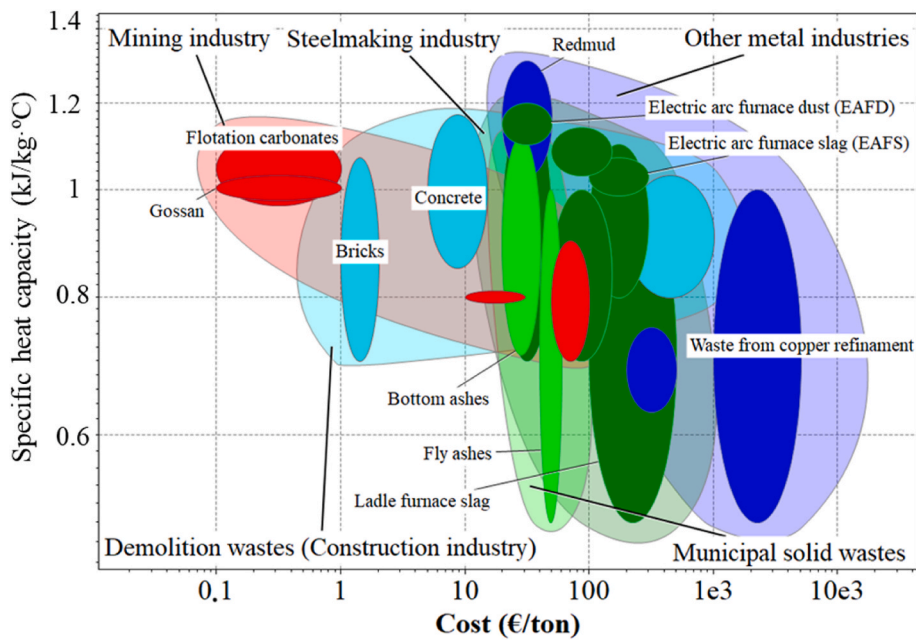


Fig. 5. Specific heat capacity vs cost of the materials considered (M_2). Chart created with a database designed with ANSYS software.

5.2. Materials compatibility

The solid particles are subjected to thermal shocks, mechanical efforts, and thermal and chemical degradation during the charging/discharging cycles accounted in the CSP system. A study of the corrosion/erosion between solids and between the HTF within the bed will be a key point in the final selection, however, the fact that solid particles are ceramic materials and less reactive, bring to fewer problems of compatibility and corrosion between the HTF and the packed-bed materials compared to hydrated salts [44]. Nevertheless, depending on the solid particle selected, some oxidation or degradation process can appear due to the highest working temperatures. Further studies of material compatibility must be conducted to assess the material

selection.

6. Conclusions

Material-based design has proven to be valuable for solid particles, given the scarcity of reported materials that exhibit the desired behavior for high-temperature thermal storage applications. By acknowledging the design objectives, not just the properties, it becomes possible to establish a material index tailored to the TES application, facilitating an initial screening and selection process.

The creation of a database of alternative metallic and ceramic wastes suitable for high-temperature applications has been completed. This database includes materials from various industries, broadening the

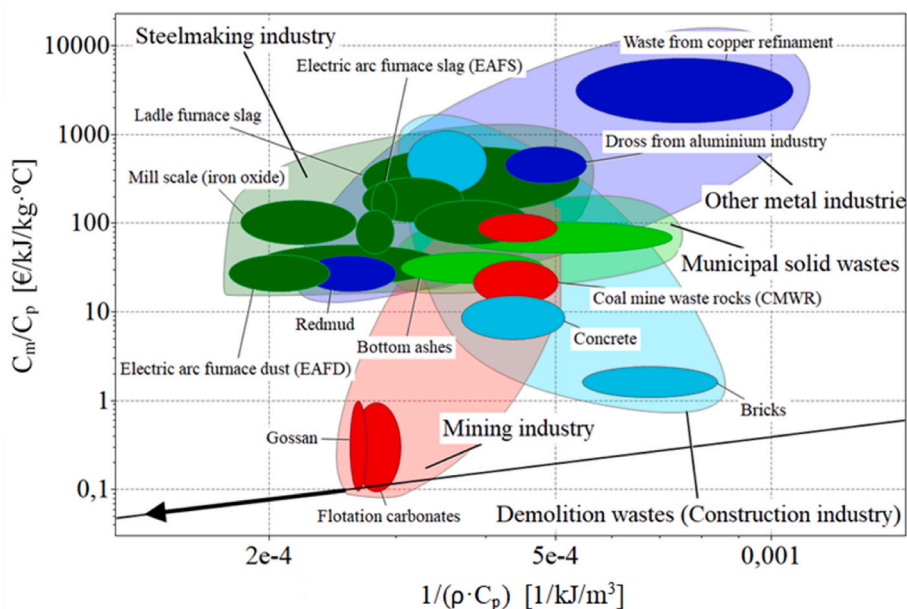


Fig. 6. M_1 and M_2 indices represented to maximize the stored heat for different cost-volume ratios for materials to be used as TES from different sectors: Mining industry, construction industry, municipal solid wastes, steelmaking industry, and other metal industries. The line in the graphic represents the relationship between M_1 and M_2 , which indicates the relation between storage volume and cost of the storage system.

Table 9

Energy stored per volume unit and energy stored per cost of all materials considered.

Material	$Q_{stored (vol)}$ (kJ/m ³)	$Q_{stored (cost)}$ (kJ/€)
Asbestos containing wastes	2855 ± 355	2.73 ± 1.82
Concrete	2320 ± 380	133.85 ± 68.15
Bricks	1510 ± 320	659 ± 245
Fly ashes	2080 ± 700	15.50 ± 5.69
Bottom ashes	2680 ± 600	34.05 ± 15.30
Carbonate Flotation (CEF)	3560 ± 280	5775 ± 4725
Gossan	3770 ± 100	5500 ± 4500
Coal mine waste rocks (CMWR)	2295 ± 305	53.35 ± 26.65
Kaolinitic sludge	2275 ± 285	11.96 ± 4.14
Electric arc furnace dust (EAFD)	4915 ± 775	40.25 ± 17.25
Electric arc furnace slag (EAFBS)	3470 ± 140	6.68 ± 3.43
SS Slag (Stainless steel)	3205 ± 505	6.29 ± 3.20
SS Dust (Stainless steel)	4045 ± 1185	32.80 ± 15.30
Ladle furnace slag	2780 ± 930	4.32 ± 2.95
Tundish	3575 ± 215	14.46 ± 7.24
Refractory wastes	2655 ± 485	11.25 ± 5.75
Mill scale (iron oxide)	4635 ± 845	11.25 ± 5.75
Waste from copper refinement	1402 ± 466	0.43 ± 0.29
Dross from aluminium industry	2080 ± 270	2.41 ± 1.04
Red mud	3905 ± 565	40.80 ± 17.80

scope of potential candidates. The detailed data on thermal properties and costs aids in making informed decisions regarding the initial selection of candidates.

To achieve optimal selection, the chosen material should excel in maximizing all relevant material indices simultaneously. This comprehensive analysis requires a multi-variable optimization study.

Focusing on the main objectives for the TES tank a material index can be obtained and used to identify the best candidates among the evaluated alternative material families. Materials from sectors such as mining, construction, and steelmaking were assessed. Materials from the mining industry exhibited the greatest potential due to their low costs, though variability in prices and environmental regulations regarding wastes posed challenges. Nevertheless, the high energy density and lower costs associated with these mining materials make them favorable candidates.

Furthermore, the durability of materials needs to be incorporated into the material selection process. However, these criteria are

intricately linked to each plant’s specific design. Additionally, specific factors related to each material must be considered (such as allotropic changes or the effects of material impurities), as they can alter material behavior.

After identifying the best sustainable low-cost material considering several waste-generating industries, the next step is to complete a long-term thermal evaluation and compatibility test that will depend on the plant design and TES tank technology employed in the CSP plant.

CRedit authorship contribution statement

Marc Majó: Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Alejandro Calderón:** Writing – original draft, Validation, Methodology. **Adela Svobodova-Sedlackova:** Writing – original draft, Methodology, Data curation. **M. Segarra:** Validation, Supervision. **A. Inés Fernández:** Validation, Supervision, Funding acquisition, Conceptualization. **Camila Barreneche:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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