Review on system and materials requirements for high temperature thermal energy storage. Part 1: General requirements

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Abstract

High temperature thermal energy storage offers a huge energy saving potential in industrial applications such as solar energy, automotive, heating and cooling, and industrial waste heat recovery. However, certain requirements need to be faced in order to ensure an optimal performance, and to further achieve widespread deployment. In the present review, these requirements are identified for high temperature (> 150 ºC) thermal energy storage systems and materials (both sensible and latent), and the scientific studies carried out meeting them are reviewed. Currently, there is a lack of data in the literature analysing thermal energy storage from both the systems and materials point of view. In the part 1 of this review more than 25 requirements have been found and classified into chemical, kinetic, physical and thermal (from the material point of view), and environmental, economic and technologic (form both the material and system point of view). The enhancements focused on the thermal conductivity are addressed in the Part 2 of this review due to their research significance and extension.

Key-words: Thermal energy storage, High temperature, Enhancement, Phase change material, system, requirements.

Table of abbreviations

BM	Base material
ACW	Asbestos containing wastes
CAPEX	Capital investment costs
CED	Cumulative energy demand
CO_2-eq	Equivalent CO_2 emissions
CSP	Concentrated solar power
DSC	Differential scanning calorimeter
ECES	Energy conservation through energy storage
FA	Fly ashes
FT-IR	Infrared spectroscopy
GHG	Greenhouse gases
GWP	Global warming potential
h	Heat storage capacity
HTF	Heat transfer fluid
IACW	Intertized asbestos containing wastes
IEA	International Energy Agency
IP	Impact points
LCA	Life cycle assessment
MDSC	Modulated differential scanning calorimeter
MWCNT	Multi-walled carbon nanotubes
NFPA	National fire protection association
OPEX	Operation and maintenance costs
PCM	Phase change material
PT	Parabolic trough
SM	Stirring method
ST	Solar tower
SWCNT	Single walled carbon nanotubes
TES	Thermal energy storage
Tm	Temperature of fusion
TSSM	Two-step solution method
XR	X-ray powder diffraction

1. Introduction

Current trends in energy supply and demand are economically, environmentally and socially unsustainable since energy-related emissions of carbon dioxide are expected to be doubled by 2050 and fossil energy demand is expected to be increased over the security of supplies [1]. The International Energy Agency (IEA) recognizes energy storage technologies as a tool to support energy security and climate change goals by helping to integrate electricity and heat systems.

Among the different energy storage technologies, thermal energy storage (TES) is an effective technique that has become a key factor on improving the efficiency of different energy systems due to the versatility in correcting the mismatch between the energy demand and supply, and by allowing the development and implementation of renewable energies. A clear example is TES in solar power plants, where the excess of solar energy during the Sun-light period, is stored to be further released during the periods when the solar energy is needed but not available, such as cloudy or night-time periods.

There are basically three main techniques for TES: sensible, latent and thermochemical, being the first two the most studied and developed by the researchers. In sensible heat storage, the storing (or releasing) of thermal energy is linked to the temperature rising (or dropping) without undergoing phase change, as a consequence of a change in the internal energy of the TES material. In latent heat storage, the media stores (or releases) the thermal energy when it undergoes phase change. Unlike sensible heat storage, latent heat storage has higher storage density because the phase-transition enthalpy is much higher (usually more than 50-100 times) [2]. Since the process is nearly isothermal, which means that the temperature barely increases (or decreases), all the energy stored comes from the molecular restructuration that takes place within the transition from one phase to the other. Finally, in thermochemical heat storage the energy is stored (or released) after a reversible chemical reaction between two substances. It means that once the heat is released due to a dissociation of a chemical product, it can be recovered in almost its totality when the synthesis reaction takes place.

TES can be implemented in many different sectors and applications. Table 1 summarizes the most known and studied TES storage applications for a range that comprises low and high temperature (from -269 ºC to around 1600 ºC).

Table 1. Review of the potential TES storage applications and sectors, as well as their range of working temperatures.

Sector and pplication	**Range of temperatures**	**Reference**
1. Heating and cooling	From -40 ºC to 350 ºC	
1.1. Cold production	*From -40 ºC to -10 ºC*	[2,3]
1.2. Space heating and cooling of buildings	*From 18 ºC to 28 ºC*	[4,5]
1.3. Heating and cooling of water	*From 29 ºC to 80 ºC*	[4,6]
1.4. Absorption refrigeration	*From 80 ºC to 230 ºC*	[7]
1.5. Adsorption refrigeration	*From -60 ºC to 350 ºC*	[8]
2. Transportation	From -50 ºC to 800 ºC	
2.1. Cabin heating and refrigeration	*From -50 ºC to 70 ºC*	[9,10]
2.2. Battery and electronic protection	*From 30 ºC to 80 ºC*	[9,10]
2.3. Exhaust heat recovery	*From 55 ºC to 800 ºC*	[9,10]
3. Thermal protection	From -269 ºC to 130 ºC	
3.1. Electronic devices thermal protection	*From 25 ºC to 45 ºC*	[11]
3.2. Chips thermal protection	*From 85 ºC to 120 ºC*	[12]
3.3. Data centers thermal protection	*From 5 ºC to 45 ºC*	[13]
3.4. Spacecraft electronics thermal protection	*From -269 ºC to 130 ºC*	[14]
3.5. Food thermal protection	*From -30 ºC to 121 ºC*	[15]
3.6. Biomedical applications	*From -30 ºC to 22 ºC*	[16]
4. Industry	*From 60 ºC to 260 ºC*	[17,18]
5. Solar energy	From 20 ºC to 565 ºC	
5.1. Solar cooling	*From 60 ºC to 250 ºC*	[19,20]
5.2. Solar energy storage	*From 20 ºC to 150 ºC*	[20]
5.3. Solar power plants	*From 250 ºC to 565 ºC*	[21,22]
6. Desalination	*From 40 ºC to 120 ºC*	[23,24]
7. Industrial waste heat recovery	*From 30 ºC to 1600 ºC*	[25,26]

TES has been of high interest for the researchers in the last decade and therefore many papers can be found in the literature dealing this topic, especially at mid-low temperatures (below 150 ºC). For example, Zalba et al. [27] reviewed and classified phase change materials (PCM) from -33 ºC on and described some of their main applications. Pielichowska and Pielichowski [22] updated this review including sensible materials. At higher temperatures the number of publications is considerably fewer. Liu et al. [28] focused their review on PCM and possible thermal performance enhancement techniques at temperatures higher than 300 ºC. Over the same temperature range worked Cárdenas and León [29] and Fernandes et al. [30], who defined

77 a suitable material selection and procedure, defined different applications for power generation,
78 and reviewed some enhancement techniques focused on different thermophyisical properties.
79 Although most of these reviews mentioned some of the requirements presented in Table 2, none
80 of them organized the information in a way that addresses each of the requirements in order to
81 help the final user to identify the right TES material, technology, system and/or enhancement
82 technique.
83
84 Table 2 classifies the different requirements that, according to the literature, TES materials and
85 systems should accomplish for an optimum thermal, physical, kinetic, chemical, economical,
86 technological, and environmental performance.
87
88 Table 2. Main requirements for selecting the suitable materials and systems focused on high temperature
89 TES. The requirements which have an * correspond only to latent storage. Based on [27,31-33].

Requirements			Reason
Material	**Chemical**	Long-term chemical stability	Keeping the initial thermochemical properties along the cycling periods
		No chemical decomposition	
		Compatibility with container materials and low reactivity to heat transfer fluids (HTFs)	Ensuring long lifetime of the container and the surrounding materials in case of leakage
		No fire and explosion hazard	Ensuring workplace safety
		No toxicity	Ensuring handling safety
		*No phase separation / Incongruent melting	Avoiding changes on the stoichiometric composition of melt
	Kinetic	*Small or no subcooling	Having the same melting/solidification temperature and avoiding heat release problems
		*Sufficient crystallization rate	Meeting the recovery system heat transfer demands
	Physical	High density	Minimizing the volume occupied by the TES material
		Low vapour pressure	Diminishing the mechanical and chemical stability requirements of the container or vessel
		*Small volume changes (low density variation)	
		*Favourable phase equilibrium	Possibility of using eutectic mixtures
	Thermal	High specific heat	Providing significant sensible heat storage
		High thermal conductivity in both solid and liquid states	Enhancing the heat transfer within the TES material by providing the minimum temperature gradients
		*Melting / solidification temperature in the desired operating temperature range	Ensuring the success of the charging and discharging processes within the operation conditions

		*High latent heat of transition per unit volume near temperature of use	Providing significant latent heat storage in small volumes
		*Congruent melting	Ensuring the complete melt of the TES material and their homogeneity
Material/System	**Economic**	Abundant and available	Being cheaper than other options
		Large lifetime	Avoiding replacements and maintenance during the lifetime of the TES system
		Cost effective	Being competitive in front other options
	Environmental	Low manufacturing energy	Reducing the environmental impact of the systems and accomplishing sustainable regulations and trends
		Easy recycling and treatment	
		Low CO_2 footprint and use of by-products	
		Non-polluting	
	Technological	Operation strategy	Optimizing the processes by adapting them to limiting factors such as maximum loads, nominal temperatures and specific enthalpy drops in load
		Integration into the facility	
		Suitable heat transfer between the HTF and the storage medium (efficiency)	Enhancing the heat transfer from the TES material to the HTF and vice versa

The main objective of the present paper is to identify the main requirements that a TES system (sensible or latent) should accomplish at high temperature (> 150 ºC) from the material and system point of view, and reviewing the literature available on this topic in order to find the research niches which can allow the researchers conducting their investigation.

This is the first review considering such a wide scope and therefore the authors have divided it into two parts. The first part consists of a revision of all the general requirements that a TES system should fulfil in order to be considered optimal (chemical, economic, environmental, kinetic, physical, technological, and thermal). The second part [34] is mainly focused on the study of the thermal conductivity enhancement techniques between the HTF and the TES material, by adding extended surfaces, and enhancing the thermal conductivity of the material itself, by combining it with highly conductive materials.

2. Material requirements

2.1 Addressing chemical requirements

Chemical requirements are very similar for sensible and latent heat storage materials (Table 2). Candidate materials should have long-term chemical stability, no chemical decomposition, should be compatible with the container materials and the HTF, non-toxic and non-flammable, and they should present no phase segregation.

Any material is suitable for TES applications if it is chemically stable and does not degrade after a number of repeated heating and cooling cycles, which means that it keeps almost the same thermochemical properties than the beginning. Many authors reported the results from their cycling tests in which the chemical stability was checked. Ferrer et al. [35] reviewed the methodologies used to assess the cyclability of TES materials. They identified that the infrared spectroscopy (FT-IR) analysis is the most widely technique used to study the chemical stability. In addition, they also identified the parameters that need to be considered when performing those tests: cycling equipment, characterization technique after the test, number of cycles, and heating rate. Only four studies regarding high temperature TES materials have been found. Solé et al. [36] studied the chemical stability of three high temperature sugar alcohols (d-mannitol [T_m = 166 - 176.9 °C], myo-inositol [T_m = 224 - 227 °C] and galacticol [T_m = 187 - 188.5 °C]) using differential scanning calorimeter (DSC) and FT-IR analyses. Results showed a poor stability of galacticol and d-mannitol and a good stability of myo-inositol. Moreover, it was observed that the contact of the TES materials with oxygen was a variable that affected the results of the study. Therefore, a TES system including these materials should be in an inert atmosphere or in vacuum. Similarly, John et al. [37] studied the effect of the upper cycle temperature on the thermal behaviour of galactitol in bulk thermal cycling for solar cookers. They observed the same poor stability results than Solé et al. [36] and concluded that this TES material is not suitable for the application proposed. Paul et al. [38] studied the chemical stability of a eutectic mixture at a 30:70 molar ratio of galactitol and mannitol (T_m = 153 ºC) via DSC, X-ray powder diffraction (XR) and FT-IR spectroscopy analyses. Those techniques confirmed that the combination of mannitol and galacticol showed good cyclic, thermal and chemical stability compared to its individual components under nitrogen or air atmospheres. Finally, Sun et al. [39] cycled 1000 times an aluminium-magnesium-zinc alloy (T_m = 450 ºC). Results showed a good stability of the alloy as it showed an 11% of loss on the heat storage capacity and a variation of 0.7 % on the melting temperature.

The compatibility of the TES material and the container material is crucial in order to ensure a long lifetime as a result of a minimum variation of its mechanical and structural properties. This property is often assessed by measuring the corrosion between the TES and the container materials. Corrosion is normally measured by immersing a sample made of the container

material in the liquid TES material. Temperature, length and repeatability of the analysis depend on the specific requirements of the applications.

Table 3 shows a review of the corrosion studies performed at high temperature and defines the TES and containers materials, working temperatures, results and year in which they were performed. Eutectic mixtures containing sodium nitrate and potassium nitrate are the most studied high temperature TES material because of their potential use in solar power plants. The combination of molten salts and the metallic parts of the solar power plants constitutes a corrosion system, where the salts act as an electrolyte, comparable to an aqueous electrolyte. However, whereas the corrosion mechanisms of metals in numerous aqueous electrolytes are well established and understood, it still exists a lack in knowledge concerning the corrosion mechanisms of metals in molten salts [40]. The corrosion of different commercial steels and other alloys are evaluated when in contact with nine different high temperature eutectic mixtures used for TES. The corrosion tests have been performed at different working temperature, ranging from 250 to 800 ºC. However, different procedures (metal weight/gain losses, corrosion rates, etc.) were used by those authors to evaluate the corrosion and, therefore, it is not possible to perform an accurate comparison of the results reviewed. Moreover, the compatibility between a TES material and its container cannot be transferred from the literature straightforward. At the working conditions (temperature, length, intermittence, etc.) of the real application in which those materials are expected to be used should be assessed. Guillot et al. [41] assessed the suitability of combining intertised asbestos containing wastes (IACW), which are industrial wastes based on calcium magnesium iron alumino-silicate with different impurities, with molten salts to be combined and used as TES material in concentrated solar power (CSP) plants. Sulphates, phosphates, carbonates and nitrates salts have been mixed with IACW and the corrosion indicated that only the nitrates have shown good compatibility with IACW materials.

Table 3. Review of the studies concerning the chemical requirements at high temperature in terms of compatibility between the container and the TES material.

Study case	TES material (wt %)	Container material		Working temperature	Results	Year	Reference
1	(HITEC) $NaNO_2$ + $NaNO_3$ + KNO_3 (40 % + 7 % + 53 %)	Steel	A516	390 ºC	Mass gain = 0.35 mg/cm^2	2015	Fernandez et al. [42]
			T11	390 ºC	Mass gain = 0.35 mg/cm^2		
			T22	390 ºC	Mass gain = 0.35 mg/cm^2		
			321	530 ºC	≈ 0.02 mm/a	2015	Federsel et al. [43]
		Other alloys	Inconel 600	530 ºC	≈ 0.02 mm/a	2015	Federsel et al. [43]
			AISI 430	390 ºC	< 0.1 mg/cm^2	2015	Fernandez et al. [44]
			T22	390 ºC	0.00044 µm/h		
			A1	390 ºC	0.00075 µm/h		
			SS316	550 ºC	> 1 mg/cm^2	2004	Goods and Bradshaw [45]
			A36	550 ºC	<0.5 mg/cm^2		
			SS304	390 ºC	<0.1 mg/cm^2	2015	Fernandez et al. [44]
				550 ºC	< 3 mg/cm^2	2004	Goods and Bradshaw [45]
3	KNO_3 + $NaNO_3$ (50 % + 50 %)	Other alloys	Inconel	677 ºC	3.05-4.83 mm/a	1985	Slusser et al. [46]
			Hastelloy		3.30-10.41 mm/a		
			Alloy		4.32 mm/a		
			RA		6.86 mm/a		
			Incoloy		10.67 mm/a		
			Haynes		17.53-21.08 mm/a		
			Nitronic		21.33-29.72 mm/a		
			Nicofer		43.18 mm/a		
			Ni		81.79 mm/a		
4	(Molten salts) $NaNO_3$ + KNO_3 (60 % + 40 %)	Steel	SS304	390 ºC	< 0.05 mg/cm^2	2014	Fernandez et al. [47,48]
				550 ºC	0.0062 µm/h		
				570 ºC	4-10 mg/cm^2	2004	Goods and Bradshaw [45]
			T11	390 ºC	2.75 mg/cm^2	2014	Fernandez et al. [49]
			T22	390 ºC	0.0081 µm/h	2014	Fernandez et al. [48]
				550 ºC	2.25 mg/cm^2		Fernandez et al. [50]
			OC-4	390 ºC	Excellent behaviour	2014	Fernandez et al. [47]
			A1	390 ºC	0.1108 µm/h	2014	Fernandez et al. [48]

			A36	316 ºC	1-2.5 mg/cm^2	2004	Goods and Bradshaw [45]
			AISI SS430	390 ºC	0 mg/cm^2	2014	Fernandez et al. [50]
				550 ºC	0.1321 µm/h		Fernandez et al. [48]
			P91	600 ºC	Scale thickness = 1330 µm	2016	Dorcheh et al. [51]
			X20	600 ºC	Scale thickness = 450 µm	2016	Dorcheh et al. [51]
			SS316	570 ºC	5-8 mg/cm^2	2004	Goods and Bradshaw [45]
				600 ºC	Scale thickness = 18 µm	2016	Dorcheh et al. [51]
			316Ti	565 ºC	≈ 0.5 % weight loss	2015	Federsel et al. [43]
			SS347H	600 ºC	Scale thickness = 18 µm	2016	Dorcheh et al. [51]
			SS321	400 ºC	Descaled loss = 0.27 mg/cm^2	2014	Kruizenga and Gill [52]
				500 ºC	Descaled loss = 1.98 mg/cm^2	2014	Kruizenga and Gill [52]
				565 ºC	≈ 0.2 % weight loss	2015	Federsel et al. [43]
				680 ºC	Descaled loss = 42.77 mg/cm^2	2014	Kruizenga and Gill [52]
			SS347	400 ºC	Descaled loss = 0.2 mg/cm^2	2014	Kruizenga and Gill [52]
				500 ºC	Descaled loss = 1.28 mg/cm^2	2014	Kruizenga and Gill [52]
				680 ºC	Descaled loss = 42.05 mg/cm^2	2014	Kruizenga and Gill [52]
		Other alloys	HA230	600 ºC	Metal losses of 23.6 µm/a	2014	McConohy and Kruizenga [53]
				680 ºC	Metal losses of 688 µm/a	2014	McConohy and Kruizenga [53]
			In625	600 ºC	Scale thickness = 9 µm	2016	Dorcheh et al. [51]
				600 ºC	Metal losses of 16.8 µm/a	2014	McConohy and Kruizenga [53]
				680 ºC	Metal losses of 594 µm/a.	2014	McConohy and Kruizenga [53]
			Incoloy Alloy 800	550-670 ºC	Oxide scales higher than 15 µm	1981	Goods [54]
5	$LiNO_3$ + $NaNO_3$ + KNO_3 (30 % + 18 % + 52 %)	Steel	SB450	550 ºC	n.a.	2015	Cheng et al. [55]
			T22	550 ºC	n.a.		
			T5	550 ºC			
			T9	550 ºC			
			X20	550 ºC			

6	Molten salts with NaCl additives	Stainless steel	304	570 ºC	7-10 mg/cm^2	2004	Goods and Bradshaw [45]
			316	570 ºC	5-6 mg/cm^2		
		Carbon steel	A36	316 ºC	2-3 mg/cm^2		
7	(FLiNaK) LiF + NaF + KF (46.5 % + 11.5 % + 42 %)	Steel	SS316L	650 ºC	19.65 mm/a	2014	Sona et al. [56]
			SS317L		17.82 mm/a		
			Inconel-625		23.70 mm/a		
			Incoloy-800H		39.30 mm/a		
			Hasteloy-B		3.02 mm/a		
			Ni-201		0.94 mm/a		
8	NaCl + KCl (50 % + 50 %)	Fe-Cr alloy	n.a.	670 ºC	n.a.	2005	Li et al. [57]
		Fe-Al alloy					
		Ni-Al alloy					
		Steel	316L	670 ºC	n.a.	2010	Abramov et al. [58]
			316Ti				
			321				
9	NaCl + KCl + $ZnCl_2$ (13.4 % + 33.7 + 52.9 %)	Hastelloy	C-276	500 ºC	Corrosion rate < 20 µm/a	2015	Vignarooban et al. [59]
				800 ºC	Corrosion rate 40 µm/a		
			C-22	250 ºC	Corrosion rate < 20 µm/a		
				500 ºC	Corrosion rate 40 µm/a		
		Stainless steel	304	250 ºC	Corrosion rate 20 µm/a		
				500 ºC	Corrosion rate 380 µm/a		

n.a: not available

In order to facilitate the handling and the safe use of the TES material, no hazardous materials are preferable. Therefore toxic or flammable TES materials should be avoided. However, most of the authors have focused only on the thermal behaviour properties when selecting TES materials without taking into account those parameters. Miró et al. [60] proposed health hazard as a part of a new methodology to select the suitable TES materials. Moreover, a case study considering five high temperature PCMs (salicylic acid, benzanilide, d-mannitol, hydroquinone, and potassium thiocyanate) was presented. The degree of health hazard of a material is based on the form or condition of the material and on its inherent properties. It is provided by the manufacturer in the material safety data sheets or by different standard associations which have developed tools to indicate the health, flammability, reactivity and special hazards for many common chemicals [60]. Results showed that potassium thiocyanate was the most dangerous TES materials within the selected ones and its short exposure could cause serious temporary or moderate residual injuries. TES material with health hazard values above 3 (according to the National fire protection association (NFPA) 704 standard in a scale from 0 to 4) should be discarded. However, if a specific application requires it, its use must be always under the established safety measures. In Table 4, the health hazard rating of the different materials studied are presented. Regarding to the flammability, Gallegos and Yu [61] proposed TES as and insulation medium in high temperatures systems when the heat flux presented values up to 80-84 $kW \cdot m^{-2}$ from flashover conditions in a firefighting environment. Among the proposed candidates, they analysed dulcitol and d-mannitol. Results showed that the molecular structure of sugar alcohols has tremendous impacts in terms of melting and boiling point and therefore in flammability.

Table 4. Health hazard rating of some TES materials based on the NFPA 704 standard [60].

	Health hazard rating
Salicylic acid	½
Benzanilide	1
d-mannitol	1
Hydroquinone	2
Potassium thiocyanate	3

Phase segregation (or phase separation) is the macroscopic separation of the phases in a PCM. When that occurs, PCM shows a significantly lower capacity to store heat [33]. According to Zhao [62], encapsulation can help to mitigate not only phase segregation during thermal cycling but also problems like low thermal conductivity and subcooling. Moreover, it protects the TES material from exposure and potential corrosion with HTF. Therefore, the encapsulation material should also be compatible with the TES material. Metals are the best candidates for

encapsulation at high temperature due to their properties such as strength, thermal conductivity, wear resistance, excellent workability and ductility [62,63]. However, the use of shells and their characteristics are strongly determined by the volumetric expansion of the material and the pressure increase during the melting process [64]. In order to avoid problems such as chemical corrosion and thermal stress, the use of ceramic shells is starting to gain relevance [65]. A more detailed review on shell materials used in the encapsulation of TES materials for high temperature is presented in Jacob and Bruno [66].

2.2 Addressing kinetic requirements

The kinetic requirements identified in this review include small or no subcooling during the solidification in order to have the similar temperatures in both the melting and the solidification processes and therefore avoiding heat release problems, and sufficient crystallization rate in order to meet the recovery system heat transfer demands. These two requirements are referred only to latent heat storage systems [67].

In the literature, only research work discussing the subcooling effect is found. This effect, also known as supercooling or undercooling [33], refers to a solidification process which does not start immediately upon cooling below the melting temperature, but starts the crystallization only after a temperature well below the melting temperature (Fig. 1). It appears mostly in inorganic PCM.

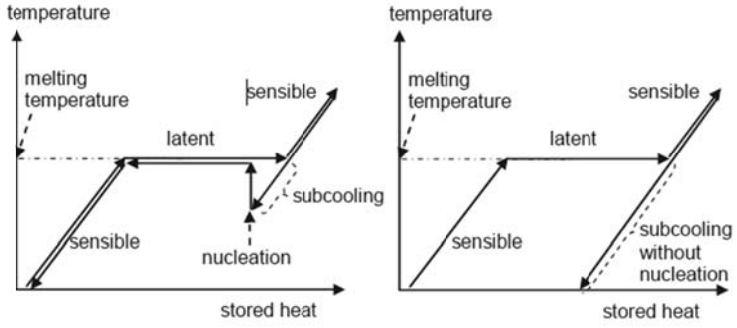

Fig. 1. Effect of subcooling on heat storage. Left: little subcooling and nucleation, right: severe subcooling without nucleation [33].

The most common approach to eliminate the subcooling effect is the addition of additives, also known as nucleating agents, into the TES material in order to cause heterogeneous nucleation. Most of the nucleating agents are materials with a similar crystal structure than the solid TES material, which allows the solid phase of the TES material to grow on their surface but with

higher melting temperature to avoid deactivation when the TES material is melted. The main problem of this solution is that similar crystal structures usually means similar melting temperatures.

Very little research has been carried out regarding kinetics at high temperature. For example, Sari et al. [68] reduced the subcooling of galacticol (Tm = 187.4 °C) by preparing galactitol hexastearate and galactitol hexapalmitate as a novel solid–liquid TES material by means of esterification reaction of the TES material with palmitic acid and stearic acid. However, this mixture leaded to a TES material with a melting temperature of around 40 °C. Paul et al. [38] studied the effect of adding up to 0.5 wt.% of different nucleating agents (graphite and silver iodide) into an eutectic mixture at a 30:70 molar ratio of galactitol and mannitol (T_m = 153 ºC). They observed that the nucleation agents reduced subcooling around 10 ºC. Other studies observed that the size of the sample is an important parameter when determining the subcooling effect [69-71]. Rathgeber et al. [69] selected nine TES materials for combined DSC and T-history measurements. From these materials, hydroquinone was the only one at high temperature. Using both DSC and T-history for the determination of enthalpy curves, the dependence of this curve on the sample size and on the temperature profile applied could be analysed and a reduction of around 13 ºC in the subcooling effect was observed. Gil et al. [70] tested at both laboratory and pilot plant scales two TES materials candidates for solar refrigeration applications (hydroquinone and d-mannitol). They realized that d-mannitol showed subcooling in both scales while hydroquinone showed subcooling only at laboratory scale. Later on, both materials were also analysed with the T-History method [71], verifying that the effect of subcooling was volume-dependent.

2.3 Addressing physical requirements

Regarding the physical requirements, TES materials should have high density in order to decrease the space needed to store the same amount of heat. In addition, low vapour pressure and low density variation between phases are needed to diminish the mechanical and chemical stability requirements of the container. Finally, and specifically for TES materials working in their latent phase, favourable phase equilibrium is required.

Despite the fact that these parameters are very important when designing the TES container or the encapsulation for the TES material, there is a paucity of literature on this requirement at high temperature. Regarding the low density variation, Archiblod et al. [71] and Solomon et al. [73] considered the thermal expansion coefficient of sodium nitrate (Tm = 306.8 °C) and the effect of an internal air void when evaluating its thermal performance within a metallic spherical

shell. They highlighted that the salt quantity inside the sell should be carefully calculated to guarantee the internal pressure. Moreover, they found that the shape of the melting front and the rate at which it moves is affected by the location of the internal air void. Hennemann et al. [74] studied the physical laws limiting the heat of fusion and the usability of TES material in applications, and an exhaustive study of entropy was done regarding expansional, positional, orientational, conformational and electronic contribution of entropy. They concluded that disregarding molecules with molecular weights less than 70 g/mol, the limiting theoretical entropy value set by physical and chemical constrains was 1.0 J/(g·K).

2.4 Addressing thermal requirements

It is a fact that most of the materials used for TES purposes have poor thermal characteristics and therefore enhancement techniques addressing these requirements need to be performed. As Table 2 shows, there are five main thermal requirements that TES materials should meet in order to optimize the processes in which they are planned to be implemented. If the thermal storage is requested to occur in the latent phase, TES materials must have their phase change temperature in the desired operating temperature range in order to increase the potential of the system. Moreover, high latent heat of transition per unit volume near the temperature of use is also desired in order to provide significant latent heat storage with small volumes and therefore, obtaining lower operation costs due to the optimization of the storage container. The last thermal requirement regarding the use of the latent phase is the utilization of a TES material with congruent melting in order to ensure that it completely changes of phase and therefore, both solid and liquid phases remain homogeneous. These three parameters can be evaluated with commercial devices.

On the contrary, most of TES materials employed for high temperature purposes are used in their sensible phases. Hence, laboratory analyses should be performed in order to determine the proper thermal properties and optimize them within the desired operation temperature range. The first requirement is that the TES material should have high thermal conductivity at both solid and liquid states. This requirement, which has received a high interest from the researchers, is fully reviewed and developed in the second part of this review [34]. The second requirement is that the TES material should have high specific heat to provide significant sensible heat storage. Normally, TES materials used for high temperature purposes have low specific heat. The most widely used technique to enhance this property is the dispersion of nanoparticles within the TES material. As mentioned in the second part of this review [34], the material composed by nanoparticles dispersed within a base material (BM) is usually presented as nanofluid, when the BM is in the liquid state, or nanocomposite, when the BM is in the solid

state. Both nanofluids and nanocomposites can be obtained from two different synthesis methods [75] (Fig. 2): the two-step solution method (TSSM) or liquid solution method [76] and the stirring method (SM) [77].

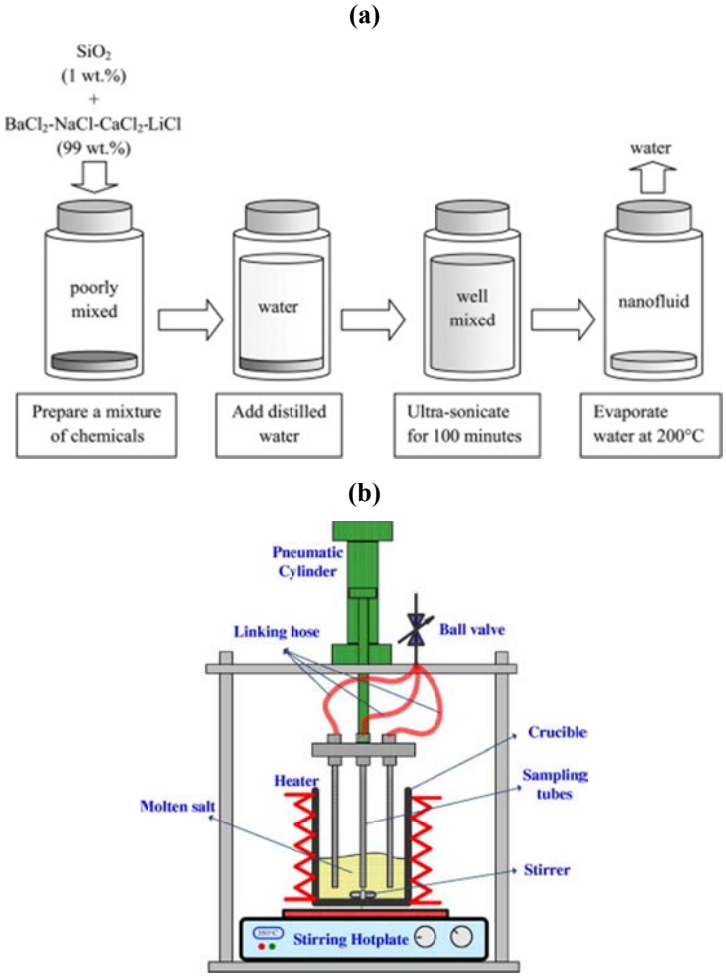

Fig. 2. Obtainment of nanomaterials at high temperature: (a) Schematic diagram of preparation of the two step solution method [76]. (b) Schematic diagram of preparation of the stirring dispersion method [77].

Despite the fact that this enhancement technique for high temperature purposes is still in the early stages of research, several studies have been carried out since 2011. Controversial results were found on these studies. It has been observed that while in the water-based and organic-based nanomaterials an increase on the specific heat was not achieved if compared to the pure material (following the traditional thermal equilibrium model) [78], in the molten salt-based nanomaterials an increase of the specific heat was observed. Shin and Banerjee [76] proposed three mechanisms to help to understand these anomalous enhancements: low vibration frequency, interfacial interaction and higher mean free path (Fig. 3). Shin and Banerjee [79] went a step further and detailed why the molten salts nanofluids do not follow the conventional effective specific heat model based on thermal equilibrium, but followed a more complex one.

The reason lied on the fact that the molten salts mixtures are formed by different ionic compounds, which have different electrostatic interaction with the nanoparticles. Therefore, when the nanoparticles are dispersed into the molten salts mixture, the different compounds are separated near nanoparticles, due to the above-mentioned difference in the electrostatic interaction and crystallize forming a fractal-like nanostructure (Fig. 4).

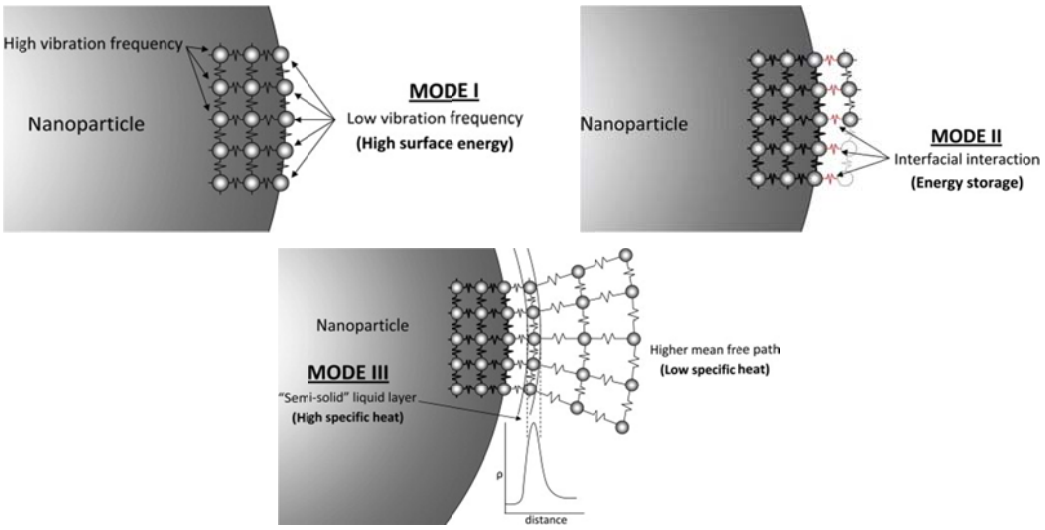

Fig. 3. Three transport mechanisms proposed to understand the anomalous enhancement with nanomaterials [76].

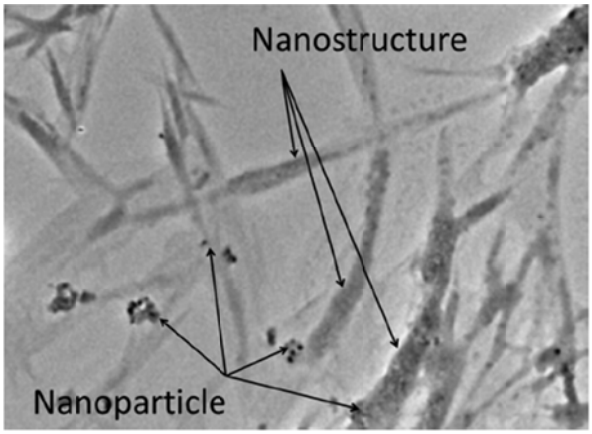

Fig. 4. Microscope view of nanoparticles and fractal-like nanostructures [79].

Practically all the different studies carried out DSC analysis to evaluate the specific heat of the nanomaterial and it is being proved that the results obtained from such analysis need to be carefully treated [80]. Table 5 reviews, in a chronological order, the different studies carried out concerning the specific heat enhancement technique of dispersing nanoparticles with TES materials at high temperature, by showing the TES material acting as BM, the nanoparticles materials, the dimension and concentration of nanoparticles, the method of synthesis, the improvement obtained and the measurement instrument.

Regarding these experimental studies, the two TES material which have been selected the most as base materials to test the specific heat enhancement because of the dispersion of nanoparticles heat have been the eutectic mixtures of sodium nitrates and potassium nitrates, and the eutectic mixtures of lithium carbonates and potassium carbonates. The different authors have studied the influence of the concentration of nanoparticles (from 0.5 to 4.6 wt %) [75,77,81,82,84-87,89], of the influence of the nanoparticles material (mica, SiO_2, Al_2O_3, TiO_2, SiO_2-Al_2O, carbon nanotubes, graphene and fullerene C60 (Fig. 5)) [82,86,87], and of the influence of the particle size (5, 10, 30 and 60 nm) [83,84,88]. The lack of standards for the preparation, the measurement and the evaluation of the results, as well as the lack of knowledge of the behaviour of the composite at nano-scale, generates an elevated uncertainty which currently makes very difficult the exercise of obtaining proper conclusions. However, Table 5 shows that the highest specific heat enhancement was achieved with a nanoparticle concentration of 1 wt.%. Regarding the particle size, there is no significant variation in the specific heat enhancement. Therefore, the fact of having the nanoparticles well-dispersed within the BM rather than agglomerated might be one of the parameters responsible of such enhancement. Ho and Pan [77] obtained the minimum concentration value at which nanoparticles starts to aggregate and it turned to be 0.016 wt.%. Therefore, a standardization of the preparation and evaluation of both the nanomaterial and the results, as well as, studies with samples containing masses higher than the studied at laboratory scale, should be considered.

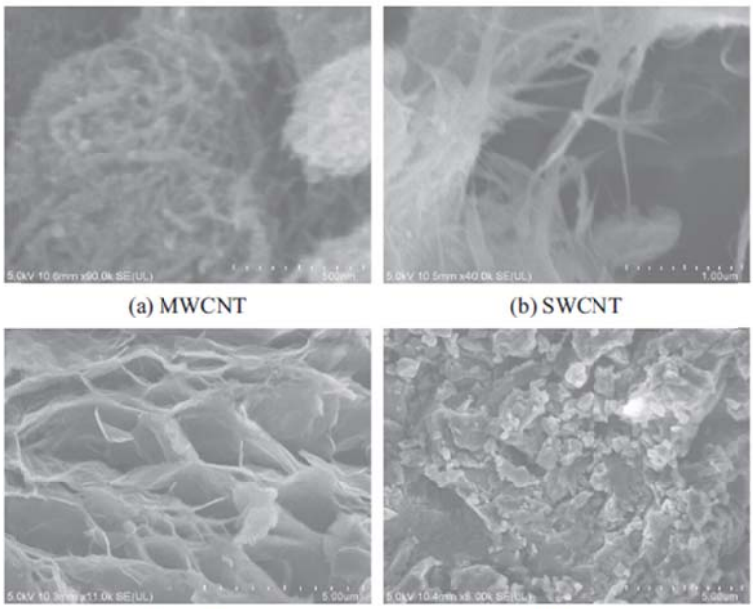

Fig. 5. Carbon nanostructures obtained by SEM analysis [87].

Table 5. Review of the studies concerning the combination of nanoparticles with TES material at high temperature in terms of specific heat enhancement.

Study case		Nanoparticle (nominal size)	Nanoparticles concentration (wt. %)	TES material (wt %)	Synthesis method	Comparison	Improvement and measurement instrument	Year	Reference
1	Experimental	Al_2O_3 (50 nm)	0.5/1.0/2.5	$[C_4mmim][NTf_2]$	n.a.	Concentration of nanoparticles	Up to 30.4 % (2.5 wt. %)	2011	Bridges et al. [90]
2	Experimental	Mica (45 µm)	0.5/1.0/2.0	$KNO_3 + NaNO_3$ (60 + 40 %)	TSSM	Concentration of nanoparticles	Up to 15 % (1.0 wt. %, solid state). Up to 19 % (1.0 wt. %, liquid state) By: MDSC (Q20, TA Instruments)	2011	Jung and Banerjee [81]
3	Experimental	SiO_2 (20-30 nm)	1.0	$BaCl_2 + CaCl_2 + LiCl + NaCl$ (15.9 + 34.5 + 29.1 + 20.5 %)	TSSM	Nanomaterial vs pure material	Up to 14.5 % By: MDSC (Q20, TA Instruments)	2011	Shin and Banerjee [76]
4	Experimental	TiO_2 (20-30 nm)	1.0	$Li_2CO_3 + K_2CO_3$ (62 + 38 %)	TSSM	Nanomaterial vs pure material	Up to 23 % By: MDSC (Q20, TA Instruments)	2011	Shin and Banerjee [91]
5	Experimental	SiO_2 (7 nm) Al_2O_3 (13 nm) TiO_2 (20 nm) SiO_2-Al_2O_3 (2-	0.5/1.0/1.5	$NaNO_3 + KNO_3$ (60 + 40 %)	TSSM	Nanoparticle and concentration of nanoparticles	*SiO_2:* Up to 14.9 % (1.0 wt. %, solid state). Up to 0.8 % (1.0 wt. %, liquid state)	2013	Chieruzzi et al. [82]

		200 nm)					*Al_2O_3:* Up to 19.9 % (1.0 wt %, solid state). Up to 5.9 % (1.0 wt. %, liquid state) *TiO_2*: No enhancement observed *SiO_2-Al_2O_3:* Up to 57.7 % (1.0 wt. %, solid state). Up to 22.5 % (1.0 wt. %, liquid state) By: Mettler-Toledo DSC 822E/400		
6	Experimental	SiO_2 (5/10/30/60 nm)	1.0	$NaNO_3$ + KNO_3 (60 + 40 %)	TSSM	Size of nanoparticles	Up to 10 % (1.0 wt. %, 60nm, solid state). Up to 28 % (1.0 wt. %, 60nm, liquid state) By: MDSC (Q20, TA Instruments)	2013	Dudda and Shin [83]
7	Experimental	Al_2O_3 (13/90 nm)	0.9/2.7/4.6	$NaNO_3$ + KNO_3 (60 + 40 %)	TSSM	Concentration of nanoparticles and particle size	No enhancement observed By: MDSC (Q20, TA Instruments)	2013	Lu and Huang [84]
8	Experimental	SiO_2 (2-20 nm)	1.5	Li_2CO_3 + K_2CO_3 (62 + 38 %)	TSSM	Nanomaterial vs pure material	Up to 54 % (solid state). Up to 124 % (liquid state)	2013	Shin and Banerjee

							By: MDSC (Q20, TA Instruments)		[92]
9	Experimental	SiO_2 (5/10/30/60 nm)	1.0	$Li_2CO_3 + K_2CO_3$ (62 + 38 %)	TSSM	Size of nanoparticles	Up to 28 % (60 nm, solid state). Up to 26 % (60nm, liquid state) By: MDSC (Q20, TA Instruments)	2013	Tiznobaik and Shin [93]
10	Experimental	SiO_2 (12 nm)	0.5/1.0/1.5/2.0	$NaNO_3 + KNO_3$ (60 + 40 %)	TSSM	Concentration of nanoparticles	Up to 25 % (1.0 wt. %). By: Mettler-Toledo DSC 822E/400	2014	Andreu-Cabedo [75]
11	Experimental	Al_2O_3 (<50 nm)	0.016/0.063/0.125/0.25/0.5/1.0/2.0	$KNO_3 + NaNO_2 + NaNO_3$ (53+ 40 + 7 %)	SM	Concentration of nanoparticles	Up to 19.9 % (0.063 wt. %) By: Perkin Elmer/DSC 7	2014	Ho and Pan [77]
12	Experimental	Sn/SiO_2 (100 nm)	1.0/3.0/5.0	$KNO_3 + NaNO_3$ (40 + 60 %) $KNO_3 + NaNO_2 + NaNO_3$ (53 + 40 + 7 %)	n.a.	Concentration of nanoparticles	KNO_3+$NaNO_2$: Up to 36.3 % (5.0 wt. %). KNO_3+$NaNO_2$+$NaNO_3$: Up to 30.1 % (5.0 wt. %). By: Mettler-Toledo DSC 822E/400	2014	Lai et al. [89]
13	Experimental	SiO_2 (60 nm)	1.0	$LiNO_3 + NaNO_3 + KNO_3$ (38 + 15 + 47 %)	TSSM	Nanomaterial vs pure material	Up to 33 % By: MDSC (Q20, TA Instruments)	2014	Seo and Shin [94]
14	Experimental	Al_2O_3	1.0	$Li_2CO_3 + K_2CO_3$	TSSM	Nanomaterial vs	Up to 33 %	2014	Shin and

		(60 nm)		(62 + 38 %)		pure material	By: MDSC (Q20, TA Instruments)		Banerjee [95]
15	Experimental	MWCNT (10-30 nm x 1.5µm)	1.0	$Li_2CO_3 + K_2CO_3$ (62 + 38 %)	TSSM	Nanomaterial vs pure material	Up to 16 % (solid state). Up to 21 % (liquid state) By: MDSC (Q20, TA Instruments)	2014	Jo and Banerjee [96]
16	Experimental	SiO_2	1.0	$Li_2CO_3 + K_2CO_3$ (62 + 38 %)	TSSM	Nanomaterial vs pure material	Up to 15 % (solid state) By: MDSC (Q20, TA Instruments)	2015	Shin and Banerjee [97]
17	Experimental	Al_2O_3 (40 nm)	0.125/0.25/0.5/0.75/1.0/1.5/2.0	$NaNO_3 + KNO_3$ (60 + 40 %)	TSSM	Concentration of nanoparticles	Up to 30.6 % (0.78 wt. %) By: MDSC (Q20, TA Instruments)	2015	Schuller et al. [85]
18	Experimental	SWCNT (5-20 nm x 1-5 µm) MWCNT (10-50 nm x 0.5-1 µm) Graphene (10-20 nm x 1-5 µm) Fullerene C_{60} (0.5-2 µm)	0.1/0.5/1.0/1.5/2.5	$Li_2CO_3 + K_2CO_3$ (62 + 38 mol %)	TSSM	Nanoparticle and concentration of nanoparticles	*SWCNT:* Up to 18.7 % (1.5 wt. %, solid state). Up to 14.4 % (1.5 wt%, liquid state) *MWCNT:* Up to 12.4 % (1.5 wt. %, solid state). Up to 14.52 % (1.5 wt. %, liquid state) *Graphene*: Up to 16.8 % (1.5 wt. %, solid state). Up to 18.57 % (1.5 wt. %, liquid state)	2015	Tao et al. [87]

							C_{60}: Up to 13.47 % (2.5 wt. %, solid state). Up to 12.05 % (2.5 wt. %, liquid state) By: n.a.		
19	Experimental	SiO_2 (7 nm) Al_2O_3 (13 nm) SiO_2-Al_2O_3 (2-200 nm)	1.0	KNO_3	TSSM	Nanoparticle	*SiO_2:* Up to 9.5 % (solid state). Up to 6.1 % (liquid state) *Al_2O_3:* No enhancement observed *SiO_2-Al_2O_3:* Up to 4.7 % (solid state). No enhancement observed in the liquid state By: Mettler-Toledo DSC 822E/400	2015	Chieruzzi et al. [86]
20	Experimental	SiO_2 (5/10/30/60 nm)	1.0	$LiNO_3$ + $NaNO_3$ + KNO_3 (38 + 15 + 47 %)	TSSM	Size of nanoparticles	Up to 16 % (10 and 30 nm) By: MDSC (Q20, TA Instruments)	2016	Seo and Shin [88]
21	Experimental	SiO_2 (30 nm)	1.0	$NaNO_3$ + KNO_3 + $Ca(NO_3)_2$ (49 + 30 + 21 %)	TSSM	Nanomaterial vs pure material	Up to 19 % By: MDSC (Q20, TA Instruments)	2016	Devaradjane and Shin [98]

MDSC: Modulated differential scanning calorimeter / *SWCNT*: Single walled carbon nanotubes / *MWCNT*: Multi-walled carbon nanotubes /*TSSM*: Two-step solution method / *SM*: Stirring method

3. System requirements

3.1 Addressing economic requirements

A common problem in the current research field is that TES is mainly focused on the analysis of the intrinsic properties of the materials and its enhancement techniques and the system requirements (Economy, technology and environment) are sometimes ignored. The economic feasibility of a TES system is assessed taking into account parameters like abundance and availability of the TES material, large lifetime of the components and cost effectiveness.

Most of the economic analyses are focused on CSP facilities as they are one of the most developed technologies at the high temperature range. More than 80% of CSP plants which are already built or under construction are based on the parabolic trough technology [106]. Hence, practically all the information regarding economic aspects refers to this technology. CSP facilities costs are mainly divided in three categories: capital investment costs (CAPEX), operation and maintenance costs (OPEX) and financing costs [107]. It is very difficult to obtain feasible and real values, since very few information is currently available because of confidentiality. Table 6 shows the breakdown of the CAPEX costs of two proposed 100 MW CSP plants in South Africa. The first one corresponds to a parabolic through CSP plant with 13.4 h of storage and estimated total CAPEX costs of 914 million USD, while the second one corresponds to a solar tower CSP plant with 15 h of TES and estimated total CAPEX costs of 978 million USD. In both cases the most economic-intensive part is the solar and heliostat field, representing one third of the total investment. From this cost, the elements made of steel and the mirrors are the largest contributors. On the other hand, the TES system represents 10-15 % of the total cost, being the TES material and the storage tanks the largest contributors. OPEX costs include the replacement costs of the damaged and broken elements of the plant, the water costs for mirror washing, and insurance among others, and have values between 0.020 and 0.036 USD/kWh for parabolic trough CSP plants, and around 65 USD/kW/year for solar tower CSP plants [106]. Finally, the authors of the study reviewed potential CSP cost reduction potentials and identified the following potential innovations: new HTFs, new storage materials, new mirror material and new collector concepts.

Table 6. Breakdown of the CAPEX of two proposed 100 MW CSP plants in South Africa [107].

Section	**CAPEX breakdown**	
	Parabolic trough CSP	**Solar tower CSP**
Solar field / Heliostat field	35 %	33 %

Site preparation	n.a.	4 %
Tower	n.a.	2 %
Receiver system	n.a.	15 %
Owner's costs	5 %	5 %
Contingencies	8 %	8 %
Engineering	7 %	6 %
Balance of plant	6 %	6 %
Power block	17 %	11 %
TES system	15 %	10 %
HTF system	7 %	-

Wagner and Rubin [109] combined the cost with the performance and the profit of a 110-MW parabolic trough CSP plant operating with a TES system, with and without natural gas-fired backup system. The use of TES was found to increase the annual capacity factor and the total plant capital costs but decreased the annual operation and maintenance costs. Nithyanandam and Pitchumani [110] studied, in terms of cost and performance, two different TES systems types (encapsulated PCM and embedded heat pipes) integrated in tower CSP plants, and compared them with the results of a two-tank molten salt storage system. Results showed that the costs of integrating the two-tank molten salt storage system is at least 1.12 ¢€/kWh and 0.71 ¢€/kWh higher compared to encapsulated PCM and embedded heat pipes systems, respectively.

Regarding to other types of TES systems, Rathgeber et al. [111] evaluated the storage capacity costs (€·kWh^{-1}) of different TES systems from the participants institutions at Energy conservation through energy storage (ECES) Annex 29 via top-down and bottom-up approaches. Some of the systems presented work at high temperature. Results showed that the annual number of storage cycles has the largest influence on the cost effectiveness.

3.2 Addressing environmental requirements

As environmental awareness increases, industries and businesses are assessing how their activities affect to the environment. Table 2 lists the environmental requirements for a whole TES system (TES material, container, piping system, insulation, etc.). These requirements aim to reduce the environmental impact of the TES systems and to accomplish sustainable regulations and trends. Therefore it is desirable to have a low manufacturing energy demand, to demand an easy recycling and treatment, and to use non-polluting and low CO_2 footprint materials. These requirements can be assessed by performing environmental analyses and/or using by-products or industrial wastes as alternative TES materials.

Regarding the environmental analysis, three main tools have been found focused on identifying the environmental affection of those systems: the carbon or CO_2 footprint, the life cycle assessment (LCA), and the cumulative energy demand (CED). The CO_2 footprint measures the greenhouse gases (GHG) emissions over the whole life of a product from the extraction of raw materials and manufacturing right through to its use and final re-use, recycling or disposal [112]. It considers direct emissions, which are emissions from sources that are owned or controlled by the reporting entity, and indirect emissions, which are emissions that are a consequence of the activities of the reporting entity, but occur at sources owned or controlled by another entity. In fact, the CO_2 footprint is a simplification of the LCA analysis, and instead of considering all the impact categories a LCA (Table 7), it only considers the global warming impact category. LCA analyses the impact of a product from the extraction, through manufacturing, transportation and use, to its disposal. LCA divides the environmental burdens analysis into three different damage categories: human health, ecosystem quality and resources. Finally, the CED considers direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials [113].

Table 7. Main impact categories of LCA classified by scale impact and their quantification, based on [114].

	Impact category	**Quantification**
Global impact	Global warming	CO_2-Eq
	Resource depletion	$\frac{\text{Quantity resource used}}{\text{Quantity left in reserve}}$
	Ozone depletion	CFC-11 equivalents
Regional impact	Smog	Ethane equivalents
	Acidification	Hydrogen ion equivalents
Local impact	Eutrophication	PO_4 equivalents
	Human toxicity	LC50 equivalents
	Ecotoxicity	LC50 equivalents
	Land use	Mass of solid waste
	Water use	$\frac{\text{Quantity water used}}{\text{Quantity left in reserve}}$

The environmental analyses found in the literature are classified in this review depending on the boundaries of the study. First, only the TES material. Afterwards, the TES system (it includes

the HTF, the container material and the insulation). Finally, the whole facility (it includes the TES system and the heating and cooling systems).

Considering only the TES material, Khare et al. [115] identified some sensible heat storage materials to work from 500 ºC on and calculated their environmental affection during the different life cycle stages. Among all the materials studied, they observed that high alumina concrete was the less energy requiring material and with the lower values of CO_2 production as a consequence of little material processing and local transport. López-Sabirón et al. [116] performed an LCA to determine whether the energy savings of conventional fuels during the operation stage were large enough to balance the environmental impact of four different latent TES system (used to recover thermal energy in a temperature range from 300 ºC to 400 ºC) from its manufacture to its disposal. Results showed a reduction in the overall impacts by the use of TES. Besides, they also calculated the carbon footprint of the main integrating components of these TES system. They observed that the HTF is the lowest contributor while the steel and the PCM are the highest contributors. In another study, López-Sabirón et al. [117] evaluated a TES system with PCM including the manufacture, use and end-of-life stages. They observed that changing the materials in the manufacture of the TES, raising the material recovery ratios, and selecting the proper HTF, can increase the positive impact of the end-of-life stage.

Regarding both the material and system, Oró et al. [118] compared the LCA of three different TES systems for solar power plants: sensible heat storage (concrete and molten salts) both in solid and liquid thermal storage media and latent heat storage (molten salts). They concluded that the system containing sensible liquid thermal storage media was the one with higher environmental impact. The same systems were analysed by Miró et al. [119], who besides accounted their CED. In this case, results showed that the latent system was the one accounting for more embodied energy. Recently, Lalau et al. [120] compared the environmental impacts of a thermocline TES system using Cofalit as the filler material to a conventional two-tank molten salt TES system. The authors used the global warming potential (GWP), CED and water indicators to calculate the Cofalit manufacturing impact. They identified a reduction in comparison with the two-tank molten salt storage of 40 % for the GWP, 30 % for the CED and 60 % for water. Moreover, the advantages of using Cofalit are its availability and its high working temperature (up to 1000 ºC).

Finally, from the point of view of the whole facility, Klein [121] analysed the water consumption, land use, and life cycle GHG emissions of different backup cooling options (wet and dry cooling combined with fossil fuels or molten salts TES) by applying a multi-criteria

decision analysis to a 1 MWh parabolic trough CSP plant. In this study, the authors suggested a preference for the TES backup. In another study, Klein and Rubin [122], applied an LCA analysis to the same CSP plant than Klein [121] and considered also different backup systems. They concluded that facilities with TES have less GHG emissions than plants using natural gas as backup system but higher land use. Lechón et al. [123] performed an LCA analysis of two solar thermal plants located in Spain using molten salts as TES material: one with the solar tower technology (17 MW) and the other with the parabolic trough technology (50 MW). They accounted for 634 kt of CO_2 savings if thermal power objectives for Spain were accomplished. Giuliano et al. [124] accounted and compared the CO_2 emissions of five 30 MW solar-hybrid plants (with and without molten salts as storage system) to a conventional fossil-fired driven plant. Results showed that larger solar fields and the integration of TES reduced the CO_2 emissions up to 68% if compared to the fossil-fired combined cycle. Whitaker et al. [125] analysed the GHG emissions, water consumption and CED of a 106 MW solar tower CSP plant. They compared the origin of the TES material (mined or synthetic) and the configuration of the storage system (two-tank or thermocline). They concluded that the use of synthetic salts increased the cumulative energy demand and the switching from two-tank to thermocline configuration was insignificant regarding all the environmental parameters. The same environmental analysis was used by Burkhardt et al. [126] in a parabolic trough CSP plant (103 MW). In this case, the same conclusion than Burkhardt et al. [126] was achieved regarding the origin of the TES material. In addition, the authors found a 7 % of GHG emissions reduction when using thermocline instead of two-tank configuration.

Table 8 shows the different studies found in the literature concerning the environmental analysis at high temperature. It is classified according to the TES material and ordered chronologically. Besides, the type of environmental analysis performed and the software and database used are also listed. It can be seen that there is a lack of environmental analysis in systems containing TES materials, since only twelve cases have been found in the literature. Among them, molten salts are the most studied TES material in the high temperature range considered in this article (> 150 ºC). Other materials studied are sodium nitrate, high temperature concrete, ferrous metals, alumina, high alumina concrete, graphite, magnesia and silicon carbide. In order to perform the different environmental analyses, EcoInvent and SimaPro are the most used software. Regarding to the parameters analysed, LCA and CO_2 footprint are the ones which have been calculated more often. Generally, when TES is evaluated and compared to conventional systems from a material point of view, its benefits are not significant. However, when the comparison is done at system level and at higher scale, the benefits of introducing TES, such as a reduction of CO_2 emissions, and energy and water consumption, are more noticeable. On the contrary, the main disadvantage is the land use.

Table 8. Review of the studies concerning the environmental analysis at high temperature.

Study case	Boundary	TES material	Parameter analysed	Software / Database used	Results	Year	Reference
1	Facility	Molten salts	LCA	SIMAPRO	ST: 9.49 g CO_2-eq/kWh PT: 14.60 g CO_2-eq/kWh	2008	Lechón et al. [123]
2	Facility	Molten salts	CO_2 emissions reduction	n.a.	ST: 0.062-0.414 kg CO_2-eq/kWh PT: 0.098-0.482 kg CO_2-eq/kWh	2011	Giuliano et al. [124]
3	Facility	Molten salts	CO_2 footprint	SIMAPRO EcoInvent database	5.01-5.21 g CO_2 eq/kWh	2011	Burkhardt et al. [126]
			Water consumption		0.19 L/kWh		
			CED		0.07 MJ/kWh		
4	Material and system	Molten salts (sensible)	LCA	Eco-Indicator 99	3376 IP	2012	Oró et al. [118]
		Molten salts (latent)			1270 IP		
		High temperature concrete			279 IP		
5	Material	Magnesium Aluminium Zinc Al+Si (88+12 wt %) Al+Mg+Zn (60+34+6 wt %)	Energy consumption CO_2 footprint	CES EcoAudit™	Energy and CO_2 production for the alloy 88Al–12Si being the lowest, followed by aluminium	2013	Khare et al. [115]
6	Facility	Molten salts	Water consumption	SIMAPRO	0.73-5 L/kWh	2013	Klein [121]
			Land use		240-286 m^2/GWh		
			CO_2 footprint		49-73 g CO_2-eq/kWh		

7	Facility	Molten salts	Water consumption	n.a.	2.3-2.4 L/kWh	2013	Klein and Rubin [122]
			Land use		n.a.		
			CO_2 footprint		0.33-0.34 kg CO_2-eq/kWh		
8	Facility	Mined and synthetically derived molten salts	CO_2 footprint	SIMAPRO EcoInvent database	The use of synthetic salts increase CO_2 footprint 12%, CED by 7%, and water consumption by 4% compared to mined salts	2013	Whitaker et al. [125]
			Water consumption				
			CED				
9	Material	KNO_3 NaOH K_2CO_3 +Na_2CO_3+Li_2CO_3 (35+33+32 wt %) LiOH+KOH (40+60 wt %)	CO_2 footprint	EcoInvent database Simapro	LiOH/KOH benefits -8 to -18 ton CO_2 eq in comparison with other cases	2014	López-Sabirón et al. [116]
10	Material	Sodium nitrate	LCA	SIMAPRO CML 2001 Eco-Indicator 99	n.a.	2014	López-Sabirón et al. [117]
11	Material and system	Molten salts (sensible)	CED	EcoInvent database	125 TJ	2015	Miró et al. [119]
		Molten salts (latent)			257 TJ		
		High temperature concrete			17 TJ		
12	Material and system	Cofalit	GWP	CML 2001	2.4 kg CO_2-eq/kWh	2016	Lalau et al. [120]
			CED		0.046 MJ/kWh		
			Water consumption		0.058 L/kWh		

LCA: Life cycle assessment / *CED:* Cumulative energy demand / *GWP:* Global warming potential / *ST:* Solar tower / *PT:* Parabolic trough / *CO_2-eq:* Equivalent CO_2 emissions / *IP:* Impact points

Regarding the use of by-products and industrial wastes to reduce environmental impact of TES systems, researchers have proposed the use of waste materials and by-products from different industries as TES materials in order to reduce the environmental impact of the facilities which contains a TES system [127]. The use of these materials reduces significantly the environmental impact if compared to other manufactured products as they avoid both extraction of raw materials and manufacturing life cycle stages. Moreover, if these materials do not need any further treatment, they are considerably cheaper. Some examples of by-products and waste materials candidates for high temperature TES purposes are: Intertized asbestos containing wastes (ACW), fly ashes (FA), by-products from the salt and metal industry and municipal wastes.

Several authors [128-131] studied the recycled industrial ceramics made of ACW. Results showed that this material presented no hazard, no environmental impact, good thermophysical properties and very low investment cost. Meffre et al. [132] studied and characterized FA as TES material. FA are micron-size particles present in gaseous effluents produced by industrial combustions in facilities such as coal fired power plants or municipal solid wastes incinerators. They are mainly composed of SiO_2, Al_2O_3 and CaO and its waste treatment is also generally performed by plasma torch processing [133]. Results from the characterization showed good thermophysical properties for sensible TES storage and an energy payback of the plasma torch waste treatment of 7.4 months for CSP applications. By-products from the salt industry were studied by Miró et al. [134] and Ushak et al. [135]. The authors performed thermophysical and morphological characterisation at laboratory scale, and evaluated their performance at pilot plant scale. It was found that this by-product had high potential for commercial TES up to a temperature of 200 ºC but corrosion should be previously solved. The steel industry produces different types of by-products (referred as slags) depending on the furnace technology used. Thermo-physical properties of ferrous slag [139-142] indicate very appropriate values for the use of this material in sensible thermal energy storage up to temperatures of 1200 ºC. Finally, some authors proposed mixtures of wastes and TES materials. For example, Ozger et al. [137] proposed nylon fibres from post-consumer textile carpet waste for fibre-reinforced concrete as candidate for high temperature sensible heat storage up to 450 ºC, and Navarro et al. [138] proposed by-products from the copper industry to be mixed with cement.

Table 9 lists the by-products which have been currently studied by different researchers and the temperature at which they have been tested. However, researchers do not only focus on by-products because of their environmental advantages but also focus on these products from the economical point of view, since they are usually cheaper than current TES materials.

Table 9. Summary of the studies concerning the environmental requirements at high temperature in terms of potential by-products and waste materials candidates for TES purposes.

Study Case	By-product	Temperature range analysed	Year	Reference
1	Asbestos containing wastes (ACW)	Up to 1000 ºC	2000-2014	Py et al. [128] Kere et al. [129] Gualtieri and Tartaglia [130] Calvet et al. [131]
2	Fly ashes (FA)	Up to 1100 ºC	2011-2012	Meffre et al. [132]
3	NaCl from salt industry	100-200 ºC	2014	Miró et al. [134]
4	Astrakanite from salt industry	570-680 ºC	2014	Ushak et al. [135]
5	Ferrous slag from metal industry	Up to 1200 ºC	2011-2014	Gil et al. [139] Ortega et al. [140,141] Mills [142]

3.3 Addressing technological requirements

Technological requirements, which include the integration of the TES material into the facility, the operation strategy of the facilities, and the good transfer between the HTF and the TES material, are not usually considered in the literature, even though these requirements are known to have an incidence in the design and the economics of the system. The integration of the TES material into the facility can help TES systems to be considered as substitutes of conventional fossil-fuel technologies. A good operation strategy can considerably enhance the overall TES system heat transfer efficiency, which is closely linked to the requirement of good heat transfer between the HTF and the TES material. Finally, the most important operation strategies containing TES at high temperature are the multiple PCMs configuration and the forced movement of the TES material while undergoing phase change.

Multiple PCMs configuration, also referred as cascaded or multistage configuration, is a TES system configuration where different PCMs (with different melting temperatures and enthalpies) are arranged in series. This configuration aims to increase low storage capacities in the single PCM due to the poor PCM thermal conductivities. As it can be observed in Fig. 6, the optimum arrangement for a multiple PCM system is obtained by placing the PCMs in a decreasing order of their melting temperatures (Tm) and in an increasing order of their heat storage capacities (h) in the HTF flow direction during the charging process, and the other way around during the discharging process [143]. The advantages of this arrangement are the

increase of the heat transfer rate during charging and discharging, especially in the latent part, the uniform and higher outlet HTF temperature for a longer period during charging and discharging process, the faster charging and discharging process, the increase of exergy efficiency and the increase of average effectiveness.

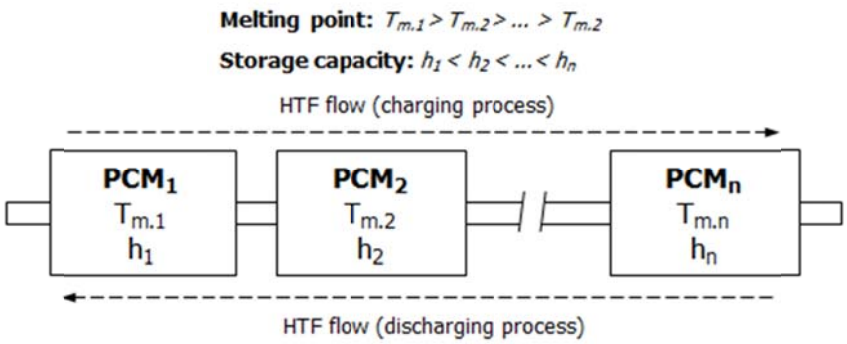

Fig. 6. Optimum arrangement of a multiple PCM system [143].

Hence, in order to achieve the greatest performance improvement, researchers need to study the thermophysical properties of the candidate PCMs with the aim of not selecting them arbitrarily but select the suitable combination and with the proper dimensions for the desired application. Tao et al. [144] performed an optimization of the PCM temperatures for a two-stage PCM storage unit using the entransy theory and Li et al. [145] optimized the geometrical parameters of their proposed storage unit.

In the literature, few multiple PCMs configuration within the high temperature range are found. Gong and Mujumdar [146] used five PCM in the range 667 – 867 ºC, Cui et al. [147] three PCM in the range 717 – 779 ºC, Michels and Pitz-Paal [148] used three PCM in the range 306 – 335 ºC, Seeniraj and Lakshmi Narasimhan [149] used five PCM in the range 873 – 767 ºC, Shagbard et al. [150] used three PCM in the range 318 – 370 ºC, Li et al. [145] used three PCM in the range 397 – 710 ºC, Tao et al. [144] used two PCM in the range 746 – 767 ºC, Wang et al. [151] used three PCM in the range 390 – 485 ºC and finally Peiró et al. [143] used two PCM in the range 158.5 – 168.5 ºC. Most of them are numerical studies [144-147,149-151] and only two experimental cases have been found [143,148].

Table 10 summarizes the characteristics of the multiple PCM configuration analysis found in the literature and their improvement versus single PCM configuration.

Table 10. Review of the studies concerning the technological requirements at high temperature in terms of numerical and experimental analysis of cascaded PCM configurations.

Study case		Heat exchanger design	Number of PCM	TES materials (mol%) and order in which they are placed	Melting temperature	Improvement vs single configuration	Year	Reference
1	Numerical	Single pass shell and tube	5	1. n.a.	1. 867 ºC	More uniform HTF outlet temperature	1995	Gong and Mujumdar [146]
				2. n.a.	2. 817 ºC			
				3. $LiF + CaF_2$ (80.5 + 19.5 %)	3. 767 ºC			
				4. n.a.	4. 717 ºC			
				5. n.a.	5. 667 ºC			
2	Numerical	Single pass shell and tube	3	1. n.a.	1. 779 ºC	Reduction of the HTF outlet temperature variations Energy rate enhancement	2003	Cui et al. [147]
				2. $LiF + CaF_2$ (80.5 + 19.5 %)	2. 767 ºC			
				3. n.a.	3. 717 ºC			
3	Experimental	Single pass shell and tube	3	1. KNO_3	1. 335 ºC	Reduction of the HTF outlet temperature variations Energy rate enhancement	2007	Michels and Pitz-Paal [148]
				2. $KNO_3 + KCl$ (95.5 + 4.5 %)	2. 320 ºC			
				3. $NaNO_3$	3. 306 ºC			
4	Numerical	Single pass shell and tube	5	1. $LiF + CaF_2$ (80.5 + 19.5 %)	1. 767 ºC	Reduction of the HTF outlet temperature variations Energy rate enhancement	2008	Seeniraj et al. [149]
				2. Eutectic mixture $LiF-MgF_2$	2. 736 ºC			
				3. n.a.	3. 700 ºC			
				4. n.a.	4. 650 ºC			
				5. n.a.	5. 600 ºC			
5	Numerical	Rectangular container with HTF flow channels	3	1. NaOH + NaCl (73.3 + 26.7 %)	1. 370 ºC	Increase 10 % exergy recovery	2012	Shagbard et al. [150]
				2. $KCl + MnCl_2 + NaCl$ (22.9 + 60.6 + 16.5 %)	2. 350 ºC			

		located at the top and bottom		3. $NaOH + NaCl + Na_2CO_3$ (65.2 + 20 + 14.8 %)	3. 318 ºC			
6	Numerical	Single pass shell and tube	3	1. $K_2CO_3 + Na_2CO_3$ (51 + 49 %)	1. 710 ºC	No comparison with single configuration has been done in this study	2013	Li et al. [145]
				2. $Li_2CO_3 + NaCO_3 + K_2CO_3$ (20 + 60 + 20 %)	2. 550 ºC			
				3. $Li_2CO_3 + NaCO_3 + K_2CO_3$ (32 + 33 + 35 %)	3. 397 ºC			
7	Numerical	Single pass shell and tube	2	1. $LiF + CaF_2$ (80.5 + 19.5 %)	1. 767 ºC	Energy rate enhancement Reduction of the entransy dissipation rate	2014	Tao et al. [144]
				2. $LiF + MgF_2$ (67 + 33 %)	2. 746 ºC			
8	Experimental	Multiple pass shell and tube	2	1. Hidroquinone	1. 168.5 ºC	Higher uniformity on the outlet HTF temperature Effectiveness enhancement of 19.36 %	2015	Peiró et al. [143]
				2. D-mannitol	2. 158.5 ºC			
9	Numerical	Zig zag configuration	3	1. n.a.	1. 450, 460, 470, 480, 485 ºC	Intensification of the charging process	2015	Wang et al. [151]
				2. n.a.	2. 440 ºC			
				3. n.a.	3. 395, 400, 410, 420, 430 ºC			

Despite the fact that very little investigation has been carried out at high temperature, a novel heat transfer enhancement technique between the TES material and the HTF is included in this review, which is known as forced movement of the TES material while undergoing phase change. Three different concepts are currently dealing with this technique: dynamic melting [152,153], screw heat exchanger [154] and PCM flux [155] (Fig. 7). They mainly consist of moving the TES material during the phase change processes with an external force (transport mechanism or pump). As a consequence, there is a dominance of the forced convection heat transfer mechanism during the melting process, which increases the overall heat transfer coefficient and therefore, the heat transfer between the HTF and the TES material. During the solidification process, this technique continuously avoids the presence of a solid layer around the heat transfer surface by removing it, which decreases the thermal resistance of the material. Three main advantages can be identified in this enhancement technique: first, the heat transfer can be controlled by adjusting the HTF and PCM velocities; second, the phase segregation can be prevented because of the forced movement; third, the packing factor, which is the ratio between the volume of PCM and the volume of the TES container, is maintained constant.

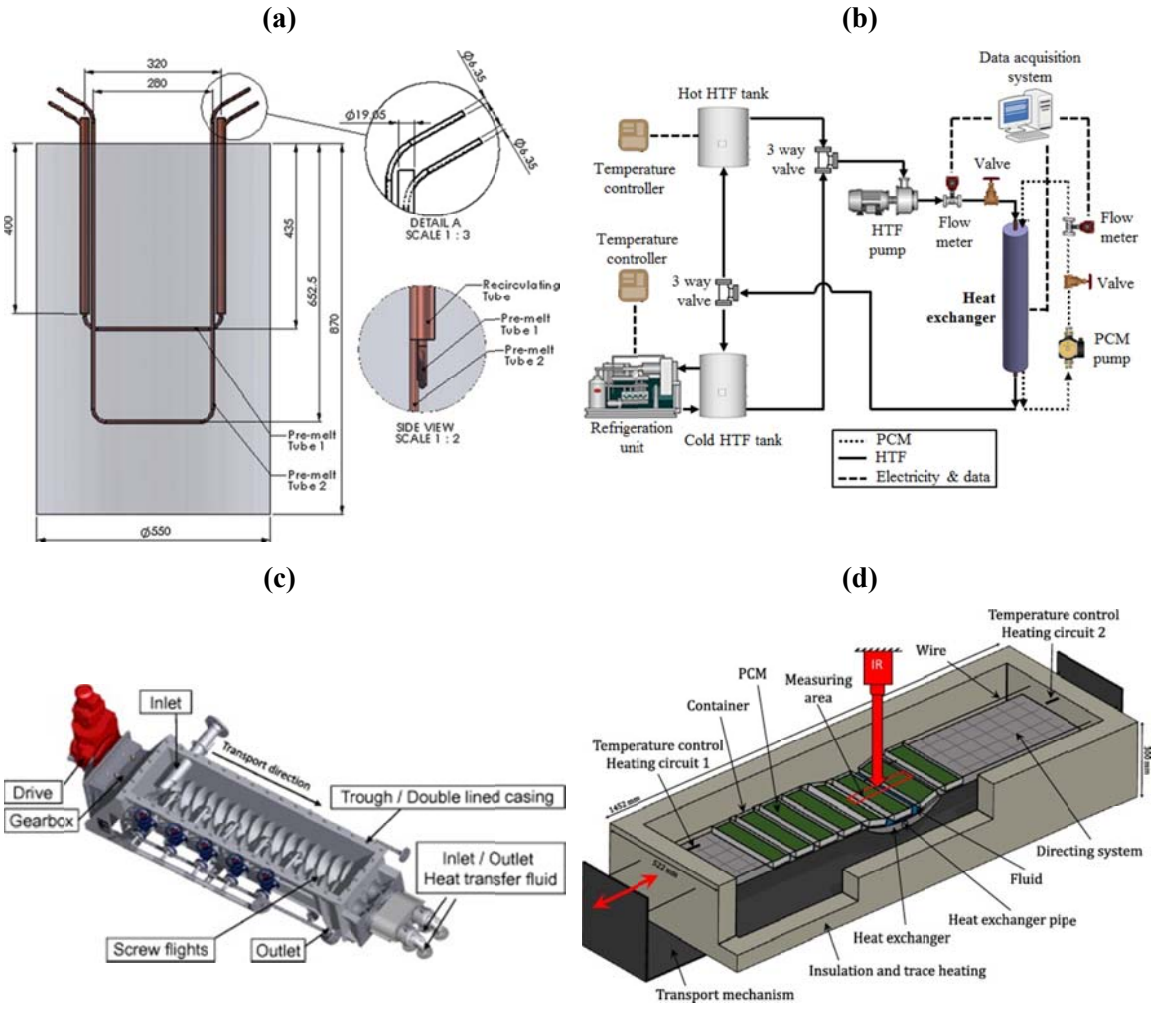

Fig. 7. Prototypes of the concepts dealing with the forced movement of the TES material while undergoing phase change: (a) and (b) Dynamic melting [152,153]; (c) screw heat exchanger [154]; (d) PCM flux [155]

Finally, a good heat transfer between the HTF and the TES material is desired in order to enhance both the charging and discharging processes. The most common and widely used HTF for high temperature purposes are listed with their maximum operation temperature and, when possible, with their reported price in Table 11.

Table 11. Cost and maximum operation temperature of the most commonly used HTFs.

Heat transfer fluid	**Max. operation temperature**	**Cost***	**Reference**
1. Liquids			
1.1. Molten salts			
Hitec XL	500 ºC	1.19-1.66 USD·kg^{-1}	[99]
Hitec	535-538 ºC	0.93-1.93 USD·kg^{-1}	[100,101]
Solar salt	585-593 ºC	0.49-1.30 USD·kg^{-1}	[100,101]
Other nitrate mixtures	565 ºC	≈ 1.1 USD·kg^{-1}	[99]
Other carbonate mixtures	850 ºC	≈ 1.3 USD·kg^{-1}	[99]
Other chloride mixtures	850 ºC	0.35-1.13 USD·kg^{-1}	[99]
Other fluoride mixtures	900 ºC	7-14 USD·kg^{-1}	[99]
Other oxide mixtures	1200 ºC	n.a	[100]
1.2. Thermal oils			
Commercial brands	280-400 ºC	2.83-105.4 USD·L^{-1}	
1.3. Liquid glasses			
Liquid glasses	450 ºC	n.a.	[101]
1.4. Liquid metals			
1.4.1. Alkali metals			

NaK (22.2 wt. % Na + 77.8 wt. % K)	785 ºC	2 USD·kg^{-1}	[102]
K	766 ºC	2 USD·kg^{-1}	[102]
Na	873-883 ºC	2 USD·kg^{-1}	[99-101]
Li	1342 ºC	60 USD·kg^{-1}	[102]
1.4.2. Heavy metals			
Lead-bismuth eutectic allow (LBE) (44.5 wt. % Pb + 55.5 wt. % Bi)	1533-1670 ºC	13 USD·kg^{-1}	[99,101,102]
Pb	1743 ºC	2 USD·kg^{-1}	[102]
Bi	1670 ºC	22 USD·kg^{-1}	[102]
1.4.3. Fusible metals			
Ga	2237 ºC	600 USD·kg^{-1}	[102]
In	2072 ºC	500 USD·kg^{-1}	[102]
Sn	2687 ºC	25 USD·kg^{-1}	[102]
2. Supercritical fluids			
Supercritical H_2O	620 ºC	n.a.	[101]
Supercritical C_2O	850 ºC	n.a.	[101]
3. Gases			
Superheated steam	600 ºC	0	[101]
Compressed air	800 °C	0	[100]

*Commercial cost at May 2015 without shipping fees

Two research groups studied how to improve the thermal conductivity of commercial HTF in order to increase the heat transfer rates between HTFs and TES materials. Cingarapu et al. [103] dispersed 5 vol.% of core/shell silica encapsulated tin (Sn/SiO_2) nanoparticles in Therminol66, obtaining an enhancement of 11 %. Torres-Mendieta et al. [104] dispersed spherical gold nanoparticles in Therminol VP-1 and obtained an enhancement of 4 %. Other authors have also proposed the lead-bismuth eutectic alloy PbBi and molten tin [102], and dense particle suspension (DPS) fluidized with air [105] for candidates as HTF.

4. Conclusions

In the part 1 of this article, the requirements that TES materials and TES system should accomplish for an optimal performance and a widespread deployment are reviewed. High temperature is considered above 150 ºC and only latent and sensible TES are studied. These

requirements are divided depending if they are focused on the TES material or on both the TES material and system. Requirements focused on the TES material are grouped into chemical, physical and thermal while the requirements focused on the TES material and systems are grouped into environmental, economic and technologic. Part 2 of this article presents a review of the numerical and experimental studies focused on the different thermal conductivity enhancement techniques in the high temperature range.

The most studied topics regarding the different requirements reviewed are:

- **Materials requirements**

  The full characterization of the TES material is very important to assess its suitability for a TES application.

  - *Chemical*

    This is the most studied requirement regarding the TES material. Long-term stability, compatibility between TES materials and their surrounding components (especially for solar salts and metals used in solar power plants), phase segregation and handling and safe use of the materials are assessed in the literature.

  - *Kinetic*

    Few studies have been found regarding the identification of the subcooling effect dealing with galacticol, hydroquinone and d-mannitol.

  - *Physical*

    Thermal expansion coefficient is found to be basic for design purposes. Therefore, the TES material quantity inside the TES container and/or shell capsule should be carefully calculated to guarantee the internal pressure and avoid leakages.

  - *Thermal*

    The main thermal requirement is the enhancement of the thermal conductivity, which is widely reviewed in Part 2 of this review. Regarding the rest of requirements, increasing the specific heat by including nanoparticles is the most attractive research topic.

- **Material and system requirements**

  These requirements are not directly related to the TES material but are basic for the design of the facility.

  - *Economic*

    Most of economic analyses are focused on CSP facilities and the capital investment costs (CAPEX), operation and maintenance costs (OPEX) and

financing costs are studied. Moreover, the annual number of storage cycles has the largest influence on the cost effectiveness.

- *Environmental*

  Carbon footprint, Life Cycle Assessment and Cumulative Energy Demand analyses have been developed at three different scales (TES material, TES system and the whole facility). Most of them consider solar power plants. Moreover, the use of by-products or industrial wastes has been assessed.

- *Technological*

  Multiple PCMs configuration and the forced movement of the TES material while undergoing phase change ~~dynamic melting systems~~ have been proposed by the researchers as important strategies for maximizing the heat transfer between the HTF and the TES material.

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References

1. Internation Energy Agency. Technology Roadmap: Energy storage 2014.
2. Wongsuwan W, Kumar S, Neveu P, Meunier F. A review of chemical heat pump technology and applications. Appl Therm Eng 2001;21:1489–519. doi:10.1016/S1359-4311(01)00022-9.
3. Meunier F. Solid sorption: An alternative to CFCs. Heat Recovery Syst CHP 1993;13:289–95. doi:10.1016/0890-4332(93)90051-V.
4. Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: A review. Renew Sustain Energy Rev 2011;15:1675–95. doi:10.1016/j.rser.2010.11.018.
5. Zhang Y, Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Build Environ 2007;42:2197–209. doi:10.1016/j.buildenv.2006.07.023.

6. Mazman M, Cabeza LF, Mehling H, Nogues M, Evliya H, Paksoy HÖ. Utilization of phase change materials in solar domestic hot water systems. Renew Energy 2009;34:1639–43. doi:10.1016/j.renene.2008.10.016.
7. Srikhirin P, Aphornratana S, Chungpaibulpatana S. A review of absorption refrigeration technologies. Renew Sustain Energy Rev 2001;5:343–72. doi:10.1016/S1364-0321(01)00003-X.
8. Demir H, Mobedi M, Ülkü S. A review on adsorption heat pump: Problems and solutions. Renew Sustain Energy Rev 2008;12:2381–403. doi:10.1016/j.rser.2007.06.005.
9. Johnson RW, Evans JL, Jacobsen P, Thompson JR, Christopher M. The changing automotive environment: high-temperature electronics. IEEE Trans Electron Packag Manuf 2004;27:164–76. doi:10.1109/TEPM.2004.843109.
10. Jankowski NR, McCluskey FP. A review of phase change materials for vehicle component thermal buffering. Appl Energy 2014;113:1525–61. doi:10.1016/j.apenergy.2013.08.026.
11. Patapoutian A, Peier AM, Story GM, Viswanath V. ThermoTRP channels and beyond: mechanisms of temperature sensation. Nat Rev Neurosci 2003;4:529–39. doi:10.1038/nrn1141.
12. Kandasamy R, Wang X-Q, Mujumdar AS. Application of phase change materials in thermal management of electronics. Appl Therm Eng 2007;27:2822–32. doi:10.1016/j.applthermaleng.2006.12.013.
13. ASHRAE Technical Committee (TC) 9.9. 2011 Thermal Guidelines for Data Processing Environments – Expanded Data Center Classes and Usage Guidance 2011.
14. Larson WJ, Wertz JR, editors. Space Mission Analysis and Design. 3rd edition. El Segundo, Calif. : Dordrecht ; Boston: Microcosm; 1999.
15. Dincer I. Heat Transfer In Food Cooling Applications. CRC Press; 1997.
16. Mondieig D, Rajabalee F, Laprie A, Oonk HAJ, Calvet T, Angel Cuevas-Diarte M. Protection of temperature sensitive biomedical products using molecular alloys as phase change material. Transfus Apher Sci 2003;28:143–8. doi:10.1016/S1473-0502(03)00016-8.
17. Kalogirou S. The potential of solar industrial process heat applications. Appl Energy 2003;76:337–61. doi:10.1016/S0306-2619(02)00176-9.
18. Schweiger H, Mendes JF, Benz N, Hennecke K, Prieto G, Cusí M, et al. The potential of solar heat in industrial processes. State of the art review for Spain and Portugal. ISES-Eur. Sol. Congr., Copenhagen, Denmark: 2000.
19. Pintaldi S, Perfumo C, Sethuvenkatraman S, White S, Rosengarten G. A review of thermal energy storage technologies and control approaches for solar cooling. Renew Sustain Energy Rev 2015;41:975–95. doi:10.1016/j.rser.2014.08.062.
20. Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. Renew Sustain Energy Rev 2007;11:1913–65. doi:10.1016/j.rser.2006.05.005.
21. Medrano M, Gil A, Martorell I, Potau X, Cabeza LF. State of the art on high-temperature thermal energy storage for power generation. Part 2—Case studies. Renew Sustain Energy Rev 2010;14:56–72. doi:10.1016/j.rser.2009.07.036.
22. Pielichowska K, Pielichowski K. Phase change materials for thermal energy storage. Prog Mater Sci 2014;65:67–123. doi:10.1016/j.pmatsci.2014.03.005.
23. Gude VG. Energy storage for desalination processes powered by renewable energy and waste heat sources. Appl Energy 2015;137:877–98. doi:10.1016/j.apenergy.2014.06.061.
24. Gude VG, Nirmalakhandan N, Deng S. Renewable and sustainable approaches for desalination. Renew Sustain Energy Rev 2010;14:2641–54. doi:10.1016/j.rser.2010.06.008.
25. Nomura T, Okinaka N, Akiyama T. Technology of Latent Heat Storage for High Temperature Application: A Review. ISIJ Int 2010;50:1229–39. doi:10.2355/isijinternational.50.1229.

26. Brückner S, Liu S, Miró L, Radspieler M, Cabeza LF, Lävemann E. Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies. Appl Energy 2015;151:157–67. doi:10.1016/j.apenergy.2015.01.147.
27. Zalba B, Marín JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl Therm Eng 2003;23:251–83. doi:10.1016/S1359-4311(02)00192-8.
28. Liu M, Saman W, Bruno F. Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems. Renew Sustain Energy Rev 2012;16:2118–32. doi:10.1016/j.rser.2012.01.020.
29. Cárdenas B, León N. Latent Heat Based High Temperature Solar Thermal Energy Storage for Power Generation. Energy Procedia 2014;57:580–9. doi:10.1016/j.egypro.2014.10.212.
30. Fernandes D, Pitié F, Cáceres G, Baeyens J. Thermal energy storage: "How previous findings determine current research priorities." Energy 2012;39:246–57. doi:10.1016/j.energy.2012.01.024.
31. Abhat A. Low temperature latent heat thermal energy storage: Heat storage materials. Sol Energy 1983;30:313–32. doi:10.1016/0038-092X(83)90186-X.
32. Dincer I, Rosen MA. Thermal Energy Storage: Systems and Applications. 2 edition. Hoboken, N.J: Wiley; 2010.
33. Mehling H, Cabeza LF. Heat and cold storage with PCM: An up to date introduction into basics and applications. Springer Science & Business Media; 2008.
34. Gasia J, Miró L, Cabeza LF. Materials and system requirements of high temperature thermal energy storage systems: A review. Part 2: Thermal conductivity enhancement techniques. Renew Sustain Energy Rev 2016;60:1584–601. doi:10.1016/j.rser.2016.03.019.
35. Ferrer G, Solé A, Barreneche C, Martorell I, Cabeza LF. Corrosion of metal containers for use in PCM energy storage. Renew Energy 2015;76:465–9. doi:10.1016/j.renene.2014.11.036.
36. Solé A, Neumann H, Niedermaier S, Martorell I, Schossig P, Cabeza LF. Stability of sugar alcohols as PCM for thermal energy storage. Sol Energy Mater Sol Cells 2014;126:125–34. doi:10.1016/j.solmat.2014.03.020.
37. John G, König-Haagen A, King'Ondu CK, Brüggemann D, Nkhonjera L. Galactitol as phase change material for latent heat storage of solar cookers: Investigating thermal behavior in bulk cycling. Sol Energy 2015;119:415–21. doi:10.1016/j.solener.2015.07.003
38. Paul A, Shi L, Bielawski CW. A eutectic mixture of galactitol and mannitol as a phase change material for latent heat storage. Energy Convers Manag 2015;103:139–46. doi:10.1016/j.enconman.2015.06.013.
39. Sun JQ, Zhang RY, Liu ZP, Lu GH. Thermal reliability test of Al–34%Mg–6%Zn alloy as latent heat storage material and corrosion of metal with respect to thermal cycling. Energy Convers Manag 2007;48:619–24. doi:10.1016/j.enconman.2006.05.017.
40. Bauer T, Pfleger N, Breidenbach N, Eck M, Laing D, Kaesche S. Material aspects of Solar Salt for sensible heat storage. Appl Energy 2013;111:1114–9. doi:10.1016/j.apenergy.2013.04.072.
41. Guillot S, Faik A, Rakhmatullin A, Lambert J, Veron E, Echegut P, et al. Corrosion effects between molten salts and thermal storage material for concentrated solar power plants. Appl Energy 2012;94:174–81. doi:10.1016/j.apenergy.2011.12.057.
42. Fernández AG, Cortes M, Fuentealba E, Pérez FJ. Corrosion properties of a ternary nitrate/nitrite molten salt in concentrated solar technology. Renew Energy 2015;80:177–83. doi:10.1016/j.renene.2015.01.072.
43. Federsel K, Wortmann J, Ladenberger M. High-temperature and Corrosion Behavior of Nitrate Nitrite Molten Salt Mixtures Regarding their Application in Concentrating Solar Power Plants. Energy Procedia 2015;69:618–25. doi:10.1016/j.egypro.2015.03.071.
44. Fernández AG, Galleguillos H, Fuentealba E, Pérez FJ. 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 2015;141:7–13. doi:10.1016/j.solmat.2015.05.004.
45. Goods SH, Bradshaw RW. Corrosion of stainless steels and carbon steel by molten mixtures of commercial nitrate salts. J Mater Eng Perform 2004;13:78–87. doi:10.1361/10599490417542.
46. Slusser JW, Titcomb JB, Heffelfinger MT, Dunbobbin BR. Corrosion in Molten Nitrate-Nitrite Salts. Jom 1985;37:24–7. doi:10.1007/bf03259692
47. Fernández AG, Rey A, Lasanta I, Mato S, Brady MP, Pérez FJ. Corrosion of alumina-forming austenitic steel in molten nitrate salts by gravimetric analysis and impedance spectroscopy. Mater Corros 2014;65:267–75. doi:10.1002/maco.201307422.
48. Fernández AG, Galleguillos H, Pérez FJ. Thermal influence in corrosion properties of Chilean solar nitrates. Sol Energy 2014;109:125–34. doi:10.1016/j.solener.2014.07.027.
49. Fernández A, Grágeda M, Galleguillos H. Impurity Influence in Physico-chemical and Corrosion Properties of Chilean Solar Nitrates. Energ Proced 2014;49:607–16. doi:10.1016/j.egypro.2014.03.066.
50. Fernández AG, Lasanta MI, Pérez FJ. Molten Salt Corrosion of Stainless Steels and Low-Cr Steel in CSP Plants. Oxid Met 2012;78:329–48. doi:10.1007/s11085-012-9310-x.
51. Dorcheh AS, Durham RN, Galetz MC. Corrosion behavior of stainless and low-chromium steels and IN625 in molten nitrate salts at 600°C. Sol Energy Mater Sol Cells 2016;144:109–16. doi:10.1016/j.solmat.2015.08.011.
52. Kruizenga A, Gill D. Corrosion of Iron Stainless Steels in Molten Nitrate Salt. Energy Procedia 2014;49:878–87. doi:10.1016/j.egypro.2014.03.095.
53. McConohy G, Kruizenga A. Molten nitrate salts at 600 and 680 °C: Thermophysical property changes and corrosion of high-temperature nickel alloys. Sol Energy 2014;103:242–52. doi:10.1016/j.solener.2014.01.028.
54. Goods SH. Creep and the corrosion characteristics of Incoloy Alloy 800 in molten nitrate salts. J Mater Energy Syst 1981;3:43–50. doi:10.1007/BF02833528.
55. Cheng W-J, Chen D-J, Wang C-J. High-temperature corrosion of Cr–Mo steel in molten LiNO3–NaNO3–KNO3 eutectic salt for thermal energy storage. Sol Energy Mater Sol Cells 2015;132:563–9. doi:10.1016/j.solmat.2014.10.007.
56. Sona CS, Gajbhiye BD, Hule PV, Patwardhan AW, Mathpati CS, Borgohain A, et al. High temperature corrosion studies in molten salt-FLiNaK. Corros Eng Sci Technol 2013;49:287–95. doi:10.1179/1743278213Y.0000000135.
57. Li Y, Spiegel M, Shimada S. Corrosion behaviour of various model alloys with NaCl–KCl coating. Mater Chem Phys 2005;93:217–23. doi:10.1016/j.matchemphys.2005.03.015.
58. Abramov AV, Polovov IB, Volkovich VA, Rebrin OI, Griffiths TR, May I, et al. Spectroelectrochemical Study of Stainless Steel Corrosion in NaCl-KCl Melt. ECS Trans 2010;33:277-85. doi:10.1149/1.3484785.
59. Vignarooban K, Xu X, Wang K, Molina E, Li P, Gervasio D, et al. Vapor pressure and corrosivity of ternary metal-chloride molten-salt based heat transfer fluids for use in concentrating solar power systems. Appl Energ 2015;159:206–13. doi:10.1016/j.apenergy.2015.08.131.
60. Miró L, Barreneche C, Ferrer G, Solé A, Martorell I, Cabeza LF. Health hazard, cycling and thermal stability as key parameters when selecting a suitable phase change material (PCM). Thermochim Acta 2016;627-629:39–47. doi:10.1016/j.tca.2016.01.014.
61. Gallegos MA, Yu W. Thermal performance and flammability of phase change material for medium and elevated temperatures for textile application. J Therm Anal Calorim 2014;117:9–17. doi:10.1007/s10973-013-3411-x.
62. Zhao W. Characterization of Encapsulated Phase Change Materials for Thermal Energy Storage. Lehigh University, 2013.
63. Nath R. Encapsulation of High Temperature Phase Change Materials for Thermal Energy Storage. Grad Theses Diss 2012.

64. Pitié F, Zhao CY, Cáceres G. Thermo-mechanical analysis of ceramic encapsulated phase-change-material (PCM) particles. Energy Environ Sci 2011;4:2117–24. doi:10.1039/C0EE00672F.
65. Fukahori R, Nomura T, Zhu C, Sheng N, Okinaka N, Akiyama T. Macro-encapsulation of metallic phase change material using cylindrical-type ceramic containers for high-temperature thermal energy storage. Appl Energ 2016;170:324–8. doi:10.1016/j.apenergy.2016.02.106.
66. Jacob R, Bruno F. Review on shell materials used in the encapsulation of phase change materials for high temperature thermal energy storage. Renew Sust Energ Rev 2015;48:79–87. doi:10.1016/j.rser.2015.03.038
67. Legay M, Gondrexon N, Le Person S, Boldo P, Bontemps A. Enhancement of Heat Transfer by Ultrasound: Review and Recent Advances. Int J Chem Eng 2011;2011:e670108. doi:10.1155/2011/670108.
68. Sarı A, Biçer A, Lafçı Ö, Ceylan M. Galactitol hexa stearate and galactitol hexa palmitate as novel solid–liquid phase change materials for thermal energy storage. Sol Energy 2011;85:2061–71. doi:10.1016/j.solener.2011.05.014.
69. Rathgeber C, Miró L, Cabeza LF, Hiebler S. Measurement of enthalpy curves of phase change materials via DSC and T-History: When are both methods needed to estimate the behaviour of the bulk material in applications? Thermochim Acta 2014;596:79–88. doi:10.1016/j.tca.2014.09.022.
70. Gil A, Oró E, Peiró G, Álvarez S, Cabeza LF. Material selection and testing for thermal energy storage in solar cooling. Renew Energy 2013;57:366–71. doi:10.1016/j.renene.2013.02.008.
71. Rathgeber C, Schmit H, Miró L, Cabeza LF, Gutierrez A, Ushak S. Analyisis of subcooling of phase change materials with increased sample size - Comparison of measurements via DSC, T-History and at pilot plant scale. 13h Int. Conf. Therm. Energy Storage, Beijing, China: 2015.
72. Archibold AR, Gonzalez-Aguilar J, Rahman MM, Yogi Goswami D, Romero M, Stefanakos EK. The melting process of storage materials with relatively high phase change temperatures in partially filled spherical shells. Appl Energy 2014;116:243–52. doi:10.1016/j.apenergy.2013.11.048.
73. Solomon L, Elmozughi, Oztekin A. Effect of Internal Void Placement on Heat Transfer Performance – Encapsulated Phase Change material for Energy Storage. Renew Energy 2015;78:438–47. doi:10.1016/j.renene.2015.01.035.
74. Hennemann P, Hiebler S, Hauer A. Physical limitations to the usage of PCM - A theoretical approach. 13h Int. Conf. Therm. Energy Storage, Beijing, Xina: 2015.
75. Andreu-Cabedo P, Mondragon R, Hernandez L, Martinez-Cuenca R, Cabedo L, Julia JE. Increment of specific heat capacity of solar salt with SiO2 nanoparticles. Nanoscale Res Lett 2014;9:582. doi:10.1186/1556-276X-9-582.
76. Shin D, Banerjee D. Enhancement of specific heat capacity of high-temperature silica-nanofluids synthesized in alkali chloride salt eutectics for solar thermal-energy storage applications. Int J Heat Mass Transf 2011;54:1064–70. doi:10.1016/j.ijheatmasstransfer.2010.11.017.
77. Ho MX, Pan C. Optimal concentration of alumina nanoparticles in molten Hitec salt to maximize its specific heat capacity. Int J Heat Mass Transf 2014;70:174–84. doi:10.1016/j.ijheatmasstransfer.2013.10.078.
78. Shahrul IM, Mahbubul IM, Khaleduzzaman SS, Saidur R, Sabri MFM. A comparative review on the specific heat of nanofluids for energy perspective. Renew Sustain Energy Rev 2014;38:88–98. doi:10.1016/j.rser.2014.05.081.
79. Shin D, Banerjee D. Enhancement of Heat Capacity of Molten Salt Eutectics using Inorganic Nanoparticles for Solar Thermal Energy Applications. In: Kriven WM, Gyekenyesi AL, Wang J, Widjaja S, Singh D, editors. Dev. Strateg. Mater. Comput. Des. II, John Wiley & Sons, Inc.; 2011, p. 119–26.

80. Lazaro A, Peñalosa C, Solé A, Diarce G, Haussmann T, Fois M, et al. Intercomparative tests on phase change materials characterisation with differential scanning calorimeter. Appl Energy 2013;109:415–20. doi:10.1016/j.apenergy.2012.11.045.
81. Jung S, Banerjee D. Enhancement of Heat Capacity of Nitrate Salts using Mica Nanoparticles. In: Kriven WM, Gyekenyesi AL, Wang J, Widjaja S, Singh D, editors. Dev. Strateg. Mater. Comput. Des. II, John Wiley & Sons, Inc.; 2011, p. 127–37.
82. Chieruzzi M, Cerritelli GF, Miliozzi A, Kenny JM. Effect of nanoparticles on heat capacity of nanofluids based on molten salts as PCM for thermal energy storage. Nanoscale Res Lett 2013;8:448. doi:10.1186/1556-276X-8-448.
83. Dudda B, Shin D. Effect of nanoparticle dispersion on specific heat capacity of a binary nitrate salt eutectic for concentrated solar power applications. Int J Therm Sci 2013;69:37–42. doi:10.1016/j.ijthermalsci.2013.02.003.
84. Lu M-C, Huang C-H. Specific heat capacity of molten salt-based alumina nanofluid. Nanoscale Res Lett 2013;8:292. doi:10.1186/1556-276X-8-292.
85. Schuller M, Shao Q, Lalk T. Experimental investigation of the specific heat of a nitrate–alumina nanofluid for solar thermal energy storage systems. Int J Therm Sci 2015;91:142–5. doi:10.1016/j.ijthermalsci.2015.01.012.
86. Chieruzzi M, Miliozzi A, Crescenzi T, Torre L, Kenny JM. A New Phase Change Material Based on Potassium Nitrate with Silica and Alumina Nanoparticles for Thermal Energy Storage. Nanoscale Res Lett Nanoscale Research Letters 2015;10. doi:10.1186/s11671-015-0984-2.
87. Tao YB, Lin CH, He YL. Preparation and thermal properties characterization of carbonate salt/carbon nanomaterial composite phase change material. Energy Convers Manag 2015;97:103–10. doi:10.1016/j.enconman.2015.03.051.
88. Seo J, Shin D. Size effect of nanoparticle on specific heat in a ternary nitrate (LiNO3–NaNO3–KNO3) salt eutectic for thermal energy storage. Applied Thermal Engineering 2016;102:144–8. doi:10.1016/j.applthermaleng.2016.03.134.
89. Lai C-C, Chang W-C, Hu W-L, Wang ZM, Lu M-C, Chueh Y-L. A solar-thermal energy harvesting scheme: enhanced heat capacity of molten HITEC salt mixed with Sn/SiOx core–shell nanoparticles. Nanoscale 2014;6:4555–9. doi:10.1039/C3NR06810B.
90. Bridges NJ, Visser AE, Fox EB. Potential of nanoparticle enhanced ionic liquids (NEILs) as advanced heat-transfer fluids. Energy Fuels 2011;25:4862–4.
91. Shin D, Banerjee D. Experimental Investigation of Molten Salt Nanofluid for Solar Thermal Energy Application 2011:T30024–T30024. doi:10.1115/AJTEC2011-44375.
92. Shin D, Banerjee D. Enhanced Specific Heat Capacity of Nanomaterials Synthesized by Dispersing Silica Nanoparticles in Eutectic Mixtures. J Heat Transf 2013;135:032801–032801. doi:10.1115/1.4005163.
93. Tiznobaik H, Shin D. Enhanced specific heat capacity of high-temperature molten salt-based nanofluids. Int J Heat Mass Transf 2013;57:542–8. doi:10.1016/j.ijheatmasstransfer.2012.10.062.
94. Seo J, Shin D. Enhancement of specific heat of ternary nitrate (LiNO3-NaNO3-KNO3) salt by doping with SiO2 nanoparticles for solar thermal energy storage. IET Micro Nano Lett 2014;9:817–20. doi:10.1049/mnl.2014.0407.
95. Shin D, Banerjee D. Specific heat of nanofluids synthesized by dispersing alumina nanoparticles in alkali salt eutectic. Int J Heat Mass Transf 2014;74:210–4. doi:10.1016/j.ijheatmasstransfer.2014.02.066.
96. Jo B, Banerjee D. Effect of Dispersion Homogeneity on Specific Heat Capacity Enhancement of Molten Salt Nanomaterials Using Carbon Nanotubes. J Sol Energy Eng 2014;137:011011–011011. doi:10.1115/1.4028144.
97. Shin D, Banerjee D. Enhanced thermal properties of SiO2 nanocomposite for solar thermal energy storage applications. Int J Heat Mass Transf 2015;84:898–902. doi:10.1016/j.ijheatmasstransfer.2015.01.100.

98. Devaradjane R, Shin D. Nanoparticle Dispersions on Ternary Nitrate Salts for Heat Transfer Fluid Applications in Solar Thermal Power. J Heat Transfer Journal Of Heat Transfer 2016;138:051901. doi:10.1115/1.4030903
99. Vignarooban K, Xu X, Arvay A, Hsu K, Kannan AM. Heat transfer fluids for concentrating solar power systems – A review. Appl Energy 2015;146:383–96. doi:10.1016/j.apenergy.2015.01.125.
100. Liu M, Belusko M, Steven Tay NH, Bruno F. Impact of the heat transfer fluid in a flat plate phase change thermal storage unit for concentrated solar tower plants. Sol Energy 2014;101:220–31. doi:10.1016/j.solener.2013.12.030.
101. Heller L. Literature Review on Heat Transfer Fluids and Thermal Energy Storage Systems in CSP Plants. STERG Report 2013.
102. Pacio J, Wetzel T. Assessment of liquid metal technology status and research paths for their use as efficient heat transfer fluids in solar central receiver systems. Sol Energy 2013;93:11–22. doi:10.1016/j.solener.2013.03.025.
103. Cingarapu S, Singh D, Timofeeva EV, Moravek MR. Nanofluids with encapsulated tin nanoparticles for advanced heat transfer and thermal energy storage. Int J Energy Res 2014;38:51–9. doi:10.1002/er.3041.
104. Torres-Mendieta R, Mondragón R, Juliá E, Mendoza-Yero O, Cordoncillo E, Lancis J, et al. Fabrication of gold nanoparticles in Therminol VP-1 by laser ablation and fragmentation with fs pulses. Laser Phys Lett Laser Physics Letters 2014;11:126001. doi:10.1088/1612-2011/11/12/126001
105. Boissiere B, Ansart R, Gauthier D, Flamant G, Hemati M. Experimental hydrodynamic study of gas-particle dense suspension upward flow for application as new heat transfer and storage fluid. Can J Chem Eng 2015;93:317–30. doi:10.1002/cjce.22087
106. International Renewable Energy Agency. Renewable energy technologies: Cost analysis series. Volume 1: Power Sector. Issue 2/5 Concentrating solar power 2012.
107. Internation Energy Agency. Technology Roadmap: Concentrating solar power 2010.
108. Fichtner GmbH & Co. Technology Assessment of CSP Technologies for a Site Specific Project in South Africa Final Report, The World Bank and ESMAP, Washington D.C. 2010.
109. Wagner SJ, Rubin ES. Economic implications of thermal energy storage for concentrated solar thermal power. Renew Energy 2014;61:81–95. doi:10.1016/j.renene.2012.08.013.
110. Nithyanandam K, Pitchumani R. Cost and performance analysis of concentrating solar power systems with integrated latent thermal energy storage. Energy 2014;64:793–810. doi:10.1016/j.energy.2013.10.095.
111. Rathgeber C, Hiebler S, Lävemann E, Hauer A. Economic Evaluation of Thermal Energy Storages via Top-down and Bottom-up Approach. 13h Int. Conf. Therm. Energy Storage, Beijing, China: 2015.
112. Carbon Trust. Carbon footprinting guide 2015. http://www.carbontrust.com/resources/guides/carbon-footprinting-and-reporting/carbon-footprinting.
113. Hirschier R, Weidema B. Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.2 2010.
114. IHOBE, Sociedad Pública de Gestión Ambiental. Análisis de ciclo de vida y huella de carbono. Dos maneras de medir el impacto ambiental de un producto. 2009.
115. Khare S, Dell'Amico M, Knight C, McGarry S. Selection of materials for high temperature sensible energy storage. Sol Energy Mater Sol Cells 2013;115:114–22. doi:10.1016/j.solmat.2013.03.009.
116. López-Sabirón AM, Royo P, Ferreira VJ, Aranda-Usón A, Ferreira G. Carbon footprint of a thermal energy storage system using phase change materials for industrial energy recovery to reduce the fossil fuel consumption. Appl Energy 2014;135:616–24. doi:10.1016/j.apenergy.2014.08.038.

441 117. López-Sabirón AM, Aranda-Usón A, Mainar-Toledo MD, Ferreira VJ, Ferreira
442 G. Environmental profile of latent energy storage materials applied to industrial
443 systems. Sci Total Environ 2014;473–474:565–75. doi:10.1016/j.scitotenv.2013.12.013.
444 118. Oró E, Gil A, de Gracia A, Boer D, Cabeza LF. Comparative life cycle
445 assessment of thermal energy storage systems for solar power plants. Renew Energy
446 2012;44:166–73. doi:10.1016/j.renene.2012.01.008.
447 119. Miró L, Oró E, Boer D, Cabeza LF. Embodied energy in thermal energy storage
448 (TES) systems for high temperature applications. Appl Energy 2015;137:793–9.
449 doi:10.1016/j.apenergy.2014.06.062.
450 120. Lalau Y, Py X, Meffre A, Olives R. Comparative LCA Between Current and
451 Alternative Waste-Based TES for CSP. Waste Biomass Valor Waste And Biomass
452 Valorization 2016. doi:10.1007/s12649-016-9549-6.
453 121. Klein SJW. Multi-Criteria Decision Analysis of Concentrated Solar Power with
454 Thermal Energy Storage and Dry Cooling. Environ Sci Technol 2013;47:13925–33.
455 doi:10.1021/es403553u.
456 122. Klein SJW, Rubin ES. Life cycle assessment of greenhouse gas emissions,
457 water and land use for concentrated solar power plants with different energy backup
458 systems. Energy Policy 2013;63:935–50. doi:10.1016/j.enpol.2013.08.057.
459 123. Lechón Y, de la Rúa C, Sáez R. Life Cycle Environmental Impacts of
460 Electricity Production by Solarthermal Power Plants in Spain. J Sol Energy Eng
461 2008;130:021012–021012. doi:10.1115/1.2888754.
462 124. Giuliano S, Buck R, Eguiguren S. Analysis of Solar-Thermal Power Plants
463 With Thermal Energy Storage and Solar-Hybrid Operation Strategy. J Sol Energy Eng
464 2011;133:031007–031007. doi:10.1115/1.4004246.
465 125. Whitaker MB, Heath GA, Burkhardt JJ, Turchi CS. Life Cycle Assessment of a
466 Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives.
467 Environ Sci Technol 2013;47:5896–903. doi:10.1021/es400821x.
468 126. Burkhardt JJ, Heath GA, Turchi CS. Life Cycle Assessment of a Parabolic
469 Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives.
470 Environ Sci Technol 2011;45:2457–64. doi:10.1021/es1033266.
471 127. Gutierrez A, Miró L, Gil A, Rodríguez-Aseguinolaza J, Barreneche C, Calvet
472 N, et al. Advances in the valorization of waste and by-product materials as thermal
473 energy storage (TES) materials. Renew Sustain Energy Rev 2016;59:763–83.
474 doi:10.1016/j.rser.2015.12.071.
475 128. Py X, Calvet N, Olives R, Meffre A, Echegut P, Bessada C, et al. Recycled
476 Material for Sensible Heat Based Thermal Energy Storage to be Used in Concentrated
477 Solar Thermal Power Plants. J Sol Energy Eng 2011;133:031008–031008.
478 doi:10.1115/1.4004267.
479 129. Kere A, Sadiki N, Py X, Goetz V. Applicability of thermal energy storage
480 recycled ceramics to high temperature and compressed air operating conditions. Energy
481 Convers Manag 2014;88:113–9. doi:10.1016/j.enconman.2014.08.008.
482 130. Gualtieri AF, Tartaglia A. Thermal decomposition of asbestos and recycling in
483 traditional ceramics. J Eur Ceram Soc 2000;20:1409–18. doi:10.1016/S0955-
484 2219(99)00290-3.
485 131. Calvet N, Gomez JC, Faik A, Roddatis VV, Meffre A, Glatzmaier GC, et al.
486 Compatibility of a post-industrial ceramic with nitrate molten salts for use as filler
487 material in a thermocline storage system. Appl Energy 2013;109:387–93.
488 doi:10.1016/j.apenergy.2012.12.078.
489 132. Meffre A, Py X, Olives R, Bessada C, Veron E, Echegut P. High-Temperature
490 Sensible Heat-Based Thermal Energy Storage Materials Made of Vitrified MSWI Fly
491 Ashes. Waste Biomass Valor Waste And Biomass Valorization 2015;6:1003–14.
492 doi:10.1007/s12649-015-9409-9.
493 133. Faik A, Guillot S, Lambert J, Véron E, Ory S, Bessada C, et al. Thermal storage
494 material from inertized wastes: Evolution of structural and radiative properties with
495 temperature. Sol Energy 2012;86:139–46. doi:10.1016/j.solener.2011.09.014.

134. Miró L, Navarro ME, Suresh P, Gil A, Fernández AI, Cabeza LF. Experimental characterization of a solid industrial by-product as material for high temperature sensible thermal energy storage (TES). Appl Energy 2014;113:1261–8. doi:10.1016/j.apenergy.2013.08.082.
135. Ushak S, Gutierrez A, Flores E, Galleguillos H, Grageda M. Development of Thermal Energy Storage Materials from Waste-process Salts. Energy Procedia 2014;57:627–32. doi:10.1016/j.egypro.2014.10.217.
136. Calvet N, Dejean G, Unamunzaga L, Py X. Waste From Metallurgic Industry: A Sustainable High-Temperature Thermal Energy Storage Material for Concentrated Solar Power 2013:V001T03A012. doi:10.1115/ES2013-18333.
137. Ozger OB, Girardi F, Giannuzzi GM, Salomoni VA, Majorana CE, Fambri L, et al. Effect of nylon fibres on mechanical and thermal properties of hardened concrete for energy storage systems. Mater Des 2013;51:989–97. doi:10.1016/j.matdes.2013.04.085.
138. Navarro ME, Martínez M, Gil A, Fernández AI, Cabeza LF, Olives R, et al. Selection and characterization of recycled materials for sensible thermal energy storage. Sol Energy Mater Sol Cells 2012;107:131–5. doi:10.1016/j.solmat.2012.07.032.
139. Gil A, Olives R, Faure R, Tessier-Doyen, Huger M. Thermomechanical characterization of recycled high temperature thermal energy storage material. Adv. Therm. Energy Storage Technol., Lleida, Spain: 2014.
140. Ortega I, Faik A, Gil A, Rodriguez-Aseguinolaza J, D'Aguanno B. Thermo-physical properties of a Steel-making by-product to be used as thermal energy storage material in a packed-bed system. Conc. Sol. Power Chem. Energy Syst., Beijing, China: 2014.
141. Ortega I, Rodriguez-Aseguinolaza J, Gil A, Faik A, D'Aguanno B. New thermal energy storage materials from industrial wastes: compatibility of Steel slags with the most common heat transfer fluids. Int. Conf. Energy Sustain., Boston, USA: 2012.
142. Mills K. The estimation of slag properties, Cradle of Humankind, South Africa: 2011.
143. Peiró G, Gasia J, Miró L, Cabeza LF. Experimental evaluation at pilot plant scale of multiple PCMs (cascaded) vs. single PCM configuration for thermal energy storage. Renew Energy 2015;83:729–36. doi:10.1016/j.renene.2015.05.029.
144. Tao YB, He YL, Liu YK, Tao WQ. Performance optimization of two-stage latent heat storage unit based on entransy theory. Int J Heat Mass Transf 2014;77:695–703. doi:10.1016/j.ijheatmasstransfer.2014.05.049.
145. Li YQ, He YL, Song HJ, Xu C, Wang WW. Numerical analysis and parameters optimization of shell-and-tube heat storage unit using three phase change materials. Renew Energy 2013;59:92–9. doi:10.1016/j.renene.2013.03.022.
146. Gong Z-X, Mujumdar AS. A New Solar Receiver Thermal Store for Space-Based Activities Using Multiple Composite Phase-Change Materials. J Sol Energy Eng 1995;117:215–20. doi:10.1115/1.2847798.
147. Cui H, Yuan X, Hou X. Thermal performance analysis for a heat receiver using multiple phase change materials. Appl Therm Eng 2003;23:2353–61. doi:10.1016/S1359-4311(03)00210-2.
148. Michels H, Pitz-Paal R. Cascaded latent heat storage for parabolic trough solar power plants. Sol Energy 2007;81:829–37. doi:10.1016/j.solener.2006.09.008.
149. Seeniraj RV, Lakshmi Narasimhan N. Performance enhancement of a solar dynamic LHTS module having both fins and multiple PCMs. Sol Energy 2008;82:535–42. doi:10.1016/j.solener.2007.11.001.
150. Shabgard H, Robak CW, Bergman TL, Faghri A. Heat transfer and exergy analysis of cascaded latent heat storage with gravity-assisted heat pipes for concentrating solar power applications. Sol Energy 2012;86:816–30. doi:10.1016/j.solener.2011.12.008.
151. Wang P, Wang X, Huang Y, Li C, Peng Z, Ding Y. Thermal energy charging behaviour of a heat exchange device with a zigzag plate configuration containing multi-

550 phase-change-materials (m-PCMs). Appl Energy 2015;142:328–36.
551 doi:10.1016/j.apenergy.2014.12.050.
552 152. Gasia J, Tay NHS, Bruno F, Cabeza LF, Belusko M. Experimental investigation
553 of the effect of dynamic melting in a cylindrical shell-and-tube heat exchanger using
554 water as PCM. Applied Energy. Submitt to Appl Energ n.d.
555 153. Tay NHS, Bruno F, Belusko M. Experimental investigation of dynamic melting
556 in a tube-in-tank PCM system. Appl Energy 2013;104:137–48.
557 doi:10.1016/j.apenergy.2012.11.035.
558 154. Zipf V, Neuhäuser A, Willert D, Nitz P, Gschwander S, Platzer W. High
559 temperature latent heat storage with a screw heat exchanger: Design of prototype. Appl
560 Energ 2013;109:462–9. doi:10.1016/j.apenergy.2012.11.044
561 155. Pointner H, Steinmann W-D. Experimental demonstration of an active latent
562 heat storage concept. Applied Energy 2016;168:661–71.
563 doi:10.1016/j.apenergy.2016.01.113