30. Characterization of thermal energy storage materials for building applications

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Abstract Thermal energy storage offers a great range of opportunities and benefits to enhance energy efficiency in buildings, improve heating and cooling systems, and to increase the share of renewable energy sources. This manuscript provides an overview of characterization parameters and requirements of thermal storage materials for building applications. It analyzes sensible, latent and thermochemical materials for low-temperature applications: up to 21ºC for cooling solutions, between 22ºC and 28ºC for comfort solutions, and over 29ºC for hot water and heating applications. Classification of available thermal storage materials technically developed and applications is reported. Physical, thermodynamic, kinetic, chemical and economic properties of conventional and second generation materials are assessed and compared. Advantages, drawbacks and challenges of diverse alternatives are discussed and future research efforts are highlighted. Sensible and latent heat storage are identified as very attractive solutions towards the development of competitive low-carbon energy measures for buildings. On the other hand, thermochemical storage materials do not present yet clear advantages for low-temperature storage applications. Despite the high energy densities and high heat ability for long-term storage periods due to negligible heat losses of thermochemical energy storage, currently there is no material available that satisfies all requirements for building operations. Additional research efforts are required to optimize operation conditions, storage cycles efficiency, material costs and systems design.

Keywords Thermal storage, Materials, Thermal properties, Building application, Energy efficiency.

1 Introduction

The building sector is the largest energy-consuming sector in the world, accounting for over one-third of final energy consumption (International Energy Agency, 2013). In the European Union, it is responsible for 40% of energy consumption (The European Parliament and the Council of the European Union, 2010) of which heating, cooling and water heating account for around 70%. On the pathway to improve the energy performance in buildings, the deployment of efficient energy measures based on thermal energy storage (TES) offers a great range of opportunities and benefits to reduce building energy consumption and emissions (Kalaiselvam & Parameshwaran, 2014).

TES solutions can be integrated in buildings in the form of sensible, latent or thermochemical storage (Tatsidjodoung et al., 2013). Also, building thermal storage applications can be classified into passive or active:

- Passive solutions are characterized by a heat exchange without mechanical action via natural convection between the indoor environment and storage material (Navarro et al., 2015).
- Active applications are based on a heat exchange assisted by a mechanical component (fan, blower or pump) (Navarro et al., 2016).

The use of TES materials through passive applications allow reducing energy demand in buildings by means of a higher thermal inertia, decreasing indoor peak-temperature, and improving the thermal comfort (Hyman, 2011; Kalaiselvam & Parameshwaran, 2014). On the other hand, the use of TES materials through active applications allow (Hyman, 2011; International Energy Agency, 2013):

- Reducing the consumption peak-load thanks to the supply of stored energy, which reduces the power for required equipment.
- Improving the efficiency of systems by adjusting the operation range (avoiding operating partial load and mitigating intermittent input).
- And mainly, a more effective use of renewable energy sources by overcoming the time mismatch between demand and the best favourable supply period.

This paper is focused on providing a critical definition and characterization of the relevant properties of sensible, latent and thermochemical TES materials technically and commercially developed for building applications. It comprises TES materials for low-temperature applications: up to 21ºC for cooling applications, between 22ºC and 28ºC for comfort applications, and over 29ºC for hot water and heating applications. Available TES materials are assessed, their properties are compared, and current research stages are discussed with the goal of clearly identifying advantages, drawbacks and challenges. The reported information is useful as a guide for the decision making process in the development of efficient TES solutions for buildings.

2 Thermal energy storage methods and applications

TES for building applications can be based on sensible, latent and thermochemical storage. Fig. 1 illustrates differences between each TES concept. Characterization parameters and requirements of each method are defined in the following sections.

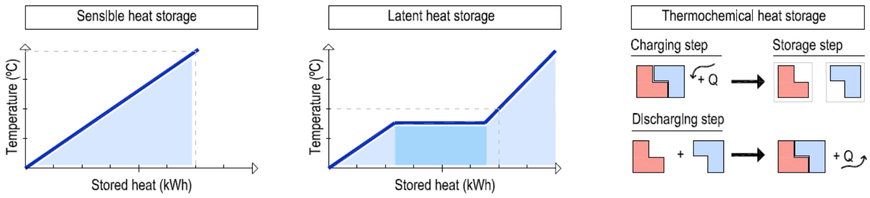

Fig. 1 Thermal energy storage methods: sensible, latent and thermochemical storage.

Sensible heat storage is just based on increasing or decreasing the temperature of a storage material with a high heat capacity. Latent heat storage is based on the heat absorbed or released when a material undergoes a phase change from a physical state to another (solid-solid, solid-liquid and liquid-gas) (Kalaiselvam & Parameshwaran, 2014; Zhou, Zhao, & Tian, 2012). Thermochemical energy storage (TCES) is based on the use of a source of energy to induce a reversible chemical reaction and/or sorption process (Yu, Wang, & Wang, 2013).
These thermal storage methods can be implemented in buildings by means of different applications. Fig. 2 illustrates the relationship between main TES applications and storage methods. TES applications can be classified into: TES in building materials or elements, thermally activated building systems (TABSs), TES components, small-scale TES units and large-scale TES systems (Lizana et al., 2016).

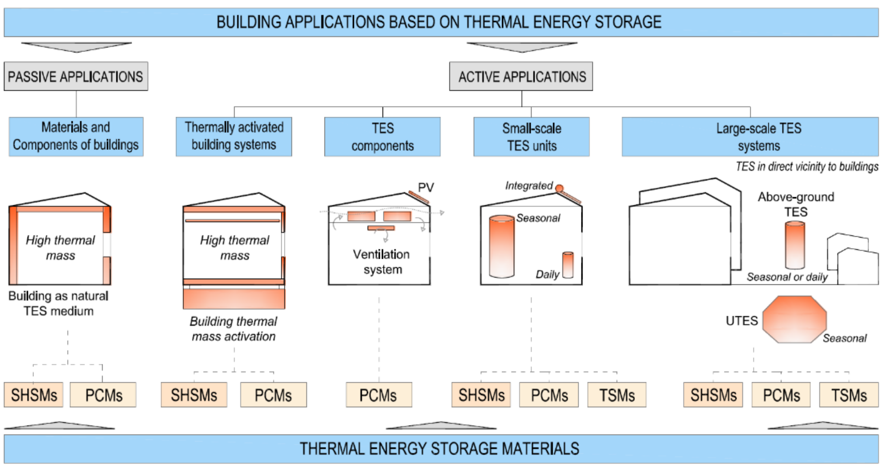

Fig. 2 Building applications based on thermal energy storage.

3.1 Definition of characterization parameters of TES materials

3.1 Sensible and latent heat storage materials

Sensible heat storage is the most widely used technique for TES in buildings. In addition, applications based on latent heat storage are gradually growing due to the fact that they allow storing high thermal energy amounts within a small temperature range. Characterization parameters of sensible and latent heat storage materials (SHSMs and LHSMs), and their influences in storage solutions are showed in Table 1 (Kalaiselvam & Parameshwaran, 2014; Mehling & Cabeza, 2008; Ståhl, 2009).

Table 1 Characterization parameters of SHSMs and LHSMs.

Property	Measure	Influences
Density (ρ)	Kg/m^3	Thermal storage capacity
Specific heat capacity (c_p)	kJ/kg·K	
Latent heat of phase change (h)	kJ/kg	
Phase change temperature	ºC	Thermal application
Thermal conductivity (λ)	W/m·ºC	Charging/ discharging time Stratification ability
Thermal diffusivity	mm^2/s	
Thermal effusivity	$W\sqrt{s}\ /m^2K$	Ability to exchange thermal energy with its surroundings (Ståhl, 2009)
Thermal expansion coefficient	%	Change of volume (Requirements for container)
Thermal reliability [a] (Efficiency after thermal cycles)	%	Performance over several thermal cycles
Chemical stability [a] (after thermal cycles)	Changes in spectrum	No decomposition of material after thermal cycles
Thermal stability [b] (Degradation at high temperature)	Weight loss %	No degradation of material with the increase of temperature.

[a] 5000 cycles are required for approximately 13-14 years (Harikrishnan et al., 2014).
[b] Commonly not important for building applications due to low-temperature of applications.

The amount of energy stored in a given mass of material (m) by sensible heat storage (Q_s) is given by Eq. 1, and by latent heat storage (Q_l) is given by Eq. 2 (Kalaiselvam & Parameshwaran, 2014).

$$Q_s = m\, c_p\, \Delta T \quad (MJ/m^3) \qquad (1)$$

$$Q_l = m\left[\left(c_{p_s}\, \Delta T\right)_{sensible} + (h)_{latent} + \left(c_{p_l}\, \Delta T\right)_{sensible}\right] \quad (MJ/m^3) \qquad (2)$$

Most important physical properties to take into consideration are: i) for sensible heat storage: high specific heat capacity and density, good thermal conductivity and low cost; ii) for latent heat storage: suitable phase change temperature for the corresponding application, high volumetric latent heat capacity, good thermal conductivity and low cost. As a reference value, sensible heat storage capacity of water, for a temperature difference (ΔT) of 60ºC, is 250 MJ/m^3.

Other requirements and constraints for selecting SHSMs and LHSMs are defined in Table 2 (Mehling & Cabeza, 2008; Tatsidjodoung et al., 2013). They are based on safety, environmental impact and compatibility.

Table 2 Requirements or constraints for selecting of SHSMs and LHSMs.

Requirements or constraints	Measure	Reasons
Small volume change	%	Less mechanical requirements of container
Not toxic, not flammable nonexplosive and nonreactive	-	Safety
Recyclability Non-polluting Low CO_2-eq footprint	% CO_2-eq/kg	Environmental impact
Non-corrosiveness	-	Compatibility with other materials
Availability and low price	€/m^3 or €/kg	Competitiveness and effective cost
Congruent melting Not subcooling/supercooling [a]	ΔT^a (ºC)	To assure that melting and solidification can proceed in a narrow temperature range.
Not phase segregation or separation [b]	-	Assure a long lifetime

[a] Subcooling refers to a liquid existing at a temperature below its normal melting temperature. If that temperature is not reached, PCM will not solidify at all and stored heat will not be released (Mehling & Cabeza, 2008).

[b] Phase segregation or separation refers to the conversion of a single-phase system into a multi-phase system (separation of components of a solution).

Main drawbacks of SHSMs are related to their low energy density (owing to space limitation for building applications) and system's self-discharge, which can be substantial due to heat losses (particularly for long-period storage) (Tatsidjodoung et al., 2013). Main drawbacks of LHSMs are related to their high cost, low thermal conductivity, relative large volume change, flammability, supercooling, corrosiveness, and thermal reliability and stability after undergoing a great number of thermal cycles (Zhou et al., 2012).

3.2 Thermochemical storage materials

TCES can be classified into chemical reactions and/or sorption processes (Yu et al., 2013). Chemical reaction is characterized by a change in chemical bounds of the compound involved during the reaction (dissociation and recombination). Energy can be stored through the endothermic reaction and released by the exothermic reverse reaction. Sorption storage can be defined as a phenomenon of fixation or capture of a gas or a vapour by a sorbent substance in condensed state (solid or liquid) by means of less intense interactions. Also, sorption processes can involve thermo-physical and thermo-chemical aspects (N'Tsoukpoe et al., 2009).

Main advantages of TCES are high stored energy density, negligible heat losses, and long-term storage capacity. Characterization parameters of thermochemical storage materials (TSMs) and their influences are showed in Table 3.

Table 3 Characterization parameters of TSMs.

Property	Measure	Influences
Density (ρ)	Kg/m^3	Thermal storage capacity
Heat input	Wh/kg - MJ/m^3	
Heat output (storage density)	Wh/kg - MJ/m^3	
Storage efficiency ($Q_{released}/Q_{stored}$)	%	
Degree of sorbate loading in the adsorption/absorption equilibrium	% (for physical sorption)	
Charging/desorption temperature	ºC	Thermal application
Discharging/sorption temperature	ºC	
Thermal conductivity (□)	W/m·ºC	Charging/ discharging time
Kinetic of reaction or reaction rate	m/s	
Evolution of output temperature close to the equilibrium point	ºC	
Operating pressure range	Pa	System design requirements
Thermal reliability (Efficiency after thermal cycles)	%	Performance over several cycles
Chemical stability (After thermal cycles)	Changes in spectrum after thermal cycles	No decomposition of material after thermal cycles
Thermal stability	Weight loss %	No degradation of material with the increase of temperature

Thermal energy stored during a specific time period through thermochemical processes is given by Eq. 3 (Kalaiselvam & Parameshwaran, 2014).

$$C_1C_2 + Heat\ input \Rightarrow C_1 + C_2 \rightrightarrows storage \rightrightarrows C_1 + C_2 \Rightarrow C_1\,C_2 + Heat\ output \quad (3)$$

Other requirements for selecting TMs are defined in Table 4. They are based on safety, environmental impact, lifetime and compatibility.

Table 4 Requirements or constraints for selecting of TSMs.

Requirements or constraints	Measure	Reasons
Not toxic, not flammable nonexplosive and nonreactive	-	Safety
Non-polluting Low CO_2-eq footprint	CO_2-eq/kg	Environmental impact
Non-corrosiveness	-	Compatibility with other materials
Availability and low price	€/m^3	Competitiveness and effective cost
Moderate operating pressure range	Pa	No excessive pressure conditions and especially no high vacuum. Less system requirements

Main drawbacks of TSMs are related to their high cost, inappropriate operation temperatures, non-effective discharge power for building applications due to low kinetic of reaction and low output temperature close to the equilibrium point, and low/moderate efficiency in storage process.

4 Results. Characterization of available thermal energy storage materials for building application

4.1 Sensible heat storage materials

SHSMs materials can be classified into liquid or solid storage materials (Kalaiselvam & Parameshwaran, 2014). Some common solid storage materials are rocks, stones, bricks, concrete, dry and wet earth/soil, wood, plasterboard, and corkboard. Usual liquid storage materials are water or oils, pure as well as of alcohol derivatives. Table 5 summarizes thermal properties of main construction materials for sensible heat storage, according to (ISO 10456:2007; Tudela 1982).

Table 5 Available SHSMs for building applications.

Reference	Material	Thermal properties			
		Density (kg/m^3)	Thermal conductivity (W/m·ºC)	Specific heat capacity (kJ/kg·K)	Volumetric heat capacity (kJ/m^3·K)
ISO 10456:2007	Gypsum (coating)	1000	0.4	1	1000
	Gypsum (plasterboard)	900	0.25	1	900
(Tudela, 1982)	Ceramic brick	1800	0.73	0.92	1656
ISO 10456:2007	Ceramic tile	2000	1	0.8	1600
	Lime mortar	1600	0.8	1	1600
	Cement mortar	1800	1	1	1800
	Concrete	2000	1.35	1	2000
	Concrete (high density)	2400	2	1	2400
	Reinforced concrete (2%)	2400	2.5	1	2400
	Wood	450	0.12	1.6	720
	Wood	700	0.18	1.6	1120
	Plywood boards	500	0.13	1.6	800
	Plywood boards	1000	0.24	1.6	1600
	Cement bonded particleboard	1200	0.23	1.5	1800
	Oriented strand board	600	0.14	1.7	1020
	Oriented strand board	900	0.18	1.7	1530
	Water (40ºC)	990	0.63	4.19	4148
	Rock	2800-1500	3.5-0.85	1	2150
	Limestone	1600-2600	0.85-2.3	1	2100
	Sand and gravel	1700-2200	2	0.910-1.180	2072
	Clay or silt	1200-1800	1,5	1.670-2.500	3252

Solid materials are preferable for heating applications. Rock beds and concrete can be operated in a temperature range from 40 to 75 ºC (Kalaiselvam & Parameshwaran, 2014). Due to typically poor heat exchange by conduction between solid materials (such as rocks), stratification can be maintained over considerable time periods (Tatsidjodoung et al., 2013). However, solids are also characterized by some limitations such as reduced energy storage density as compared to water (on an average of 1200kJ/m^{3}K (Tatsidjodoung et al., 2013)), associated costs involved in operation and maintenance of the storage units, and risks of self-discharge in long-term storage.

Liquid materials are widely used for cooling and heating purposes. Water is the best available liquid material employed due to its high specific heat capacity, availability and low cost. Main drawbacks are related to the high investment cost of liquid storage infrastructures and the risk of leakages.

4.2 Latent heat storage materials

Solid-liquid PCM is the most common process in building solutions. They are classified into organic compounds (paraffins, fatty acids, alcohols and esters), in-organic compounds (salt hydrates and metals) and eutectics mixtures (which are mixtures of inorganics and/or organics) (Abhat, 1983; Zhou et al., 2012) (Fig. 3).

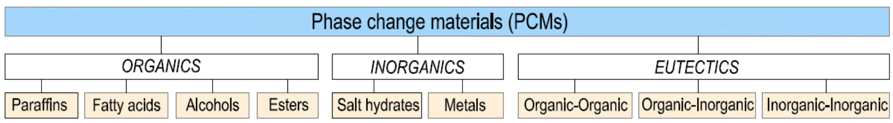

Fig. 3 Classification of solid-liquid PCMs.

Paraffins, fatty acids, salt hydrates and eutectic mixtures are the most common PCMs for building applications (Zhou et al., 2012). The use of paraffins is derived from their favourable properties (negligible supercooling, non-corrosiveness, chemical stability, no phase segregation and low cost) (Abhat, 1983; Hasnain S.M., 1998; Tatsidjodoung et al., 2013). They are characterized by an average latent heat capacity (LHC) around 170 MJ/m^3 and an average thermal conductivity around 0.2 W/mK (Zhou et al., 2012). Meanwhile, salt hydrates have higher LHC and thermal conductivity, around 350MJ/m^3 and 0.5 W/mK, respectively (Zhou et al., 2012)). They often present some drawbacks such us low thermal reliability for long-operation periods (Sharma, Tyagi, Chen, & Buddhi, 2009), phase segregation, subcooling and corrosiveness (Hasnain S.M., 1998; Mehling & Cabeza, 2008; Tatsidjodoung et al., 2013). Eutectics are mixtures of inorganic PCMs (mostly hydrated salts) and/or organic PCMs. One of the most important characteristics of eutectics is their capability to phase change congruently without phase segregation (Tatsidjodoung et al., 2013).

Fatty acids, esters and alcohols are usually highly flammable and present low thermal conductivity and varying level of toxicity (Sharma et al., 2009), thus their application to buildings is hindered. Regarding metals, despite they present high volumetric fusion heat because of their high density (Sharma et al., 2009), and high thermal conductivity (Tatsidjodoung et al., 2013), their usage in buildings is limited due to their scarce availability and their very high cost.

Currently, numerous PCMs are available in the market for temperature range from -10 to +120ºC. Fig. 4 illustrates volumetric latent heat capacity and melting temperature of 250 commercially available PCMs from main existing companies (Table 6). They are mainly based on paraffins, salt hydrates and eutectic alloys. Sensible TES process in water is also illustrated as a reference value (yellow line).

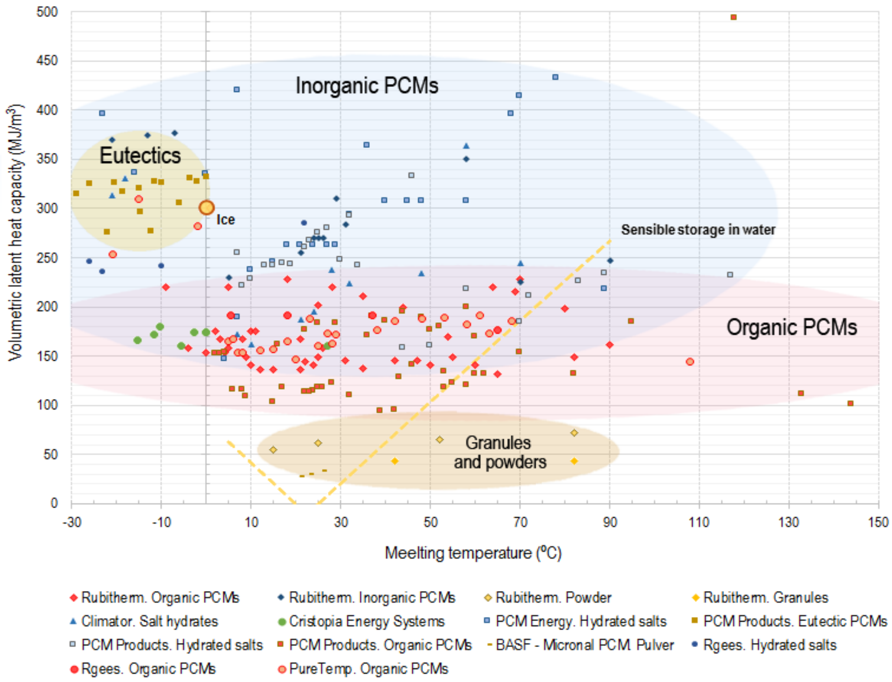

Fig. 4 Available PCMs from different companies for building applications. Own elaboration

Table 6 Main available PCM companies around the world.

Company	Country of origin	Available materials
Rubitherm GmbH	Germany	Organics, inorganics, powders and granules
Climator	Sweden	Salt hydrates
Cristopia Energy Systems	India and France	-
PCM Energy	India	Salt hydrates
PCM Products Ltd	UK	Sub Zero Eutectics, salt hydrates and organics
BASF - Micronal PCM	Germany	Powders
RGees. savENRG™	EEUU	Organics and inorganics
Entropy solutions. PureTemp	EEUU	Organics

The LHC of available inorganic materials (blue colour marks) ranges between 150 and 430MJ/m^3. On the other hand, the LHC of available organic materials is found in a lower range, between 100 and 250 MJ/m^3 (red colour marks). Sensible heat storage in water, which can be used as reference, has a capacity around 50 and 250MJ/m^3 for cooling and heating respectively.

4.3 Thermochemical storage materials

Nowadays TSMs are not available as commercial solutions for TES in buildings. Research in this field is in an early stage (Tatsidjodoung et al., 2013). High cost of materials, poor heat and mass transfer capacity, and system energy density substantially lower than material energy density are the main barriers for a commercial deployment (N'Tsoukpoe et al., 2009). Materials under research for building applications are mainly focused on solar energy storage solutions for long-term storage. According to Fig. 5, tested TSMs in the literature are classified into physical adsorption materials (zeolite and silica gel), liquid absorption materials, and chemical reactions through solid chemical reaction materials or composite materials (CSMP) (N'Tsoukpoe et al., 2009; Yu et al., 2013).

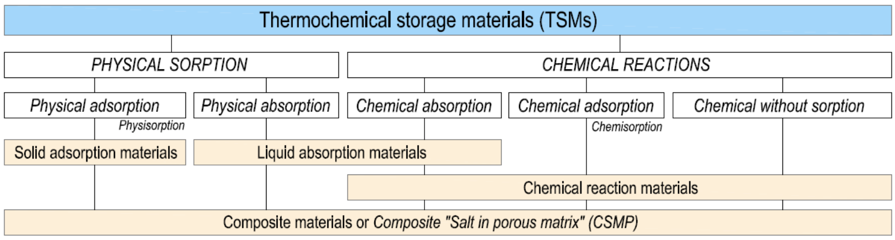

Fig. 5 Classification of TSMs for building applications.

Most promising materials have been tested through coordinated international programs and projects. Some of these studies are related to Task 32 (2003-2007) (C. Bales et al., 2008; Chris Bales et al., 2008), and Task 42 (2009-2015) (Davidson et al., 2013) in the framework of the Solar Heating and Cooling Programme of the International Energy Agency (SHC-ECES). Other are related to European projects such as HYDES, MODESTORE (2003-2012), MERITS (2007-20013), COMTES (2012-2016) or E-HUB (2010-2014). Table 7 shows the performance results of tested TSMs for building applications.

Silica gel 127B and zeolites (4A, 5A, 13X and NaX) have been tested in open and closed physical adsorption cycles. Silica gel 127B/H_2O has been studied in a closed adsorption cycle within the HYDES and MODESTORE projects (2003-2012). The results showed that the silica gel/water system has to operate between water contents of 3-13%, which reduced its real TES capacity. Thus, for achieving a real seasonal energy storage capacity, large storage volumes are necessary. Zeolite 13X has been identified as one of the best adsorbents due to its high water uptake, which provides a high energy storage density. Hence, this material has attracted the interest of researchers, being most of current demonstration projects based on zeolite 13X, such as E-Hub project (2010-2014) or COMTES project (2012-2016). Besides, novel solid porous materials for adsorption processes have been proposed for the use TES applications, such as aluminophosphates (AlPOs), silico-aluminophosphates (SAPOs) and metal-organic frameworks (MOFs). However, their high production cost is a main barrier for implementation (Yu et al., 2013).

Liquid materials such as LiCl, NaOH, $CaCl_2$ and LiBr have been tested in closed absorption cycles. These aqueous absorption materials present higher energy density values than solid adsorption materials, with temperatures in a proper range for building applications. Also, liquid desiccants can be pumped and used directly as heat transfer fluid.

Table 7 TSMs reported in literature for building applications.

	Reference	Material	Thermal properties		
			Charge (ºC)	Discharge (ºC)	Volumetric storage (MJ/m^3)
Solid physical adsorption	**Modestore** (Chris Bales et al., 2008; Wagner, Janhig, Isaksson, & Hausner, 2006)	Silica gel 127B/H_2O	88	70-40	180
	SPF (Chris Bales et al., 2008)	Zeolite 13X/ H_2O	180	55	648
	E-Hub project (Finck et al., 2014)	Zeolite 5A/ H_2O	103	53-36	170
	COMTES project (Helden et al., 2014)	Zeolite 13XBF/ H_2O	150	75-47	277
	MonoSorp (Chris Bales et al., 2008)	Zeolite 4A/Air	180	35-10	576
	(Zettl, Englmair, & Steinmaurer, 2014)	Zeolite 4A/Air	180	60-35	346
			230	60-35	421
	(Johannes et al., 2015)	Zeolite NaX/Air	180	57	
			120	57	
	E-Hub project (Vanhoudt et al. 2014)	Zeolite 13X/Air	120-160	70-45	
	(Hauer, 2007)	Zeolite 13X/ H_2O	130-180	65	446
Liquid absorption	**TCA -** TASK 32 - IEA-SCH (Chris Bales et al., 2008)	LiCl salt/H_2O	46-87	30-25	911
	(Chris Bales et al., 2008; Weber & Dorer, 2008)	NaOH/H_2O	95-150	70	900
	COMTES project (Berg Johansen & Furbo, 2015; Daguenet-Frick et al., 2014)	NaOH/H_2O	95	32.8 or 56	
	(Davidson et al., 2013; Quinnell et al., 2012)	$CaCl_2/H_2O$	117-138		382-1372
	(N'Tsoukpoe, Le Pierrès, & Luo, 2013)	LiBr/H_2O	75-90	30-40	
Chemical reaction	TASK 32 - IEA-SCH (Chris Bales et al., 2008)	$MgSO_4·7H_2O$	150		1512
	Dutch WAELS project (van Essen et al., 2009)	$MgSO_4·7H_2O$	60-275	25	1800
	E-hub project (Vanhoudt et al., 2014; Zondag et al., 2013)	$MgCl_2/H_2O$	130	64-50	500
CSPM	**MCES** (Lammak et al., 2004)	Na_2S-graphite/H_2O	80-95		
	SWEAT (de Boer et al., 2004)	Na_2S-cellulose/H_2O	>83	45-35	
	(Mauran, Lahmidi, & Goetz, 2008)	$SrBr_2$-ENG/H_2O	80	35	216
	Adv. CWS-NT. Combisystem (Davidson et al., 2013; Mette et al., 2013)	Zeolite 4A-$CaCl_2/H_2O$	130	25	900

Chemical reaction materials such as magnesium sulphate ($MgSO_4$) or calcium chloride ($CaCl_2$), which have higher energy storage density than previous materials, have been tested. However, very slow reaction rates associated with a low temperature lift in the reactor (Mette et al., 2013) and low chemical stability after cycling (Vanhoudt et al., 2014) are usually found. In order to improve chemical storage material properties, and particularly to enhance the reaction rate and heat release, a new family of composite sorbents, called Composite “salt porous matrix” (CSPM), has recently been proposed. These composite materials are based on two sorbents: the host matrix with porous structure and high thermal conductivity to improve the reaction rate and thus the heat release (zeolite, silica gel, alumina, expanded vermiculite, aerogel, etc.), and an inorganic salt solution (LiCl, $CaCl_2$, $MgCl_2$, $MgSO_4$, $Ca(NO_3)_2$, $LiNO_3$, etc.), placed inside the matrix, which enhances further the energy storage.

Taking into account all reported TSMs, and despite their high energy density, there is not currently any available material that satisfies all requirements for efficient thermochemical storage in the building sector. High cost, low discharge capacities, variable thermal power over time, and thermal stability and reliability under cycling are commonly issues to be overcome. Also, final prototype energy density is significantly below the material storage density (by more than a 50% (N’Tsoukpoe et al., 2009).

5 Conclusions

Energy storage using sensible heat storage materials and latent heat storage materials is identified as a very attractive strategy for high energy efficiency buildings. The characteristic evaluation of available thermal energy storage materials allows us to conclude that:

- Water and underground materials are currently the best available materials due to their high sensible storage capacity and moderate thermal diffusivity. Besides, underground solutions show the benefit of using the ground as insulation, thus they store thermal energy more efficiently than above-ground solutions.
- Currently, there are a large number of different organic and inorganic latent heat storage materials commercially available. Phase change materials based on hydrated salts are assessed as the best material due to their high volumetric latent heat storage capacity and high thermal conductivity. However, further considerations on long-term stability and reliability and other issues that may affect safety, reliability and practicability should be considered.

Regarding thermochemical storage materials, despite high energy densities and high storage ability for long-term storage periods due to their negligible heat losses, currently there is no available material that satisfies all requirements for a viable deployment. Thermochemical storage is not mature enough for building applications. Additional research efforts are needed to optimize operation conditions, storage cycles efficiency, material cost and systems design. In addition, thermochemical solutions require different tanks and heat exchangers reducing significantly the effective storage density and increasing final costs, which should be carefully considered for small-scale applications.

Acknowledgements The authors would like to thank the Spanish Ministry of Education, Culture and Sport for financial support via a research grant: the FPU contract granted to Francisco Jesús Lizana Moral (FPU14/06583).

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