Review on Sustainable Thermal Energy Storage Technology with Packed Bed Regenerator

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Abstract

The information regarding various Thermal Energy Storage (TES) techniques and methodology (Sensible, Latent and Thermo-chemical) typically classified and followed in numerous literatures has been comprehensively discussed in the present study. In view of, up surging demand, rising cost and depleting resources of fossil fuel on earth. There has been a great rise in the demand of TESs predominantly STES in the recent days. The goal of the present paper is to exhaustively analyses different storage methodology & materials which are techno-feasible and cost effective. On the basis of above theoretical investigation the results and conclusion are drawn.

Keywords—Energy Storage Method, Thermal Energy Storage, Latent, Sensible, PCM Materials, Thermo-chemical.

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1. Introduction

According to the BP Statistical Review approximately 84% of the world energy consumption depends primarily on non-renewable sources of energy contributing (Petroleum 34%, Coal 28% & Natural Gas 22%) and rest on renewable sources of energy. Because of exhaustive extraction of these non-renewable sources of energy through mining, drilling and digging well on land and offshore by each and every developing and developed economy and Growing demand and consumption of fossil fuels (hydrocarbon-containing material) like coal, petroleum, natural gas, crude oil and non-renewable wastes formed in the earth's crust after millions of years due to geological actions under high heat and temperature, obviously being limited in existence lead to depletion of such resources and increase dependencies on other alternative renewable sources of energy.

Nomenclature

Q	Heat (J)	V	Volume (m^3)
M	Mass (kg)	ρ	Density (kg/m^3)
T	Temperature (K)	T_m	Melting temperature (K)
T_i	Initial temperature (K)	α	Thermal diffusivity[m2/s], $\alpha=\lambda/(\rho C_p)$
T_f	Final temperature (K)	ΔV	Volume change on melting (m^3)
Δ_{hm}	Heat of melting (J/kg)	C_p	Specific heat capacity (J/(kg-K)
Δ_{Hr}	Enthalpy of reaction (J/kg)	ΔT	Temperature difference (K)
λ	Thermal conductivity (W/m-K)		

TES is the technologies which can be used for space heating and solar drying in order to, reduce consumption and sustainability issue. Therefore, TESs is the most prevalent &attractive method of storing solar heat which can be purposely utilized has been the active area of R&D.

The focus of present literature review is to investigate different storage system their pros-cons and characteristics. Particularly this review is based on STES, PCMs and thermo-chemical storage.

2. Energy Storage

Availability of energy with efficiency is the backbone of any nation's economic growth and development. As the society grapple about environmental impact of fossil fuel, engineers and stakeholders are eventually rapidly projecting their concerns towards energy storage methods and technology. Energy storage aids to resilience by operating as a standby energy source when power plant output is disrupted. The notion energy storage isn't a new concept. The desire for a more robust and cleaner grid has prompted to a huge provision in the establishment of new energy storage facilities, as well as the development of new or improved energy storage systems as shown in figure 1. The efficacy of an energy storage facility is judged by its ability to respond fast to changes in demand, the rate of energy loss throughout the operation, its estimated energy storage capacity, and how readily it can be recharged.

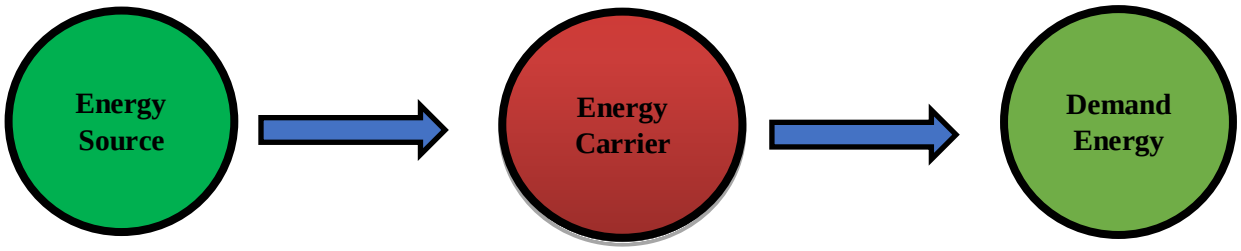

Figure 1: Energy Storage Concepts [22]

3. Energy Storage Method Classification:

There are several methods for storing energy as shown in figure 2, each with its own set of benefits and drawbacks. However, as a result of technological advancements, methods and technologies have continued to evolve and improve throughout time. The battery was the first systematic device, and it is still the most often utilized technology for energy storage. These technologies can be grouped separately based on the purpose for which the energy is being stored. Electrical energy storage and thermal energy storage are two of them.

4. Thermal Energy Storage System and their classification:

TES stores heat energy by heating or cooling a storage device, which may then be used for heating, cooling, or power generation at a later time as shown in figure 3. Energy can be stored in several forms in U.E, K.E, P.E, and chemical energy, as well as the transformation and transfer of energy between these forms, are all part of thermal energy storage processes.[23]Thermal storage and hybridization have been recognized as significant R&D technological targets for improving operational versatility and energy dispatchability [13]. Thermal energy storage (TES) technology is seen to offer the best chance of balancing demand and supply by overcoming the intermittency and volatility of real-world heat sources, resulting in a more versatile, sustainable, and dependable thermal energy system. TES finds a role in thermodynamic systems due to its inconsistency in availability and continual change in solar radiation [15]. Patrice Pinel et al. (2011). Thermo-chemical

storage is the act of storing energy by breaking the bond between water with apposite substance, one of the particular products is evaporated and condensed for future usage. The act of storing heat almost isothermally in a material is known as latent storage referred as PCM. Melting ice, paraffin, fatty acid, and salt are often utilized in this method of storage. Building a dedicated huge concrete seasonal solar storage system would appear to be less cost effective than utilizing free material, like solid or rocks. most past and present systems have therefore stored heat in sensile form. Given the financial constraints, and sensible seasonal storage system lend to be large, therefore water rocks and soil are mostly used as a storage medium.[5] The following factors can be used to define an energy storage system: size, power, effectiveness, storage duration, and cost, as shown in figure 4, depicts the many forms of solar energy thermal energy storage.

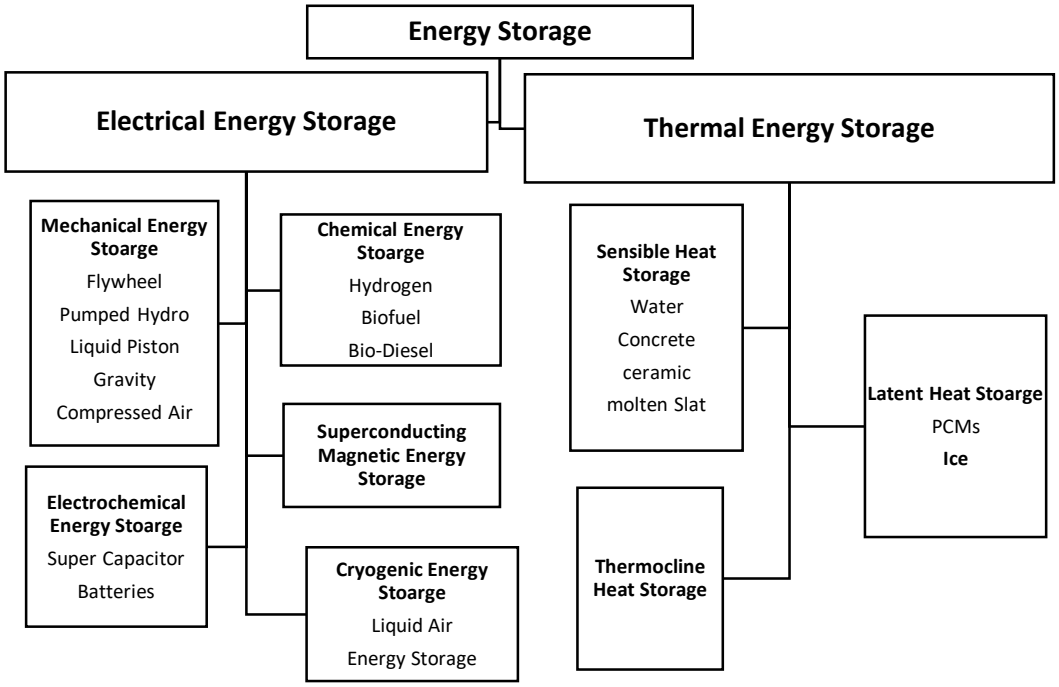

Figure 2: Energy Storage Technology Classification [23]

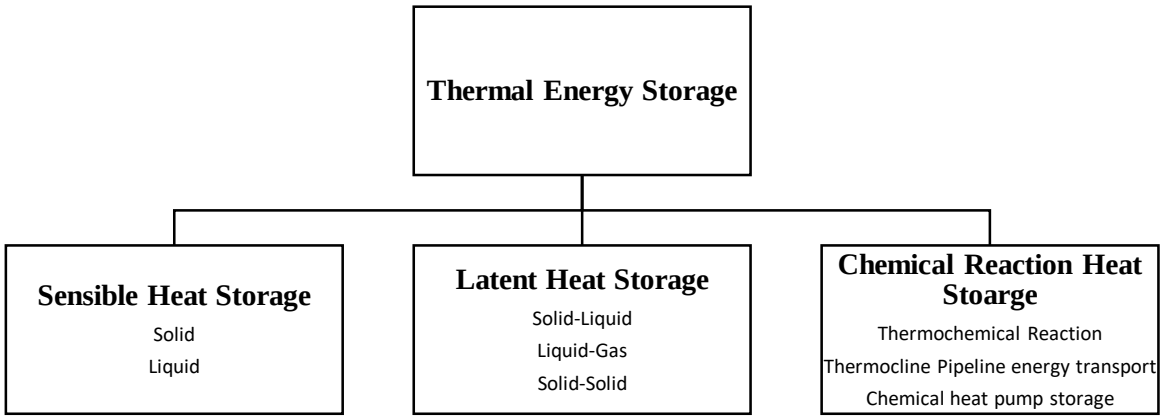

Figure 3: Classification of Thermal Energy Storage [24]

5. Sensible Heat Thermal Storage system:

Sensible heat storage is associated with storage material temperature change (ΔT) and Specific heat capacity at constant pressure (Cp). When heat is absorbed, the temperature of the storage material rises, and when energy is rejected, the temperature decreases. Sensible heat storage relies on the temperature gradient and requires appropriate insulation to prolong the temperature distribution [13]. The quantitative correlation among Specific heat capacity at constant pressure (Cp) & temperature change (ΔT) is governed by simple equation:

$$Q\ sensible = \int_{T1}^{T2} m.\ Cp(\Delta T) \quad (1)$$

$$Q\ sensible = m.\ Cp(T2-T1) \quad (2)$$

ensible heat storage material is either in solid or liquid form water is commonly employed as sensible heat storage medium in various industrial and residential applications. Other alternative solid and liquid materials like concrete, ceramic and oil which are available at cheap rate and having excellent Thermal conductivity (λ), Specific heat capacity (Cp) and density(ρ) are tested, Amaya V. Novo et al. (2010). A variety of shapes and configurations were assessed, in order to de-escalate the heat losses and economic aspects and it was determined that "the volume storage unit expands as ^3 of characteristic dim., while the Area heat-loss rises as ^2, reducing the amount of loss-to-capacity ratio as the size increases." Because of its enormous heat capacity [3], waterwith density(ρ) (at 4 oC)999.975 kg/m3, Thermal conductivity (λ) 0.598 W/mK at 20 °C, Specific heat (Cp) (at 15°C/60°F): 4.187 kJ/kgK and energy density(ε) of 11.7Kwh/m3 seems to be most suitablemedium for SHS. Also, sensible heat store in the material depends on heat capacity (Cp) and thermal diffusivity (α = λ/(ρCp)). Decho Phueakphum, Kittitep Fuenkajorn (2010) The goal of this study is to figure out how effective and efficient a solar thermal energy storage system using basaltic rock, Buriram basalt has a density of 2810 kg/m3 on average, specific heat 1174 KJ/Kg-K, thermal conductivity 1070 W/m-K, diffusivity of heat 5015*10-7 m2/s, coefficient of thermal expansion 504*10-6 K constructing a scaled down model.[2] A.I. Fernandez et al. (2010) A design-led strategy is established in order to pick the highest-grade materials performance for a certain specification, ensuring that the decision is appropriate based on factors such as (limits of electrical and thermal properties, minimizing cost, mass etc.). In the temperature range of 150-200 degrees Celsius, two instances for the storage of sensible thermal energy were investigated. For long-term storage, a substance must fulfill the following requirements: The maximum service temperature should not go below 150°C, and thermal conductivity should be excellent. [4] The LHS system with a PCM media [6] has a storage capacity Q in J, which is given by:

$$Q\ total = Q\ sensible,\ solid + Q\ latent + Q\ sensible,\ liquid$$

$$Q\ pcm/latent = \int m.\ Cp,\ solid\ \Delta T + m.\ \Delta hm + \int m.\ Cp,\ liquid\ \Delta T \quad (3)$$

$$Q\ pcm/latent = m\ \{Cp,\ solid\ (Tm-Ti) + \Delta hm + Cp,\ liquid\ (Tf - Tm)\} \quad (4)$$

D.L. Zhao et al. (2011) The goal of this project was to accomplish two things. The initial stage was to build a solar heating model with a gravel bed as the heating storage medium and the next step was to build a model for the system in the TRNSYS environment and tweak the design parameters to boost the solar fraction. The ideal values, as well as the yearly solar percentage, were generally in line with common practice.[6]R. Srinivasan, B.N. Raghu Nandan (2012) For packed beds with lengths of 200 mm and 300 mm, Reynolds numbers based on packing diameter were calculated, in range of 0.6-104 to 8.5-104. solid packing of the bed was made up of 9.5 mm and 5 mm steel-spheres that were positioned correctly to prevent flow entrance and exit effects. The packing proportion and intake flow Reynolds number had a significant impact on axial heat dissipation rates along the packed duct/conduit. At high Reynolds numbers, the internal energy transformation of the packed bed owing to axial conduction was insignificant. [9] M.E. Navarro et al. (2012) The higher the volumetric heat retention capacity of the solid, the less Volume/Thermal unit is required; Alternative

low-cost for sensible heat energy storage devices for solid material are examined through the vaporization of by-products produced from the mining and metallurgical industries. These recycled materials have been demonstrated to have a lot of potential in terms of thermal energy storage.[10] Parfait Tatsidjodoung et al. (2012) One of the most essential features of storage materials is their energy density. Because space is so important in structures, the volumetric energy density will be assessed. For each of the three principal thermal energy storage modalities (sensible heat, latent heat, and thermo-chemical heat), Water is still the most prevalent material that delivers the optimal cost-to-heat-retention-capacity, density-to-environmental-impact ratio. [11]

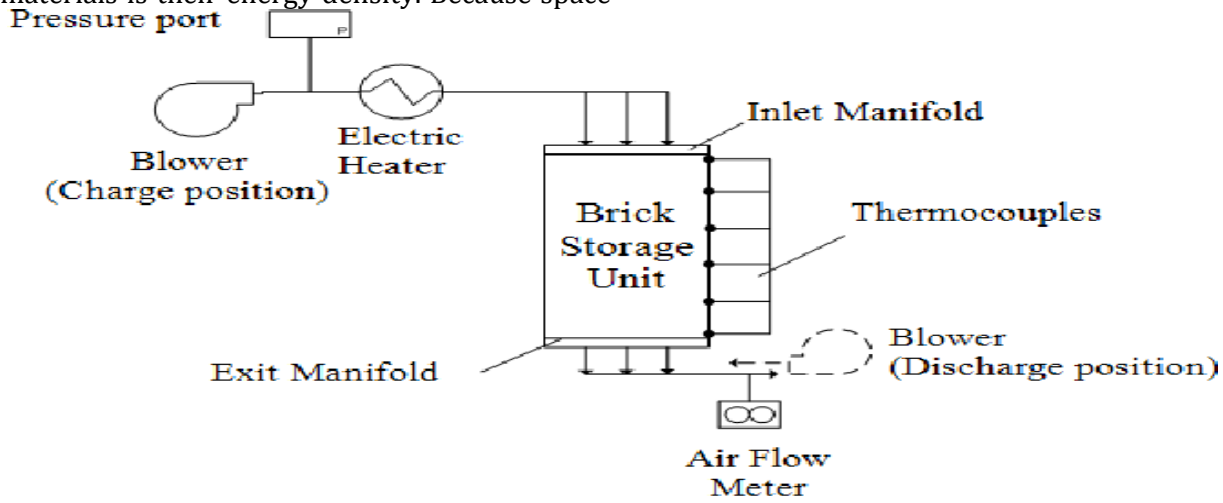

Figure 4: Schematic layout of thermal energy storage (Sensible/latent) [21]

Mitsuo Sagara(1969) For determining thermal characteristics in packed beds columns of solid particles, a temperature pulse method was devised. A highly conductive fluid, such as mercury, is required for exact measurements. The axial Peclet number may be calculated using water. The technique uses diffusion rate, fluid-to-particle propagation, and intra particle transport as heat dispersion interpretations. The technique fails because solid-to-solid conduction is crucial for small particle sizes. [17] G. Spiga, M. Spigat (1982). The goal of this study is to find a unique solution to the problem of sensible heat flow and storage in solid-fluid phenomena. Any cyclical thermal energy source's fluid and solid temperature profiles are thoroughly explored, and a simple solution approach for determining the fluid and solid temperature profiles is presented.[18] The Pebble-Heater buffers the heat energy of the flue gas by using natural materials and ceramic materials such as basalt rock or (Al2O3) alumina oxide gravels. Because this design separates power generation from heat energy delivery, the CHP may provide grid-balancing electrical power while also supplying thermal energy on demand. The Pebble-Heater has proven to be effective in both theoretical and practical trials.[19] When storage height is increased from 600 to 1400 cm, the normalized thermocline thickness decreases 42 to 32 %, reducing the effective discharge performance from 89.5 percent to 86 percent. In addition to efficiently minimizing thermal losses from the system, proper insulation for a standby system with a consistent starting temperature assist to a homogenous circulation of molten salt temperature in the circumferential direction.

Table 1: Properties of sensible heat storage material (Solid/ Liquid)

Materials		**T, [ºC]**	**ρ, [kg/m3]**	**Cp, [kJ/(kg·K)]**	**λ, [W/(mK)]**	**10^6 α, [m2 /s]**
SOLID	Brick	20	1800	0.84	0.5	0.33
	Concrete	20	2200	0.72	1.45	0.94
	Graphite	20	2200	0.61	155	120

	Soil (gravel)	20	2040	1.84	0.59	0.16
	NaCl	20	2165	0.86	6.5	3.5
LIQUID	Water	20	998	4.183	0.598	0.142
	Molten salt	230	1950	1.57	0.5	0.16
	Paraffin	20	900	2.13	0.26	0.14
	Sodium	100	927	1.385	85.84	66.85

6. Latent Heat Thermal Energy Storage System:

Because of their ability to release or absorb energy as their physical state changes, either from solid to liquid or liquid to gaseous, LHS materials are referred to as PCMs. Heat storage happens without any considerable change in temperature. When a storage medium transitions from solid to liquid, liquid to gas, or gas to liquid, LHS is dependent on the heat absorption or release. Mahmud M. Alkilani et al. (2011) A PCM with high latent heat and wide surface area for heat flow is desired for an improved thermal performance of a solar air heater. The researchers' ideas are targeted at pairing solar energy collector and thermal energy storage to extenuate heat dissipation, volume, and system cost. [7] Eduard Oro et al. (2012) The very first computational model relies on the Brinkman equation and is a progressive model, whereas the 2nd numerical model considers phase change material capsules as discrete particles, energy-equation model. In packed bed systems, the Brinkman model may be used to describe the flow pattern inside porous media and the heat transfer processes. On the other side, the energy-equation model may be utilized to investigate the temperature differential within the PCM capsules. Both ideas are supported by the authors' experimental findings.[8] Y. Tian a, C.Y. Zhao (2013) The three types of concentrating solar accumulator reviewed and contrasted are parabolic dish collectors, heliostat field collectors and parabolic trough collectors. A comparison of materials used in high-temperature thermal energy storage systems, as well as a brief contrast of different types of thermal energy storage systems, is provided. Molten salts with excellent properties are the best materials for high-temperature thermal storage applications [12]

C. Xu et al. (2012) augmenting the intake flow rate by 10 times or altering the temperature differential between the heated and cooled salt from 200 ° C to 50 ° C had no dominance on thermocline formation and the accompanying net discharge efficiency. Because when porosity surpasses a threshold value (0.22), it has no influence on thermocline formation, a low porosity may be employed for an economical storage system as long as it is not too small.When it comes to storage height, increasing from 600 to 1400 cm lowers the widely accepted thermocline thickness from 42 to 32 percent, lowering the effective discharge efficiency from 89.5 percent to 86 percent. [20]

Table 2: Properties of PCMs

PCMs		T (°C)	Δhm(J/g)	λs(W/mK)	λl(W/mK)	Cp,s(J/gK)	Cp,l(J/gK)	ρl(g/cm³)
Salt hydrates	H2O	0	334	2.3	0.56	2.1	4.22	1
	H2O	30	180	1.1	0.5	1.4	2.1	1.56
Pure Metals	Na	98	113	122	87	1.36	1.38	0.93
	Al	660	397	211	91	1.18	1.18	2.38
	Zn	419	112	100	50	0.45	0.48	6.76
Anhydrou	KF·4H2	19	230	~	~	1.8	2.4	1.46

s salts	O							
	LiNO3	254	36	1.4	0.6	1.8	1.6-2.0	1.78
	NaNO2	270	180	0.7-1.3	0.5-0.7	~	1.6-1.8	1.81
	NaOH	322	210	0.9	0.8	2	2.1	2.13
	KNO3	337	180	~	0.4-0.5	1.4	1.3-1.4	1.87

7. Thermo-chemical Energy Storage System:

Thermo-chemical materials are used in TCS. Energy is stored in chemical compound by reversible Endothermic and Exothermic reaction. An endothermic process stores energy in the form of chemical molecules A and B, which are then recombined in an exothermic reaction to restore the energy.

D.S. Murthy Fixed-bed regenerators are extensively employed for heat recovery and storage at the solid-gas interface. A novel Moving-Port technology is being developed to allow a fixed bed to replicate the functionality of a mobile bed, in order to assess the effectiveness of stationary and moving simulators.

It has been observed that at practicality of substituting three blast furnaces and the heat regeneration of an adsorption duct/bed with a simulated kinetically mobile bed regenerator. Findings reveal that, better heat dissipation intensification has been discovered to be attainable [14].

A computational technique for handling unstable temperature in immobile bed heat regenerators has been developed under the restrictions of nonuniform onset temperature variation and altering fluid transfer rate. Examples highlight the effects of critical design and operational features on the ensuing boundary control approach, the dynamic reaction of solids and fluid temperatures throughout the duct, and the system's thermal performance. Certain remarkable events have been discovered in the parallel flow system. [16]

8. Result and Discussion:

The comparative study allows us to draw the following results: Sensible heat storage is conceptually the best and widely used method for storing heat. Solid sensible heat storing materials like rock, marble, pebble gravel, soil and clay are all chemically inert, cheap and abundant some having great potential of heat storage but the drawbacks are they have large pressure drop also they occupy more storage volume, as shown in figure 5 & figure 6.

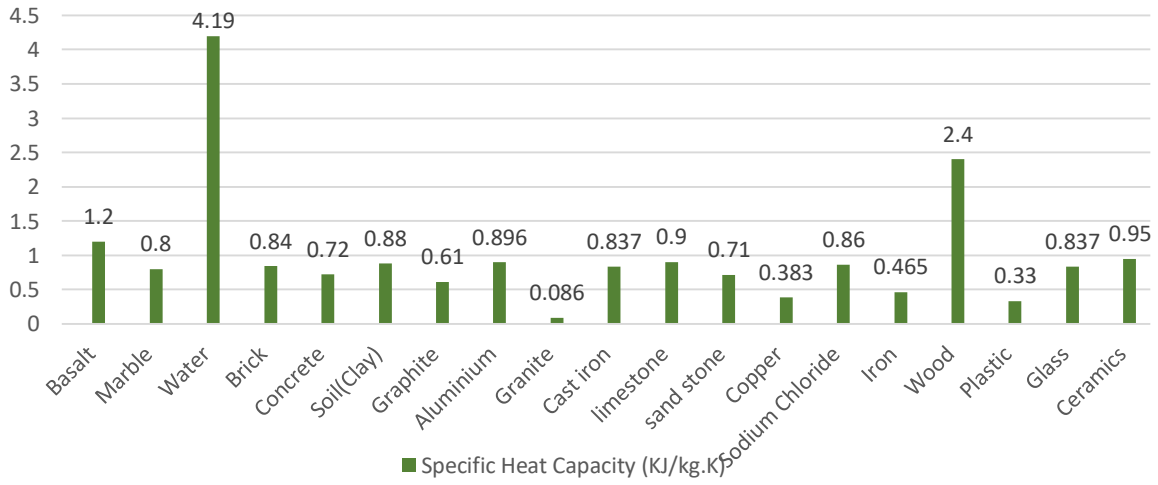

Figure 5: Specific Heat Capacity of SHS materials

Water is still most prevalent method for storing heat because of its abundance, techno-economic feasibility and having high heat capacity and thermal diffusivity rate. gas are great heat carriers at elevated temperature but because of their extremely low diffusivity rate and volumetric specific heat capacities they are found to be unsuitable, as shown in figure 6 & figure 9.

[25-29] PCMs or latent heat storage material store 14 time more heat as compared to SHS material they are environment friendly and enhanced thermo-physical properties high enthalpy of fusion, large range of melting/solidification temperature offering higher heat storage capacity and intent charging and discharging time. PCMs (Salt hydrates, Metal alloys &Sugar alcohols) need to be focused and synthesized because they are most suitable for specific applications, as shown in figure 9 & figure 8.

Thermocline storage systems (Chemical reaction TSMs and liquid adsorption materials and Chemical composites) offer great potential because of its high energy storage density and volumetric storage capacity. heat absorption and emission are equivalent to reaction enthalpy of the chemical compound but the inadequacy of knowledge and thermal reliability and stability have not been studied exhaustively their usage are limited to small scale application only.

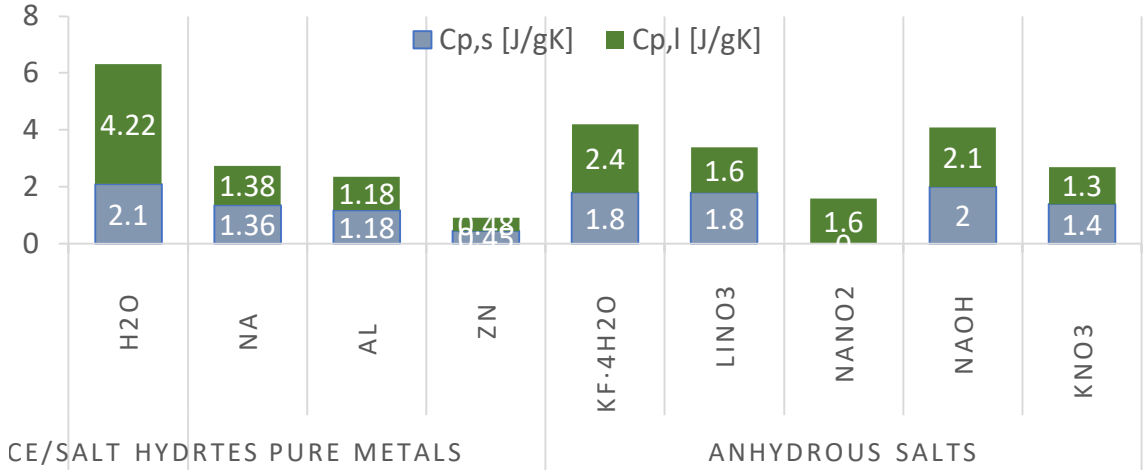

Figure 6: Specific Heat Capacity of PCMs

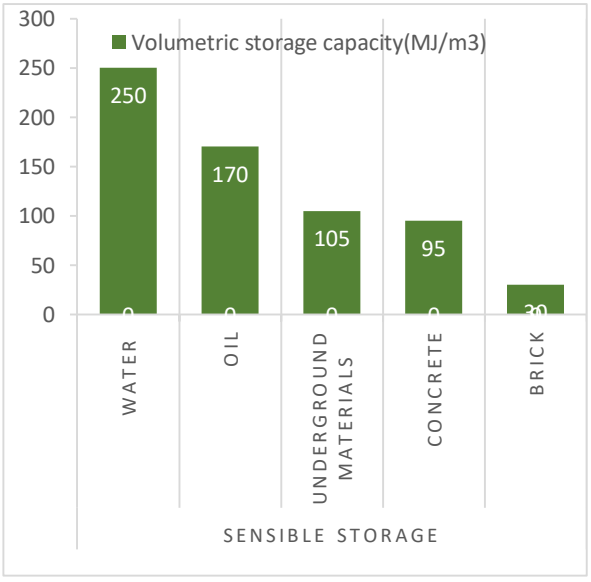

Figure 7: Volumetric Storage Capacity of SHS

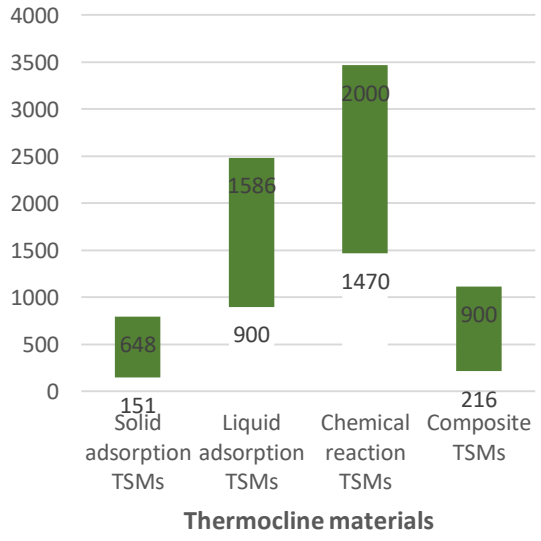

Figure 8: Volumetric Storage Capacity of TCM

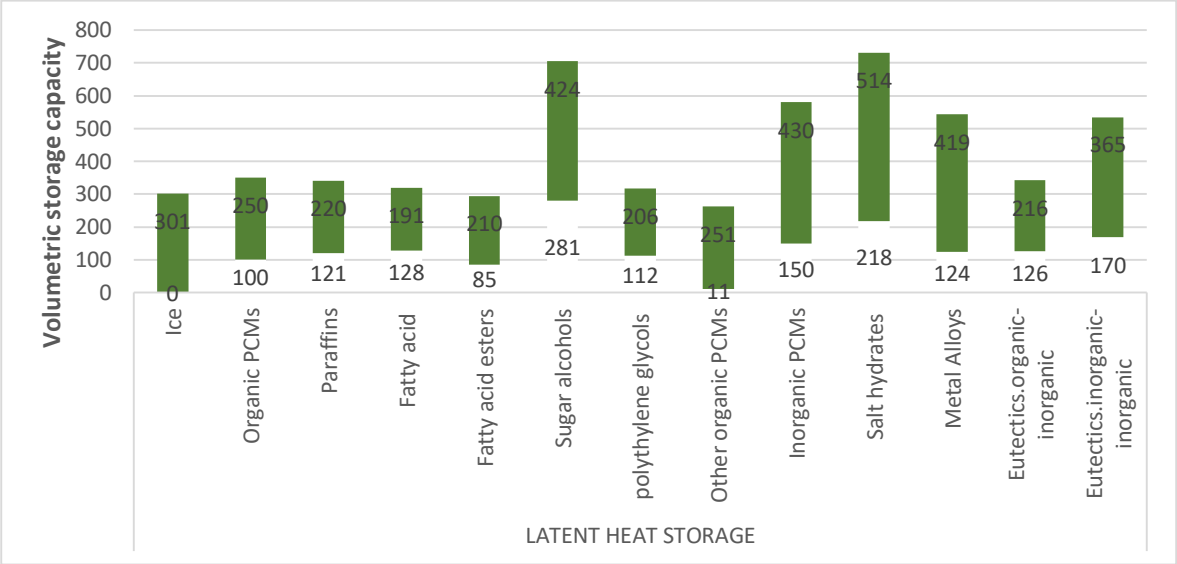

Figure 9: Volumetric Storage Capacity PCMs

9. Conclusion:

The present review has still a diverse research gaps need to be improved and addressed with the recent advancement in the coming years to enhance the performance reliability and applicability of TESs. in order to bridge some research gaps following conclusion have been proposed from the present study:

- Although the presented study is restricted to the study of comparative study of thermo-physical properties of TES material but to select a suitable material& TESs one should consider other parameters such as applicable scale, storage time and period, range of operating temperature, capacity range, energy density, recycle time.
- Different rock, marble and pebble-bed based heat storage system has been studied previously. Many other materials like (Nylon-6,6, Rubber &Clay) having good thermal performance wisely need to be Research& Developed
- While selecting a suitable material and TESs one should must consider dimensionless parameter (Reynolds number, Nusselt number, Grashoff number).
- mass flow rate charging and discharging time, operation time &cost socio-economic benefit, techno-economic feasibility is also need to be considered

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