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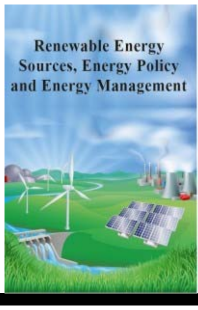

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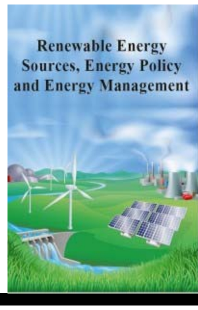

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Review Article

Thermochemical Heat Storage System for Domestic Application: A Review

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ABSTRACT

Solar radiation is regarded as one of the most possible sources of energy in many parts of the planet. Around the globe, scientists are investigating alternative and renewable energy sources. It is just as critical to developing energy storage systems as it is to study alternative energy sources. The current challenge for technology experts is to store energy in the right form and turn this stored energy into the traditionally desired format. Energy storage not only eliminates the supply-demand imbalance, but also increases the capacity, reliability, and energy efficiency of energy systems. This review article discussed the different types of thermal energy storage and the principles of thermochemical energy storage, as well as the three most important conditions: charging temperature, energy density, and the cost factor of common materials with temperatures near to the boiling point of solar air collector standards , , as well as who achieves a higher energy density and cheaper price. As a result, this review article has recommended the most acceptable materials for seasonal heat storage systems in residential applications based on these main aspects.

Keywords: Solar Energy, Thermal energy storage, Thermochemical material, Thermochemical heat storage, Thermochemical energy storage, Cost effect

1. Introduction

Climate change has an important influence on energy systems, including temperature shifts and greenhouse gas emissions [1-2]. Solar energy has the highest energy potential of any renewable energy option because it is both free and limitless [3- 4]. The transient storing of thermal energy in the form of hot or cold substances for later use under varying conditions such as temperature, location, or power is known as thermal energy storage (TES). There technologies are important in systems involving renewable energies and other energy resources because they can make their activity more effective. Especially by bridging the time between when energy is extracted and when it is used, and thus can help to overcome the mismatch between energy production and energy usage [5-6]. That is, they are normally useful for correcting the mismatch between the supply and demand of energy.

Solar thermal power generates very few polluting emissions or raises environmental concerns that conventional, fossil, or thermal power generation does [7]. Recently, thermal energy storage looks to be critical for improving energy efficiency and maximizing the use of renewable energy resources on a broad scale [8]. Furthermore, thermochemical energy storage systems (THSS) offer a cost-effective solution to the problem of storing solar energy during the summer for usage during the winter [9].
There are three principle thermal energy storage (TES) modes: sensible, latent , and thermochemical [10-11]. Generally, a sensible warm stockpiling framework store the thermal energy by expanding the temperature of the capacity medium, without causing any stage progress in the capacity material [12]. A latent heat TES (LHTES) system stores energy when a material transitions from one phase to another, such as solid to solid, solid to

liquid, and liquid to gas, while maintaining a constant temperature [3,13]. Cost decrease, load moving, coordinating with request with accessibility, and petroleum product reusing are the whole benefits of energy stockpiling. It likewise intends to limit energy squander and further develop energy usage quality, just as force lattice arrangement, activity, and recurrence control [14-16].

Figure 1. Classification of energy storage type [10].

2. Thermochemical Energy Storage

The chemical TES classification incorporates sorption and thermochemical reactions [17-18]. In thermochemical storage, "thermal energy is typically stored in the form of bond energy of a reversible chemical reaction involving one or more chemical compounds as the storage material " [19]. Generally, there are three working stages: endothermic separation, stockpiling of response items, an exothermic response of the separated items as displayed in figure 6. The heat is recovered by re-vanishing the consolidated item and re-holding it (sorption) with the other substance. Some molecules, referred to as sorbents, have a high affinity for water (sorbate) with which they develop a strong bond. An endothermic process involves the breakdown of that link (desorption) and subsequent evaporation of one of the components. Sorption, the opposite process, is exothermic. Adsorption (by a solid), absorption (by a liquid), and solid/gas reactions are the three types of sorption processes. [20] the fascination between the gas and strong in physisorption are brought about by Van der Waals power [21]. A framework utilizing level plate solar collectors applied to direct floor heating exhibited the relations between the accomplished force levels and the heating storage limits of reactive composites [22].

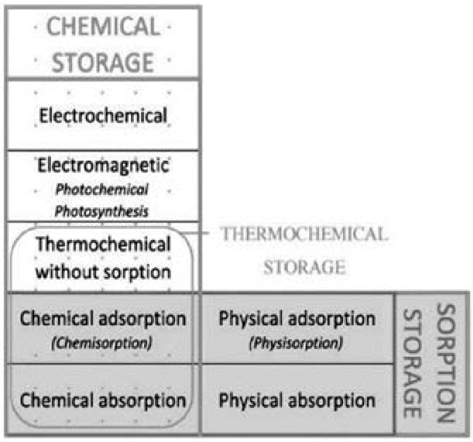

Figure 2. Classification of chemical storage and sorption [23].

Thermochemical energy storage systems can be ordered into two major types, called open system and close system. In an open system, the functioning liquid in the vaporous state is straight for wardly delivered to the climate (or space) (delivering entropy). In the other mean, moist air from the general climate is utilized to hydrate the substance. In a closed system, no fluid is shared with the air, and the working liquid isn't quickly discharged. However, the entropy is discharged to the environment by a heat exchanger interface [24-28]. A heat exchanger, commonly referred to as the condenser/evaporator, transfers heat to and from the adsorbent in a closed sorption system. To keep the HTF, generally water, flowing from the adsorber to the condenser, the heat must be delivered to the absorber at the same time as it is removed from the condenser. The energy density is lower in closed sorption systems than in open sorption systems.

Air transports water vapour and heat in and out of the adsorbents in an open sorption storage system. Hot air desorbs the water from the adsorbent during the desorption process, leaving the system colder and saturated. The adsorption process begins with humidified chilly air entering the adsorbent, which adsorbs the water vapour and releases heat, leaving the air warm and dry [5].

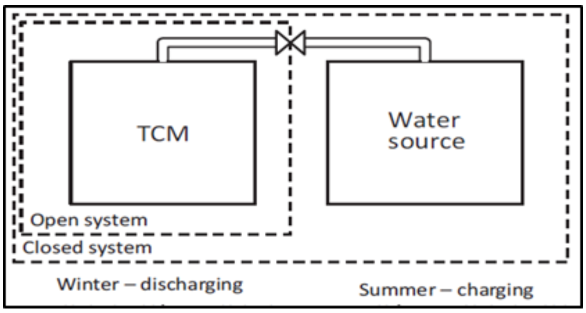

Figure 3. A schematic overview of a thermochemical material reactor [29]

2.1. Energy Density

Energy density is the main property of any material to be used in thermochemical energy storage (TCES) [30]. The effective system energy density is dependent to the choice of an open or closed system. With capacity limits going from 0.5 to 3 GJ m^3 (140-830 kWh m^3) and recovery temperatures going from 20 to 200 °C, the energy thickness for a close system is 3.0 GJ/m^3 and a porosity of 30%. While the energy density for an open system is 1.8 GJ/m^3 [31, 29]. Because of higher energy density. TES systems can provide more conservative energy storage compared with latent and sensible TES. This attribute is particularly beneficial where space for the TES is limited [32] as shown in figure 4.

Materials used in sorption storage have the highest storage density of all repetitive Storage media and some of the materials may even offer storage density close to that of biomass [34] as shown in figure 5.

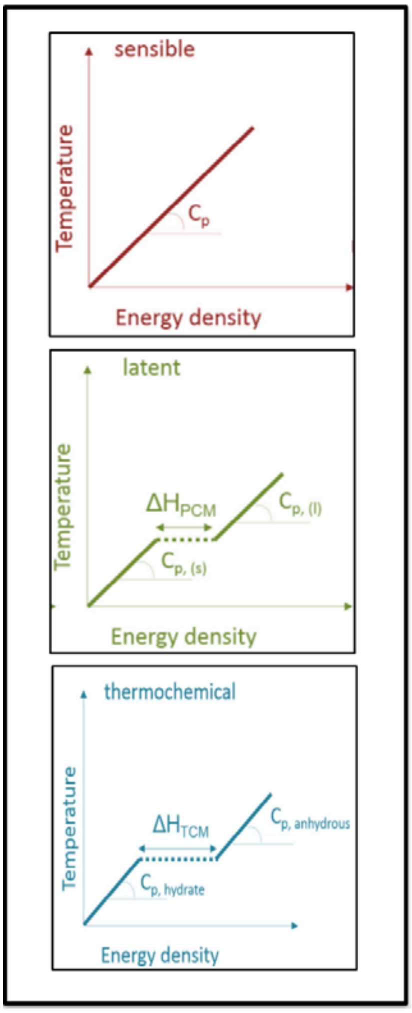

Figure 4. Schematic diagram of temperature against energy density for sensible, latent, and thermochemical heat storage [33]

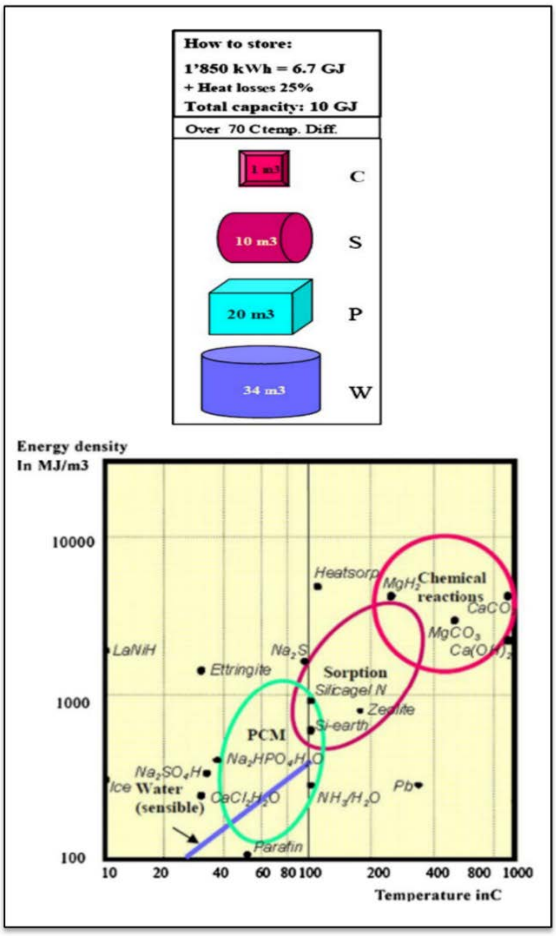

Figure 5. Energy storage distributions of various energy storage models are presented [35]

2.2 Principle of Thermochemical Energy Storage

The thermochemical energy storage system deals with the rule of reversible compound responses. In this system, the energy is stored by break bringing down the compound particles, and then energy is released by joining the separated molecules [18, 62]. The basic reaction process utilized here is:

C (solid) + Q (heat) ⇔ A (fluid/gas) + B (solid)

Adding solar heat at a reaction temperature greater than the turnover temperature causes the solid C to breakdown into the fluid or gas A and the solid B throughout the summer. In winter materials A and B are kept apart, A and B are combined in the winter to initiate the reverse reaction at a lower temperature than the turnover temperature. This generates heat for domestic consumption [36]. Material A can be a hydroxide, hydrate, carbonate, ammoniate, or other compound, whereas substance B can be water, CO, ammonia, hydrogen, or another compound. There are no phase restrictions, although C is generally a solid or a liquid, whereas A and B can be any phase [32].

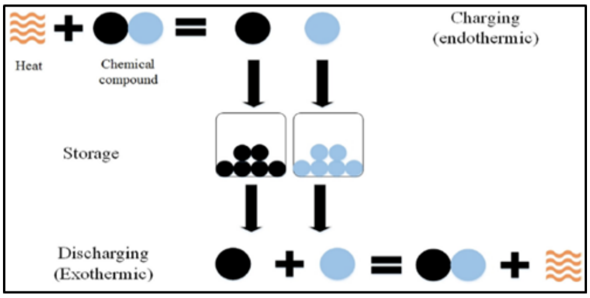

Figure 6. Processes involved in a thermochemical energy storage cycle [10]

2.3 Thermochemical Energy Storage Components and Processes

There are at least three phases in the Thermochemical Energy Storage process: charging, storing, and discharging. [6]. The process of charging is an endothermic reaction. The dissociation of compound C necessitates the application of a necessary energy supply it can occur in various ways and depends predominantly on the thermo-chemical material used [37]. For hydrates or hydroxides and zeolites, this is obtained by drying in which bound water is expelled. On the other hand, storage media based on oxidation and reduction reactions need the energy to reduce oxidizing formulation.

Storing means that material A and B will be created and both are stored at this stage with discharging. A and B are combined in an exothermal reaction and material C is regenerated. In the meantime, the recovered energy is liberated from this stage [37] where the method of unloading the TCS is dependent on the material used. Whereas metallic materials (redox) must be oxidized and moistened by burning the material, zeolites, together with hydrated and hydroxide materials [38].

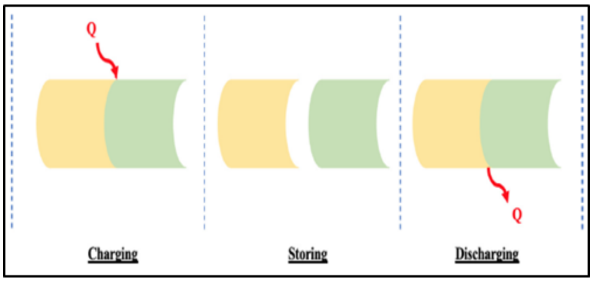

Figure 7. The process of a thermochemical energy storage cycle [30]

Table 1 Steps in the charging and discharging operations [13].

Discharging Temperature	Charging Temperature
Solar air collectors preheat the air between (20-25°C).	In (80-100°C) The solar air collectors heat the air.
The air has been humidified. The relative humidity (RH) ranges between 60 and 80 percent.	This technique uses a by-pass line and does not humidify the air.
Humid air enters the THS	Hot dry air enters the THS
Heat is generated whilst vapor is absorbed by the sorbent (45 – 55) °C.	The heated air is transmitted to the sorbent, which then releases moisture.
An exit duct collects the hot air.	A duct collects the warm, humid outlet air.
Heat is transferred to the building with fan coils.	Exhaust air is discharged into the surrounding environment.
The exhaust air is released onto the environment.	

3. Thermochemical heat storage materials

Several parameters should be tested before choosing a thermochemical substance since they influence THS structures such as cost, availability, toxicity, protection, corrosiveness, energy storage density, reaction temperature, heat transfer coefficient, heat transfer fluid, good thermal and chemical stability under operating conditions are all important considerations [39- 41].

Moreover, ideal materials for a THS scheme should have the following special characteristics:

(i) High storage density of energy.
(ii) High sorbate absorption.
(iii) To guarantee designed output strength, appropriate heat and mass transport characteristics are required. Easy to handle non-poisonous
(iv) Low-cost per-kWh heat energy recovery [42, 35].

The vapor pressure under the specified operating conditions should be used to select the solvent for a specific heat storage system. The safety measures imposed by higher vapor pressures with three suitable solvents [43-44]. The thermochemical materials water, ammonia, and methanol can be described as heat storage solutions. These three solvents may form complexes with high-energy inorganic salts, and the discharge temperature for most complexes is between 20 and 150 degrees Celsius [45] as shown in table 2.

Table 2 Three solvents' core properties for heat recovery in solvent complexes [45].

Solvent	NH_3	CH_3OH	H_2O
Vapor pressure at 300 K (MPa)	1.2	0.05	0.012
Boiling temperature (K)	240	337	373
Melting temperature (K)	196	176	273.2
Flammability (%)	15 – 25	6 – 36	-
Toxicity (ppm) (US PEL)	50	200	-

3.1. Types of Thermo-Chemical Heat Storage

The four primary kinds of heat storage are "liquid absorption, solid adsorption, chemical reaction, and composite materials." [46-49]. Besides, the terms 'desorption' and 'dehydration' interchangeably to denote the release of water from the hydrated salt [49]. The binding of a gas or liquid on the inner surface of a porous substance is referred to as adsorption. During the desorption process, heat is applied to the material, extracting the adsorbed components from the surface. Heat is released as soon as adsorption begins, and this shows the discharging phase of the storage period [5]. A powerful material must have a large surface region with a well-structured porous structure, high mechanical toughness and flexibility, and low regeneration temperature (120°C) [42].

3.1.1. Adsorption of solids and novel porous materials

The reactions in solid adsorption are typically exothermic (discharge heat). Table 3 would broadly expound on this sort of sorption substance. Because of the porosity of the adsorption materials, average materials, for example, muds (vermiculite, column layered silica), silica gels, zeolites, carbon fiber, etc are frequently utilized as host grids to give the composite design [42, 50-51], consider that by utilizing zeolite or silica gel as an adsorbent, there can be up to 30–40% of the heaviness of the capacity medium [5]. The critical disservices of solid-gas substance responses are helpless heat and mass exchange yield in the receptive bed and the straightforward cycle's low thermodynamic capacity [52].

3.1.2. Liquid absorption

Fluid retention is a substance/real interaction that occurs when a fluid adsorbent enters the top layer of a sorbent, reverting to its design and adjusting its definition [53-54]. According to the reference[13], these mentioned salts in table 2 suffer from an extreme problem known as deliquescence. In which hygroscopic salts become saturated at some relative humidity (RH) thresholds, and phenomena such as swelling and agglomeration must be considered, since they can create unnecessary impediments to mass transfer, resulting in a decrease in charging and discharging rate [47].

Table 3 THS materials used in solid adsorption [45]

Thermochemical Materials	SSA (M^2/g)	Porosity (Cm^3/g)	Water Uptake (Kg/Kg)	Regeneration Temperature ℃	*Cost ($ /Kg)
Vermiculite	8–10	2.8	0.03	25.6 – 48.1	1.00 - 4.31
Silica Gel	750-850	1	0.23	130 -150	41.65
Zeolite	550-600	0.18-0.47, 0.3	0.3	> 200	0.10
Activated Carbon Powder	700-1850	0.5-1.5	0.19	150- 180	1.00 - 2.00
SBA-15 (8.1 nm)	483	0.66	0.5-0.7	~100	1.6
SBA-15	486	0.78	-	-	2.66
MCM-41	933	1.12	0.7	19.85-149.85	2.66
Attapulgite	98-113.7	Average Pore diameter =64 nm	0.2	105	10.00 - 50.00
Activated carbon fiber	700-2500	Average Pore diameter =1.2 – 3 nm	-	-	2.25 – 4.00
Zeolite	680	Pore diameter (Å) =8	0.24	120-180	10.67

Furthermore, the use of these products is dependent on the exothermic reaction of salt in a low state of hydration with water vapor, which results in the formation of either a higher hydrated phase or a salt solution within the pores. Water uptake is affected by the relative humidity of the decay (HRD). If the relative humidity (RH) of the atmosphere increases the DRH, the salt absorbs water and dissolves until it reaches equilibrium, that is, until the solution's water activity matches the relative humidity. At relative humidity levels below HRD, salt absorbs water vapor, resulting in a more hydrated state without a solution. The equations below describe the two scenarios [55].

Salt(s)+H_2O(g)↔hydrated form (s) for RH < DRH **Eq. 1**

Salt(s)+H_2O(g)↔solution(l) for RH > DRH **Eq. 2**

RH_{del}–RH_{deh} 20% at 25°C, RH_{del} refers to the RH at which the highest load dissolves, whereas RH_{deh} refers to the RH at which the highest load dehydrates. The hygrothermal stability of salts, as demonstrated by the HRD values, is another valuable property of salts during the sorption reaction phase. This property indicates the degree of moisturization [13].

In referance [29] Under these conditions, the energy density on the material level ought to be more prominent than 1.3 GJ/m^3, the hydration temperature ought to be more noteworthy than 50 °C. The parchedness temperature ought to be under 120 °C, and the liquefying point ought to be more noteworthy than the drying out temperature.

Table 4 Characteristics of certain materials used in the fluid absorption process.

Year	Authors	Thermochemical Materials	DRH Value	Load Temp (°C)	Discharging Temperature (°C)	Energy Density GJ/m³	***Cost ($/Kg)	References
2008	Van Essen, others	$MgSO_4$	92 % at 25°C	<150°C	-	*0.694	191.52	[57]
2018	Sögütoglu, others	$MgCl_2$	33 % at 25°C	104	61	*`0.477	57.45	[33]
		K_2CO_3	-	65	59	1.3	67.80	
		Na_2S	-	82	66	2.79	32.45	
2018	Jarimi, others	LiCl	11 % at 25°C	66-87	30	*1.2	7.08	[13]
		LiBr	7 % at 30°C	40-90	30	*0.56	245.54	
		$CaCl_2$	29 % at 30°C	45-138	-	*0.22	114.47	
2018	Krese, others	KOH	-	-		**0.727	31.48	[21]
		NaOH	-	50-95	70	**0.55-0.89	32.89	
		$SrBr_2$	-	80	-	**0.2-1.1	0.78	

* The original unit of energy density in the source was by KJ/kg where 1KJ/kg=0.001GJ/ m³
**The original unit of energy density in the source was by kWh/m³ where 1GJ=277.78kWh.
***The original price from https://www.sigmaaldrich.com/ was in Euro (€) where converter by Currency into ($).

3.1.3. Development of compound sorption materials

Recent research on THS involves composite materials that blend salts and matrices, or salts in a matrix. Composite tissues have undergone extensive research to reduce the inconvenience associated with the use of salt hydrates , this can be accomplished by using a materialmixing or impregnation and consolidating the salt into an inert (expanded graphite, vermiculite, etc.) or active (zeolite, silica gel) material [56]. In addition, the host matrix is essential for preventing agglomeration and swelling of salts, contributing to improved moisture diffusion during thermal regeneration.

3.1.4. Chemical Reaction

There is currently a range of products and reactions compatible with energy storage thermochemical systems. It is important that salt hydrates can incorporate large amounts of water into the crystal network. When a hydrated salt is heated, the crystalline water is flushed out. In an occasionally extended capacity setting. Solar heat can be used to dry salt hydrate in summer. Therefore, the anhydrous salt is set aside as needed. In winter, this salt encounters an opposite response and provides energy in the form of heat, which can be used for building applications like heating water and central heating. Furthermore, this salt passes through a reverse response, providing energy in the form of heat, and may be used in developing applications, for example, hot water [57-58].

A portion of the promising thermochemical storage materials that have been as of late recognized is recorded in table 5. The table additionally gives the two significant variables to material determinations the upsides of the response temperature and Energy thickness ES [37]. In this unique situation, which should all be more noteworthy than 1.4 GJ/m^3 for an open framework and 2.0 GJ/m^3 for a closed system [29].

Table 5. The features of TCM have been investigated by various authors.

Year	Author	Compound	Dissociation reaction			Energy density of C GJ/m³	Charging Temperature ℃	*Cost ($ /kg)	Ref.
			Product (C)	Solid Reactant (A)	Working Fluid (B)				
2013	Solé, other	Magnesium Chloride Hexahydrate	$MgCl_2.6H_2O$	$MgCl_2.2H_2O$	$4H_2O$	0.9	115-130	61.14	[59]
2017	Scapino, other	Calcium Chloride Dihydrate	$CaCl_2.2H_2O$	$CaCl_2.H_2O$	H_2O	0.4	95	45.39	[60]
2013	Ding, other	Calcium Sulphate Dihydrate	$CaSO_4.2H_2O$	$CaSO_4$	H_2O	1.4	89	125.59	[37]
		Sodium Sulfide Pentahydrate	$Na_2S.5H_2O$	Na_2S	$5H_2O$	2.8	110	75.71	
		Calcium (II) Hydroxide	$Ca(OH)_2$	CaO	H_2O	2.2	25	47.60	
2005	Bales, Chris	Magnesium Sulphate Hexahydrate	$MgSO_4.7H_2O$	$MgSO_4$	H_2O	2.8	122-150	62.35	[24]
		Strontium Bromide Hexahydrate	$SrBr_2.6H_2O$	$SrBr_2.H_2O$	$5H_2O$	0.22	70-80	** 10.00-50.00	
		Copper (II) Sulfate Pentahydrate	$CuSO_4.5H_2O$	$CuSO_4.H_2O$	$4H_2O$	-	40-60	73.60	
		Aluminum Potassium Sulfate Dodecahydrate	$KAl(SO_4)_{2.12}$ H_2O	$KAl(SO_4)_{2.3}$ H_2O	$9H_2O$	-	65	*** 338.00 479.00	

*The original price from https://www.sigmaaldrich.com/ was in Euro (€) and was converted by Currency into ($).
** The price form https://www.alibaba.com/
*** https://www.chembid.com/

4. Cost Analysis

The price of the thermochemical content used for storage. As a result, the volume of storage material influences the costs for shipping, storage, and the energy used to charge and discharge the storage material. The ware cost is a basic limit condition impacting the monetary suitability of any heat storage system.

Thus, uncommon earth metals, for example, $EuCl_3$ and $GdCl_3$ are not thought of. As an asid, the price is stated in euros per kilogram, which is the price of one kilogram of stable hydrate under all circumstances.

5. Results and Conclusions

This article is a review and evaluation of previous studies conducted in the field of seasonal energy conservation and all the information discussed and eligible results are taken from previous studies.The primary goal of this research is to discover chemical materials that can be used to store seasonal energy. A variety of materials and their properties were explored, with emphasis on materials with charge temperatures ranging from 100 to 130 °C and their energy density who can work in an open environment without protection or stability, as well as the acceptable price between them.

According to the major conditions reviewed in this article, $MgCl_2$ and $CaCl_2.2H_2O$ were the best substances for attaining the requisite charging temperatures, while both $MgSO_4.7H_2O$ and $Na_2S.5H_2O$ show increasing in energy density. In contrast, when the cost factor of the reviewed substances was considered, the salt hydrates $MgSO_4.7H_2O$ had the lowest price compared to the others.

Finally, the results generally suggested that salt hydrates might fulfill the occasional heat storage criteria based on the properties of the materials reviwed that performed energy storage (for domestic heating and hot faucet water utilizing the hydration response).

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