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Review

Current, Projected Performance and Costs of Thermal Energy Storage

Laura Pompei [1,*], Fabio Nardecchia [1] and Adio Miliozzi [2]

[1] Department of Astronautical Electrical and Energy Engineering—DIAEE, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy
[2] Energy Technologies and Renewable Sources Departement, ENEA—Casaccia Research Center, Via Anguillarese, 301, 00123 Rome, Italy
* Correspondence: laura.pompei@uniroma1.it

Abstract: The technology for storing thermal energy as sensible heat, latent heat, or thermochemical energy has greatly evolved in recent years, and it is expected to grow up to about 10.1 billion US dollars by 2027. A thermal energy storage (TES) system can significantly improve industrial energy efficiency and eliminate the need for additional energy supply in commercial and residential applications. This study is a first-of-its-kind specific review of the current projected performance and costs of thermal energy storage. This paper presents an overview of the main typologies of sensible heat (SH-TES), latent heat (LH-TES), and thermochemical energy (TCS) as well as their application in European countries. With regard to future challenges, the installation of TES systems in buildings is being implemented at a rate of 5%; cogeneration application with TES is attested to 10.2%; TES installation in the industry sector accounts for 5% of the final energy consumption. From the market perspective, the share of TES is expected to be dominated by SH-TES technologies due to their residential and industrial applications. With regard to the cost, the SH-TES system is typically more affordable than the LH-TES system or the TCS system because it consists of a simple tank containing the medium and the charging/discharging equipment.

Keywords: renewable energy resource; thermal energy storage; thermochemical energy storage; TES applications

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1. Introduction

The current energy transition promoted by global and local policies increases the relevance of overcoming the constraints of renewable energy source (RES) employment [1]. Such limitations are related to the intermittent nature of RES, as well as its dependence on climate conditions [2]. Within this framework, growing investment in storage technologies has been attributed to the ability to enhance renewable energy systems in a variety of ways, including increased flexibility, energy source utilization, and demand response.

Electrical, thermal, and thermochemical storage are the main types of storing energy, and each of them involves a wide range of technological systems [3–6]. In addition, a promising energy storage technology involves an electrolyzing process to produce hydrogen during a period of surplus energy and resupply it to microgrids [7,8]. Hydrogen energy storage systems are employed in large-scale power systems due to being more flexible compared with other TES [9,10]. However, there are various types of thermal storage systems available on the market that can be selected based on the application of performance and cost [11]. Several studies in the literature highlight the role of TES in supporting solar energy systems, such as concentrated solar power (CSP) [12]. In CSP technology, molten salt is typically used since it has an operating temperature between 150 and 560 °C, which is suitable for steam turbines [13]. Moreover, the current TES costs are low compared with those of storage in chemical batteries [14,15].

With regard to thermochemical energy storage (TCS), the high storage density allows for the reduction in storage space, and it ensures long-term storage [16,17]. This peculiarity is still an attractive one compared with other TES types. TCS can be obtained with two types of thermochemical processes: adsorption, and reaction. Heat storage using thermochemical adsorption with salt hydrates has received increasing international attention because of its environmental adaptability, heat storage capacity, environmental protection standards, and preparation costs [18]. As highlighted in the literature [19,20], TCS is also well-suited to storing solar power for buildings as their thermochemical materials provide much lower heat loss, enabling long-term seasonal storage and lower charging temperatures. However, the performance of TCS systems needs to be improved in terms of cost-effectiveness and efficiency [19].

The potential of phase change materials (PCMs) can be very useful for improving the performance of thermal systems that are operated on solar energy [20]. Experimental studies evaluating the performance of solar thermal systems based on a range of PCMs were observed [21]. Asgharian et al. [22] conducted modelling and simulations of solar energy storage systems with PCMs. The authors show that the most uniform temperature distribution can be achieved by using a PCM with a melting temperature for each specific climate. Among fast-charging innovations, it is suggested that further reduction in charging times can be achieved by improving the design of fast-charging thermal energy storage (dynamic melting) [23]. For this numerical study, two layers of metal foam were used to further accelerate the process, demonstrating the importance of a liquid PCM film that accelerates the melting process throughout the convection mechanism. Following this path, another study investigated the melting process of the nano-enhanced phase change material by applying the Taguchi optimization approach [24].

Since district heating (DH) systems typically use water as their heat carrier, water can often be used as a storage medium for DH systems [25–27]. A wide range of capacities and charge/discharge rates are possible with water tanks due to their high heat capacity, availability, chemical stability, low cost, and suitability for DH operations [27].

The seasonal nature of solar energy, characterized by high solar insolation in the summer and low solar insolation in the winter, allows ground source heat pumps (GSHP) to be useful for solar energy systems [28]. In line with this, it was demonstrated by Xia et al. [29] that GSHP-PVT (Photovoltaic thermal) systems can enhance long-term system performance by conserving the ground's thermal energy when charged by the PVT. As demonstrated by Dannemand et al. [30], configurations and controls can make a huge difference in the performance of PVT and heat pumps, implementing buffer storage. The PVT collector is designed to store excess heat, which is not immediately used for the hot water storage or the heat pump, in buffer storage.

Summarizing the introduction section, the main TES can be collected within the relevant studies that are focused on (Table 1).

Table 1. Thermal energy storage typology and applications.

Thermal Storage Type	Technology	Potentialities	References
Sensible Heat Thermal Energy Storage (SH-TES)	Water for low temperature (hot water thanks)	Variety of capacities and charge/discharge rates; high heat capacity; chemical stability; low cost; suitable for district heating	[25–27]
	Molten salts for higher temperatures	Suitable for solar energy systems; low cost compared with other TES.	[11–14]
	Solid storage materials		

Table 1. *Cont.*

Thermal Storage Type	Technology	Potentialities	References
Latent Heat Thermal Storage (LH-TES)	Phase change materials (PCMs)	High thermal storage capacity; improved thermal conductivity and less corrosiveness (especially inorganic PCM).	[20–24]
Seasonal Thermal Storage	Ground source heat pumps (GSHP)	Useful for solar energy systems; buffer storage within PVT	[28–30]
Thermochemical Energy Storage (TCS)	Thermochemical adsorption (e.g., hydrate salt)	Well-suited to storing solar power for buildings; lower heat loss, enabling long-term seasonal storage and lower charging temperatures.	[15–19]

Many review studies are already available in the literature [18–20], but few of them are focused on the market and costs of the current TES application [2,31]. In this framework, this study presents a first-of-its-kind specific review of the current projected performance and costs of thermal energy storage. This study also makes a relevant contribution to the latter. Starting from the previous work developed by the same authors [31], this study allows the reader to obtain an overview of the main challenges and future directions of the TES systems in Europe. The paper is divided into four sections: Section 2 describes the main TES typologies. Section 3, the core of the paper, investigates the market penetration of each technology as well as the project performance and cost. Last but not least, the potential and barriers to TES application, especially in Europe, are reported in Section 4, followed by the Conclusion paragraph.

2. Processes and Technology Status of TES

By heating (or cooling) a storage medium, thermal energy storage systems (TES) store heat (or cold). As a result, further energy supply is not required, and the overall energy efficiency is increased. In most cases, the stored heat is a by-product or waste heat from an industrial process, or a primary source of renewable heat from the sun. Additionally, they can contribute to power generation, such as increasing annual electricity production through the conversion of solar heat into electricity when the sun's irradiance is not available [28,32]. TES can also reduce the amount of electricity produced by the conventional backup power system in a base load of a CSP-conventional hybrid power plant (Figure 1). As a consequence, the spread of solar energy depends on the efficiency, reliability, and cost-effectiveness of TES systems. Three types of thermal energy storage are available in the current market, such as sensible heat (SH-TES), latent heat (LH-TES), and thermochemical energy (TCS) [28,29]. Based on the operating temperature, the TES system can be classified into four groups as listed below:

- Cold TES systems ($T < 20$ °C);
- Low-temperature TES systems (20 °C $< T <$ 100 °C);
- Mid-temperature TES systems (100 °C $< T <$ 250 °C);
- High-/very-high temperature TES systems ($T >$ 250 °C; (high) $T >$ 500 °C (very high).

The main properties of the TES are as follows: capacity; power (also involves the discharge and charge velocity of the TES system); efficiency; storage period (expressed in hours or days or season storage); cost expressed in EUR/kWh or per unit of delivered power expressed in EUR/kW; charge/discharge time. Table 2 summarized the typical data on the three TES system typologies.

Table 2. Typical characteristics of TES systems [32].

TES System	Power (MW)	Capacity (kWh/t)	Efficiency (%)	Cost (€/kWh)
SH-TES	0.001–50	10–50	50–94	0.1–30
LH-TES	0.001–10	50–150	75–90	0.4–70
TCS	0.01–5	120–150	75–100	10–130

Short-term TES encompasses daily systems as well as those with varying storage capacities from a few hours up to a few weeks. It is usually possible to preserve heat in these systems at a temperature that is appropriate for the end user; for example, in a district heating network, hot water (both a storage medium and a medium for transferring heat) is kept at 95 °C, suitable for residential use. Starting from the 1950s, many efforts have been applied to develop an energy storage system able to store heat during summertime and use it during winter. This kind of TES is called a long-term seasonal TES, with the storage time of more than 3–4 months. Some countries located in the north of Europe tested experimental large-scale TES systems at district levels. Solar thermal collectors were employed with TES to capture heat34 during the summer and store it at low-medium temperatures. In those cases, an underground storage system was applied; the storage medium was a large volume of water, as a low-cost source. With regard to the high-temperature long-term storage, TCS (redox reactions involving metal oxides, carbonates, or calcium hydroxides) was used in combination with the solar power plant. Although the seasonal storage facilities have been developed in cold climates (northern Europe), the south European latitude has an especially favourable seasonal storage for solar systems associated with high temperatures, as summer solar irradiance is about three times as great as winter solar irradiance [33–38]. As previously mentioned, the storage time is a relevant property of TES; therefore, a classification based on both short- and long-term storage is presented in Figure 1 [39–41].

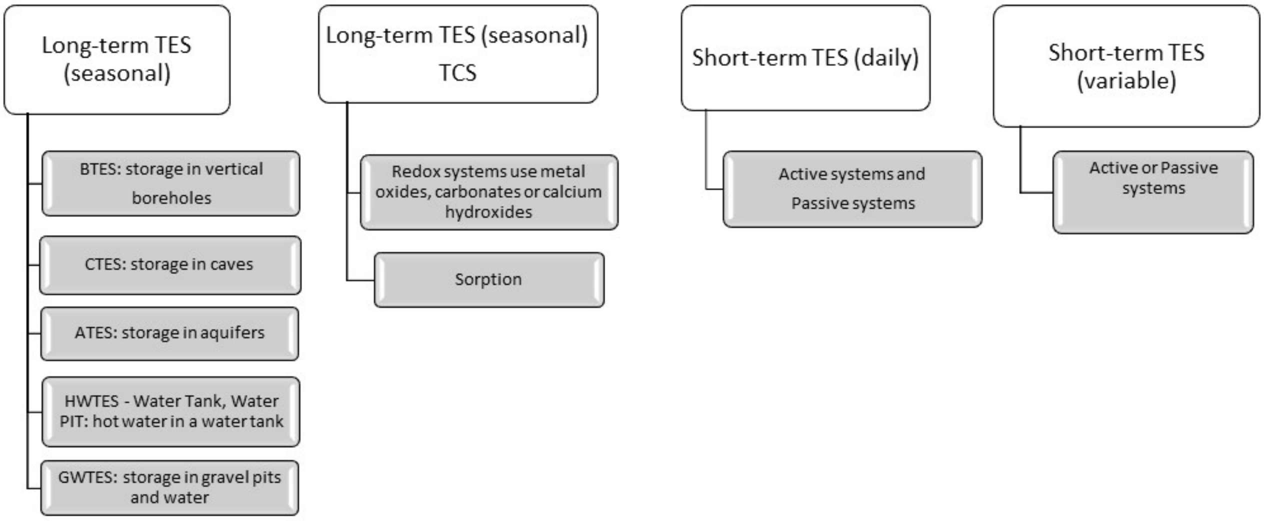

Figure 1. TES grouped based on the storage time [34–36].

2.1. Sensible Heat Thermal Energy Storage

Due to being less expensive than LH-TES and TCS systems, sensible heat storage is suitable for both residential and industrial applications wherein hot water tanks were used. However, SH-TES requires the appropriate design of the systems as well as large volumes because of its low energy density. Consequently, the storage capacity strongly depends on the storage medium characteristics, such as heat loss coefficient (depends on surface/volume ratio), vapour pressure (physical/chemical stability), thermal conductivity, heat diffusivity, and so on. It is possible to have water stored in tanks for both low-temperatures (<10 °C) and mid-temperatures up to 95–98 °C (atmospheric pressure) till 120–130 °C in costlier pressurized systems. A common variant of SH-TES technology is underground thermal energy storage (UTES), which pumps hot or cold water underground for later use as a heating or cooling source. A borehole (B-TES), a cavern (C-TES), and an aquifer (A-TES) can be employed as a tank. Storage pits are open-cast pits filled with water (often gravel) and insulated. A good thermal capacity can be obtained with molten salt when used between 250 and 550 °C, particularly with "solar salt", a mixture of sodium and potassium nitrates (40–60 wt% $NaNO_3$-KNO_3). At room temperature, solar salt is solid, melts at about 220 °C, and solidifies at 240 °C. The liquid phase of the molten salt is used in concentrating solar power (CSP) plants to store solar heat. When the sun is not available during the day (cloudy or at night), the heat is used to produce electricity. Two tanks are typically employed to store the molten salt in these systems: the hot salt gets heated up to 550 °C by the solar field, and the cold salt gets heated at 290 °C after an exchange with the power block. A single-tank system is also being investigated to avoid two-tank systems by exploiting the phenomenon of the thermocline in which cold and hot salts have different densities within the tank, creating a transition zone within the tank [37–39]. Using a low-cost solid filler, such as concrete, rocks, or metallic solids alongside the liquid medium, is also studied to decrease the amount of salt and material costs. It has to be noted that those systems may be subjected to plastic deformation of the tank, as expressed by [39]. This type of weakness is under evaluation and could be overcome using bricks as well as a suitable design of the tank [40]. Recently, it is possible to find on the market a grid-connected molten salt storage capacity for CSP larger than 30 GWth [41]. Solid storage materials, such as brick, concrete, and ceramic materials, are also employed in SH-TES systems for low, medium, and high temperatures. Concrete is the most durable, low-cost, and sustainable material used in TCS systems. Adding metallic or nylon fibre is the current path to finding a balanced concrete composition suitable for high temperatures (over 500 °C) [42]. This kind of storage material requires a heat transfer system (fluid combined with a heat exchanger) during its charging and discharging processes. Solid storage materials, such as ceramic bricks, natural stones, or beds of smaller particles, can be heated to 1000 °C using regenerator-type storage systems that transfer the heat directly from a gaseous medium. Table 3 shows the key elements of the aforementioned TCS technologies.

Table 3. Characteristics of low/high-temperature sensible energy storage technologies [43,44].

Type of TES	The Energy Density (kWh/m^3)	Feasible Size	Cost of Storage Unit (per kWh)
UTES	15–80	Up to 15 GWh	EUR 0.1–10
LT storage in liquids	60–100	Up to 1000 GWh	EUR 0.4–10
HT storage in liquids	75–200	350–4000 GWh	EUR 20–70
HT storage in solids	75–150	1000 GWh	EUR 15–40

2.2. Latent Heat Thermal Energy Storage

Without changing its temperature, LHTES, such as phase change material (PCM), can store heat based on the heat absorption/release during the phase change of the element [45]. PCMs present high energy storage density therefore they are very valuable on the market. However, a constant temperature during the process is difficult to reach due to the presence of sensible heat. Most LH-TES employ solid-liquid phase change materials (PCMs), while liquid-gas transitions are not used because they require large volume changes. Based on the temperature, PCMs can be grouped into low-temperature ranges (ice storage) and aqueous salt solutions (for temperatures below 0 °C); salt hydrates and paraffin waxes are also employed to obtain processes below 100 °C. Three main types of PCMs are currently applied in different sectors: organic (paraffin, non-paraffin compounds, etc.), inorganic (salts, metals, etc.), and eutectic.

In the organic PCM world, paraffin (hydrocarbons) has been extensively studied because it provides many advantages, such as high latent heat of fusion, chemical stability, low vapour pressure, and no phase separation (Table 4).

Table 4. Characteristics of PCMS [32].

PCM	Melting, °C	Latent Heat, kJ/kg
Paraffin C_{14}	5.5	228
Paraffin C_{21}–C_{30}	66–68	189
Non-paraffin formic acid	7.8	247
Non-paraffin capric acid	32	152.7
Non-paraffin stearic acid	69.4	199
Benzamide	127.2	169.4
Salt hydrate$NaCO_3$-$10H_2O$	32	246.5
Salt hydrate$MgCl_2$ $6H_2O$	117	168.6
Metal Gallium	30	80.3
Salt $LiNO_3$	253	373
Salt $NaNO_3$	307	172
Salt KNO_3	336	116
Salt Li_2CO_3	732	509
Eutectic o/o (34–66 wt%)	24	147.7
Eutectic i/I (33–67 wt%)	133	170

During phase changes, paraffin also undergoes large volume changes and has low thermal conductivity. Thermal storage is commonly achieved with technical-grade paraffin since it is cheaper than other types (e.g., commercial waxes, n-eicosane, n-octadecane). A variety of non-paraffin organic materials have also been studied in residential buildings for heating. However, they are very flammable and offer low thermal conductivity. With regard to the inorganic ones (such as salts, salt hydrates, and metals), they offer high specific heat, melting point, and high latent heat, similar to those of organic compounds. Meanwhile, they also have their drawbacks, for example, inorganic salts with a solid-to-liquid phase change have a temperature between 200 and 300 °C and a thermal conductivity of 0.5 W/mK (like air, a good insulator). After several cycles, salt hydrates show super-cooling and phase separation because they contain water molecules in their crystal structure. The most common salt hydrates are calcium chloride hexahydrate, sodium carbonate decahydrate, disodium phosphate dodecahydrate, sodium sulfate decahydrate, and sodium thiosulfate pentahydrate. These materials are applied to low-temperature processes because their melting point ranges between 30 and 50 °C. The use of metals and their alloys for PCMs is possible at both low and high temperatures. Compared with paraffin, metals are more chemically and physically stable, and they have a higher thermal conductivity (8 to 237 W/mK). In contrast, metals with low melting points also have low latent heat, which cannot be compensated for by high density. With regard to eutectics, they are based on a mix of two or more elements having a good melting temperature. Over the past few decades, there have been numerous studies on eutectics (inorganic and organic compounds) as a thermal energy storage medium. Several techniques are available or under development for improving heat transmission, including high thermal conductivity [41,42] (Figure 2).

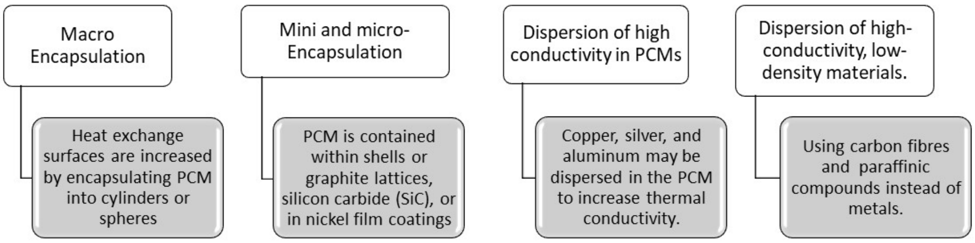

Figure 2. The main techniques to improve the heat transmission of PCMs.

The macro-encapsulation involves an increase in volumes and consequently higher costs. The mini- and micro-encapsulation provide a greater heat transfer surface per unit of volume and a higher exchange rate. There are many advantages to PCM encapsulation, such as better compatibility, easier handling, and a smaller volume than macro-encapsulation; this technology is commonly applied in buildings (passive heat storage systems) to reduce energy consumption. To ensure sufficient storage density, the dispersion of high-conductivity materials in PCM requires an optimal combination of metallic conductors and PCM as well. Finally, using low-density material (carbon fibres and paraffinic compounds instead of metals) provides a minimal reduction in PCM mass and volume to minimize the loss of storage capacity.

2.3. ThermoChemical Energy Storage (TCS)

During reversible chemical reactions, thermochemical storage systems absorb and release energy. The most promising reaction is the gas-solid one. Some gas-liquid and gas-gas reactions can be exploited; however, weak chemical bonds are involved, and temperatures are lower (20–200 °C) in these cases, as well as the chemisorption process [41,42]. Among these, "sorption" TES methods are very affordable for building applications; their heat density is in the range of 200 kWh/m^3 for zeolite [45,46] and 230 kWh/m^3 for silica gel [47]. Two different storage tanks were employed for sorbent and sorbate (water/water vapour). The discharge mode involved the adsorption of water vapour and the release of the evaporative heat (DhV) and binding energy (DhB). During the charging mode, a higher temperature was required to dry the sorbent. Approximately 45 kJ per mole of water was generated by water vapour adsorption on silica gel and alumina, while approximately 62 kJ were generated by zeolite [48]. An advanced prototype called the advanced CWS-NT concept has been proposed by Kerskes et al. [49] for the purpose of covering the heat demand of a single-family house using solar energy. They used a TES composed of zeolite and salt (Zeolite $4ACaCl_2/H_2O$). As a result, CWS-NT-concept offers energy savings of 73% (6.1% more than the initial system). However, a storage volume of 10 m^3 is also required to cover 70% of the heat demand because the material has a low energy density. With regard to the classification of TCS, it can be divided into open and closed cycles [49]. During an open thermochemical cycle, the working fluid is released at atmospheric pressure into the indoor environment; the water is used as the fluid and therefore less equipment is needed. Consequently, the open cycle is very cost-effective compared with the closed one. The closed circuits, wherein the fluid circulates inside a tube, can be employed for heat pumps and refrigerators. In comparison with an open cycle system, a closed cycle system provides a higher discharge temperature for heating applications and high investments.

In the framework of Task 32 (2003–2007) and Task 42 (2009–2015), the International Energy Agency (IEA) has developed different prototypes [50,51]. The general advantages of TCS technology include high energy density (about 500 kWh/m^3) and seasonal storage capacity. However, TCS systems are still under analysis due to their complexity as well as the material deterioration during charge-discharge cycles. Table 5 reports the main characteristics of TCS.

Table 5. Characteristics of TCS technologies.

TCS	The Energy Density (kWh/m^3)	Feasible Size	Cost of Storage Unit (per kWh)
Chemical reaction	100–400	System-dependent	EUR 10–90
Sorption Processes	120–250	2–4 MWh	EUR 10–130

2.4. Advanced Thermal Energy Storage Materials

Nanofluids, first reported by Choi [52] as a colloidal suspension of solid nanoparticles in a liquid, can be used to increase the thermal properties of fluids through the addition of copper or aluminium nanoparticles. A lot of efforts are made to improve the physical properties of PCMs, especially related to thermal conductivity [53]. Size, concentration, fluid composition, surfactant, and pH are generally important factors in determining relevant results. The use of nanoparticles could enhance PCM thermal capacity and conductivity [54–56], reducing the TES system cost, volume, and charging and discharging times.

3. Technology Maturity, Current Market, and Cost

3.1. Technology Maturity and Demo Projects

Currently, for low-temperature and high-temperature applications, sensible heat storage (SH-TES) is the most widespread TES system. Those types of systems use solids or fluids as storage mediums. Concrete is a relevant low-cost option, but it requires a scale demonstration to analyze the process in depth. Within the framework of various Italian and international projects, the ENEA is testing two modules with a capacity of about 6.5 kWh at the prototype level. Arkansas (USA) hosts stainless steel heat exchangers embedded in concrete prisms; molten salt (nitrate) is used as a heat transfer fluid for high-temperature concrete-based SH-TES systems. Several tests have also been carried out to investigate the potentialities of polytetrafluoroethylene (PTFE) and a heat-curing, fibered paste (HCFP) as interface materials to mitigate the stress in the concrete [52]. To summarize, TCS systems (low-temperature) are still in the developmental stage, while LH-TES systems are already extensively used at low temperatures in civil and industrial applications, but they require more demonstration for higher temperatures. The German Aerospace Center (Deutsches Zentrum für LLuft undRaumfahrt) developed and tested multiple storage systems in 2009 that could store 1 MWh of sensible heat, which was stored in concrete for water preheating and steam superheating, utilizing a PCM as a two-phase evaporator. DLR, Züblin AG, and Siemens AG within a project (ITES) funded by the German Ministry for the Environment [46], ref. [57], tested the connection of basic modules in series and parallel, with modules packed into four storage units with sizes of about 300 × 100 m. With 900–1000 °C operating temperatures and energy densities of 56 and 224 kWh/t, metal oxides (Mn_2O_3), calcium carbonates ($CaCO_3$), and calcium hydroxide ($Ca(OH)_2$) are the most promising materials adopted for high-temperature TCS. As mentioned in the literature [58], there have been several types of reactors-receivers fed by solid materials, including rotary kilns [59,60], reacting film [61], fluidized beds [62], and swirl flows [63].

3.2. Current Market Penetration

As reported in [64,65], the TES market is estimated to grow up to about 4.7 billion US dollars by 2020 and about 10.1 billion US dollars by 2027. The market share of TES is expected to be dominated by SH-TES technologies in the future due to their residential and industrial applications. District heating and cooling systems use underground storage (UTES), which uses either liquid or solid storage medium. Among power generation applications such as CSP plants, they need a large-scale storage system to compensate for the solar variability, reduce energy demand peaking, and balance grid supply. In this context, molten salt is expected to hold the largest market share. There is no doubt that CSP deployment will be mainly concentrated in the sunbelt regions, such as the Middle East, Africa, and other sunny and dry areas. With regard to Italy, few small-size, low-temperature TES markets are currently engaged compared to the international level (Table 6).

Table 6. Current typical values and range of the TES on the market.

Technology Systems	Units	SHTES (Min/Max)	LHTES (Min/Max)
Market share	%	0.25	Negligible
Installed capacity	GWh_{th}	3.2 (0.01 Italy)	<<1

3.3. Current and Projected Performance and Costs

Performance and cost exposed in this paragraph are related to specific TES technologies and applications. The most common applications of TES are dedicated to residential heating, industrial heat storage, and solar thermal power plants. Due to the variety of TES technologies, a list of key performance indicators (KPI) is needed to describe and compare each TES system (Table 7).

Table 7. Description of the main key performance indicators (KPI) [66].

KPI	Units
1- Reduction in TES systems investment cost	The typical investment cost of TES systems is 2010 and 2050 from 35 EUR/kWh to 15 EUR/kWh
2- Increasing storage efficiency	By minimizing heat losses and increasing energy density, TES systems could improve their thermal efficiency from 94 to 96%.
3- Reduction in the size of the TES system	It can be achieved by increasing the energy density.
4- Increasing the plant operating time	When TES is integrated with variable renewable power plants, it brings the potential for an increase in operating hours for the systems (plant capacity factor).
5- Reduction in the cost of produced energy	By increasing capacity and increasing energy efficiency, production, and cost can be reduced.

Based on the KPI, it was possible to collect the main data about the performance of the main TES (Table 8).

Table 8. Current typical values of technical performance of TES.

Technology Variants	SHTES (Min/Max)	LHTES (Min/Max)	TCS (Min/Max)
TRL IA	7–9	4–7	3–5
Storage capacity	10–50	50–150	50–500
Thermal power	0.001–50	0.001–1	0.001–5
Efficiency	50–94	75–90	75–100
Storage period	d–m	h–d	d–m
Technical lifetime	10–30+ (depending on storage cycles, temperature, and operating conditions)		
Load (capacity) factor	80	80	55
Max. (plant) availability	95	95	95
Typical (capacity) size	500	100	50

Data projections for 2020–2030 are reported in Table 9 wherein the main characteristics of TES are also considered.

Table 9. Data projections between 2020 and 2030 years.

Properties	SHTES (Min/Max)	LHTES (Min/Max)	TCS (Min/Max)
TRL IA	8–9	7–9	6–9
Thermal energy efficiency (%)	96	94	40–90
Lifetime		30	
Typical (capacity) size (MWh_{th})	800	300	100
Typical size (MW)		0.01–80	
F/V OM cost (USD/kW/y)	100	225	18–50
Cost (EUR/kWh)	20	30	50
Installed capacity (GWh_{th})	6	2	1

The SH-TES system is typically more affordable than the LH-TES system or the TCS system because it consists of a simple tank containing the medium and the charging/discharging equipment. While TES systems are frequently integrated with other systems (such as residential heating) or plants (such as power plants or industrial plants), the plant's investment cost increases in line with its productivity (such as power plants).

Therefore, it is useful to compare the economic cost/benefit analysis of a TES system with a no-TES system. According to Tehrani et al. [39], the TES-specific costs do not necessarily reflect the real economic potential of the technology since they reflect only the cost of the TES system, regardless of any impact on the hosting plant. Therefore, taking into account the costs and benefits of electricity generation from CSP plants, they suggest adopting "a normalized TES cost" (NCOTES), which normalizes the cost of storage systems with regard to their annual electricity generation capacity [39]. The following table (Table 10) illustrates the results (in USD) of a cost analysis of different molten salt-based TES systems for CSP plants, including (a) two-tank (2-tank) systems; (b) single medium thermocline tanks (SMT); (c) dual medium thermocline tanks (DMT); and (d) shell-and-tube tanks. To calculate the total cost of electricity generation, we need to divide the total cost by the number of power plants. Depending on the temperature, it varies in each of the four cases.

Table 10. Cost breakdown and Specific Cost for various SH-TES for CSP plants [18].

Components	2 Tanks	SMT	DMT	ST
HTF	7,429,913	7,429,913	1,627,462	1,627,462
Filler	-	-	399,850	399,850
Tubes	-		-	
Welding	-	-	-	521,221
Chunking	-		-	
Headers	-	-	-	52,995
Tank shell	1,874,946	873,823	1,445,264	914,400
Header insulation	-	-	-	131,870
Tank insulation	409,386	148,500	155,409	155,409
Foundation	422,736	401,599	439,835	439,835
Piping and valves	565,110	282,555	282,555	282,555
Electric instruments	1,304,100	652,050	652,050	652,050
Overhead	1,200,619	978,844	500,242	964,456
Installation	2,641,362	2,153,457	1,100,533	2,121,804
Total USD	15,848,173	12,920,741	6,603,200	12,730,821

This article [39] asserts that mode (a) allows maximum power production, independent from the temperature discharges at around 650–800 K. The other cases vary from (b) to (d). The latter, indeed, at 800 K has a gross power generation that is just over half of that at 650 K. In this way, for the well-insulated tanks, no decrease in NCOTES of the two-tank system is observed, and the decrease for the SMT system is very small. The NCOTES of two-tank systems is 136 USD/MWhe. With regard to other cases, these values can be reduced to 62 USD/MWhe (a 55% reduction) or 73 USD/MWhe (a 46% reduction), respectively, if the DMT or ST (without embedded pipes) systems are employed [66].

As noted in [44], the values are valid only for the Gemasolar plant (19.9 MW of power with 15 h of thermal storage) due to the influence of other factors, such as solar multiples, control strategies, and geographical location. Further, Laing et al. [67] compared a hypothetical TES using concrete modules instead of molten salt at the AndaSol-I CSP plant (Spain). According to the authors, concrete modules are particularly promising when used in modular shape. The shape can guarantee a specific storage cost of 14.1 EUR/kWht, as well as a lower environmental impact followed by a 9.5% reduction in emissions. There is a significant difference between LH-TES (and also PCM) and TCS systems since in many cases, especially TCS, they utilize enhanced heat and mass transfer technologies to deliver needed storage capacity and power. PCM systems typically cost between EUR 10 and EUR 50 per kWh [50]. In contrast, TCS required basic storage materials (e.g., pelletizing or layering over supporting structures) as well as buying containers (for both heat and mass transfer). Based on this framework, TCS is more expensive, but it is also under development to improve its performance and lifetime [68]. An important advantage of TCS is its potential for long-term storage compared to SH/LH TES.

In the current commercial industry, seasonal storage systems generally consist of water containers ranging in size from 5000 m^3 to 10,000 m^3, with energy content ranging between 70 and 90 kWh/m^3 and an investment price ranging from EUR 50/m^3 to EUR 200/m^3; this allows to have an investment cost ranging from EUR 0.5 to EUR 3.0 per kWh [69]. In summary, Table 11 reports the current typical values and range of cost per each TES typology.

Table 11. Current typical values of TES prices.

Costs	SHTES (Min/Max)	LHTES (Min/Max)	TCS (Min/Max)
Cost (EUR/kWh)	0.1–50	8–50	8–100
Investment cost (EUR/kW)	3400–4500	6000–15,000	1000–30,000
O&M cost (fixed and variable) (EUR/kW/y)	70–250	120–750	20–1500
Economic lifetime (y)		20	

4. Potential and Barriers

The potentialities and the penetration of TES are varied from country to country [70]. In fact, in Europe, where new buildings are built at a rate of about 1.3% per year and renovations occur at a rate of around 1.5%, TES penetration in the building sector is comparably slow. TES systems in buildings are being implemented at a rate of 5% [71] in the European scenario. Cogeneration application with TES is attested to 10.2%, and it can be higher in countries characterized by new construction rates [72]. With regard to the industrial sector, TES installation accounts for 5% of the final energy consumption.

The CSP sector is currently a driver in TES applications because new power plants in operation or under construction are equipped with short-term heat storage systems, mostly based on the molten salt SH-TES. There is no doubt that this is the most significant development for large, centralized TES systems [73]. The use of concrete-based material is attractive due to its simplicity and low cost. The LH-TES and TCS systems, instead, represent the upcoming future of thermal storage; TCS is suitable for long-term seasonal storage, which may improve the operational continuity for variable renewable technologies and reduce their energy production costs. Lead players in the current thermal energy storage market include Abengoa Solar, Areva, Baltimore Aircoil Company, BrightSource Energy, Caldwell Energy, Calmac, DN Tanks, Evapco, Ice Energy, EnergyNEST, SolarReserve, Sunwell Technology, and others. At the global market, databases of TES are provided by US-DOE Global [74]. Figure 3 shows the global TES capacity equal to 2.85 GW for all European countries, based on 161 projects, with a growing trend between 2010 and 2016. Spain is the first country in terms of molten-salt TES applications connected to the CSP plants. The total power installed is attested to 1.13 GW related to 26 projects.

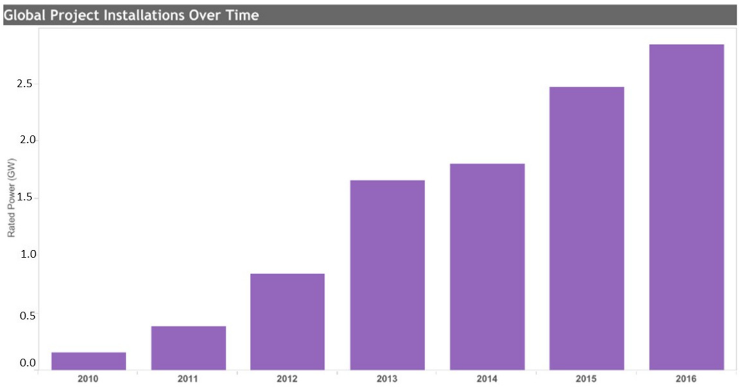

Figure 3. DOE Global energy storage database for all the European countries [74].

There are several commercial-scale CSP plants in the pipeline, including one in Fuentes de Andaluca (Seville) that has a 15 h molten-salt TES that allows electrical generation for up to 15 h without sunlight. Conversely, Italy needs relevant improvements to increase the application of TES in its territory. A new central electricity and heat plant was built as part of the Dal Molin project in Vicenza, Italy, on a former joint Italian/US military base. In this project, TES tanks with a nominal power of 400 kW and some 8 h of energy storage can save energy and costs. Regarding the CSP plant based on molten salt, the first application was the "Archimede", realized in Sicily, Italy, by Enel in cooperation with the ENEA. It is a 5 MWe hybrid CSP plant equipped with a direct 2-tank system.

TES systems represent a potential source in Italy despite a limited number of key actors and applications (around 5120 kW installed [74]). A well-directed policy on energy efficiency and renewable energies is required for the development of a national market, which would also contribute to the rapid growth of the Italian TES industry. Several projects developed by ENEA are underway, such as STS MED [75], MATS [69], and ORC-PLUS [76], including demo plants for TES optimization. For instance, STS-MED aims to improve energy efficiency in public buildings by implementing TES solar technologies. To meet the heat demand of 20,000 users in the Mediterranean local communities, 4 demonstration plants will use 500 kW concentrating solar collectors to become a showcase for this application. The MATS project plans to construct and test a multipurpose solar facility in Egypt that can generate electricity, desalinate water (230 m^3/day), and provide district heating and cooling. As part of this installation, a 14 MWh, molten-salt heat storage solution has been installed, with significant innovations including a stratifying storage tank, a once-through steam generator built into the tank, as well as an auxiliary heater for an optional backup of 2.3 MW_{th} to be used in case of emergency [77]. CSP plants with a scale of 1–5 MW are addressed by ORC-PLUS with two different options for storage materials: solid and liquid oil [76].

With regard to other barriers to TES, cost is one key element. Most R&D efforts are, indeed, focused on PCM and material TCS (Table 12).

Table 12. Status, barriers, and R&D topics for TES.

Technology	Status, % Market/R&D	Barriers	R&D Topics
Hot water tanks (buffer)	95/5	-	Super insulation
Large water tanks (buffer)	25/75	System integration	Material tank, stratification
UTES	25/75	Regulation, high cost, low capacity	System integration
High-temperature liquids	50/50	Cost, T < 600 °C	High temp materials
Cold storage, ice	90/10	Low temp	Ice production
Cold storage, others	75/25	High cost	Material (slurries)
Passive cooling buildings	75/25	High cost, performance	Material (encapsulation)
High-temperature PCM	0/100	High cost, mat. stability	Material (PCM container)
Adsorption	5/95	High cost, complexity	Material (reactor design)
Absorption	5/95	High cost, complexity	Material (reactor design)
Other chemical reactions	5/95	High cost, complexity	Material (reactor design)

5. Conclusions

At present, one of the hot topics in energy policy is improving energy utilization rates and promoting renewable energy. The current energy crisis, as well as reducing the energy consumption by buildings, is still an urgent call for the construction world. The construction sector is involved in this trend due to its complexity and the request for different kinds of energy systems, including grid applications. In this framework, thermal energy storage plays an essential role to enhance renewable energy systems in a variety of ways.

This review aimed to explore the main characteristic of TES, its application, and forecast analysis of its performance and cost. Based on an in-depth investigation, sensible heat storage (SH-TES) is the most used TES system. Molten-salt TES systems are commonly employed in CSP power plants both in operation and under construction. On the other hand, LH-TES systems are already extensively used at low temperatures in civil and industrial applications, but they require more demonstration for higher temperatures. R&D is focused on improving the application and feasibility characteristics of LH-TES because it is considered the future way to store energy. The market share of TES is expected to be dominated by SH-TES technologies due to their residential and industrial application. With regard to the cost, the SH-TES system is typically more affordable than the LH-TES system or the TCS system because it consists of a simple tank containing the medium and the charging/discharging equipment.

It is worth mentioning that TES systems require more efforts to expand their employment, to overcome the current high-cost and performance limitations, especially LH-TES (TCS) systems. Based on this review, some gaps could be filled to improve the heat exchange between the heat transfer fluid and storage medium through the adoption of appropriate conductivity systems. Increasing the thermal properties of the storage medium, specifically its thermal diffusivity, through the adoption of nanotechnologies (nano-enhanced PCM) could be a relevant path. In this way, it is possible to better exploit the storage medium by reducing the extension of the heat exchange surface and, thus, increasing the compactness and reducing the cost of LH-TES systems.

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Nomenclature

CSP	Concentrated solar power
DH	District heating
DHW	Domestic hot water
GSHP	Ground source heat pumps
LH	Latent heat
NCOTES	Normalized cost of thermal energy storage
PCM	Phase change materials
PVT	Photovoltaic thermal
RES	Renewable energy resource
R&D	Research and Development
SH	Sensible heat
SAHP	Solar-assisted heat pump
TES	Thermal energy storage
TCS	Thermochemical Energy Storage
UTES	Underground thermal energy storage

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