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Review

Thermal Energy Storage in Concentrating Solar Power Plants: A Review of European and North American R&D Projects

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Abstract: Thermal energy storage (TES) is the most suitable solution found to improve the concentrating solar power (CSP) plant's dispatchability. Molten salts used as sensible heat storage (SHS) are the most widespread TES medium. However, novel and promising TES materials can be implemented into CSP plants within different configurations, minimizing the TES costs and increasing the working temperature to improve the thermal performance of the associated power block. The first objective of this review is to provide an overview of the most widespread CSP technologies, TES technologies and TES-CSP configurations within the currently operational facilities. Once this information has been compiled, the second aim is to collect and present the existing European and North American TES-CSP Research and Development (R&D) projects within the last decade (2011–2021). Data related to these projects such as TES-CSP configuration path, TES and CSP technologies applied, storage capacity, power block associated and the levelized cost of electricity (LCOE) of the commercial up-scaling project are presented. In addition, project information such as location, research period, project leader and budget granted are also extracted. A timeline of the R&D projects launched from 2011 is built, showing the technology readiness level (TRL) achieved by the end of the project.

Keywords: concentrating solar power; thermal energy storage; TES CSP integration paths; TES CSP R&D projects

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1. Introduction

One of the most important measures to mitigate greenhouse gases (GHG) emissions is to increase the share of renewable energy sources (RES) in the energy mix, according to the Intergovernmental Panel on Climate Change (IPCC) [1]. At the end of 2021, the renewable energy share in global electricity production was 28.3% with a renewable power capacity exceeding 3000 GW, including hydroelectric power. The annual contribution to renewable power capacity must be multiplied by three to achieve the scenarios of net zero emissions by 2030 and 2050 [2]. Higher daily production of RES could be achieved if those issues related to the variability of electricity production were solved through the storage of energy surplus.

RES which directly supplies electricity to the grid, such as photovoltaic solar power or wind power, may be combined with electromechanical or electrochemical storage systems leading to efficiencies of the load/discharge cycle up to 90% [3]. In contrast, concentrating solar power (CSP) plants which supplies thermal energy to the power cycle, obtain yields close to 100% through their combination with thermal energy storage (TES) systems [3,4]. Furthermore, the capital cost of TES is lower than mechanical or chemical storage systems [5]. The most widespread storage materials used in TES systems are the molten salts which allow for the extension of the operating hours of CSP plants by storing energy as sensible heat during daylight hours. However, thermochemical energy storage (TCES) systems could enable higher conversion efficiencies in CSP plants in the medium–long term [6]. Although the CSP installed capacity in 2021 (6 GW) was significantly lower than the installed capacity of other RES, the average CSP costs in plants with integrated TES have dropped by 70% in the last decade [2]. The construction of CSP plants in the last decade has grown exponentially throughout the world, indicating an optimistic future for the solar-based RES [7]. Therefore, CSP with TES is emerging as a potential competitor of conventional base load plants, such as fossil fuel power plants [8]. The latest research highlights the importance of techno–economic studies to promote the implementation of TES in CSP. However, the environmental aspect scarcely appears in the literature, even less complete life cycle assessments [9]. Thus, the first objective of this review is to describe the most advantageous integration pathways of TES into CSP plants.

A thorough bibliographic search points out that recent reviews dealing with energy storage technologies coupled with CSP plants may be divided into two categories: (i) latest advances in CSP and TES technologies and (ii) integration concepts. Several studies focus on the most widespread CSP technologies and the future trends in research development [10–13], including an overview of the distribution of CSP facilities by regions [7]. Regarding TES technologies, the reviews were focused on sensible, latent and thermochemical energy storage materials developed since 2000 [14] and the future challenges to be integrated into CSP [15]. The latest research on sensible heat storage was related to (i) the discussion of the best integration of molten salts medium [5], (ii) the potential of solid particles as a heat transfer medium and TES [16] and (iii) the proper future use of cheaper materials such as rocks [17]. The latent heat storage for high temperature operation was investigated to, firstly, overcome challenges of coupling to CSP [18] and to define the phase change materials capable to be used in CSP application [19]. The recent advances on thermochemical reactions as TES for CSP are the most investigated in the last 5 years, given the high operating temperature and long-term durability of solid–gas reversible reactions [20]. Most recent reviews were focused on the most suitable reactors for enhancing heat transfer [21] and chemical reactions efficiency [22]. Secondly, the integration between TES and CSP was defined according to the conventional configurations of first and second generation CSP plants [11,23], requiring new integration concepts for the next generation of CSP plants [24]. In summary, previous reviews focused on TES CSP configurations of currently operational facilities from prototype to commercial scale (first and second generation) and novel trends for TES integration in the next CSP generation. The main gap found among these reviews is the existence of a thorough summary of completed and ongoing research and development (R&D) projects of TES integrated in CSP plants. Thus, the second objective and the main novelty of this revision manuscript is to present a complete international picture of the TES CSP R&D projects from Europe and North America within any technology readiness level (TRL), from lab/pilot to almost commercial scale. Both regions concentrate 65% of the installed capacity of CSP plants currently in operation [25]. Thus, Europe and North America have been the world regions chosen for the review of R&D projects for being at the forefront in the development of CSP technology.

A bibliometric study was performed to search the references for the following sections in the present manuscript (Sections 2 and 3). The Web of Science database was selected for citations belonging to Section 2, focused on CSP and TES technologies, as well as the most spread integrations of TES into CSP plants. In addition, the SolarPACES tool [25] was required to obtain the project profiles of operational CSP facilities around the world. The information about R&D projects in Section 3 was extracted from other databases, such as the Community Research and Development Information Service (CORDIS) [26] and Solar Energy Research Database from the Solar Energy Technologies Office (SETO) [27]. CORDIS provides results from R&D projects funded by the EU's framework programmes, while SETO collects all the active and inactive R&D projects awarded by the U.S. Department of Energy. Table 1 shows the different keyword combinations used to select the scientific references appearing in the present review.

Table 1. Search map to extract information on CSP and TES technologies.

Excluded Phrase	Main Search Phrase	Complementary Search Phrase	Total Papers	Papers in the Last 5 Years (2018–2022)
Photovoltaic	Concentrated solar power	Review	381	191
		Review + Technologies	212	112
		Review + Thermal energy storage	137	78
		Review + Sensible heat storage	28	17
		Review + Latent heat storage	31	18
		Review + Thermochemical energy storage	34	19
		Thermal storage configuration	207	104
		Thermal energy storage + Active system	22	12
		Thermal energy storage + Passive system	15	6

The keywords shown in Table 1 were used to collect the citations related to CSP and TES. The excluded phrase for all searches performed is 'photovoltaic' and the main phrase 'concentrated solar power' is the base word used for all searches. Both main and complementary phrases were searched for as topics in the Web of Science database. The total scientific papers found by each row search are also presented in Table 1. Most of the publications are found by more than one search row, being the sum of all articles higher than the total papers. Moreover, cross references are removed from the present review. At least 88 scientific articles within total papers found have been used to describe the CSP and TES review information, of which 41 were published in the last 5 years from 2018 to 2022.

Table 2 shows the total number of CSP facilities and TES CSP R&D projects found under a proposed keyword map for each research tool: SolarPACES, CORDIS and SETO.

Table 2. Search map to found TES CSP facilities and R&D projects.

Research Tool	Search by	Total TES CSP Facilities	Total TES CSP R&D Projects
SolarPACES	Operational status	119	-
	Operational status + Thermal energy storage	61	-
CORDIS	Concentrated solar power + Energy storage	-	46
SETO	Concentrated solar power + Thermal energy storage + Inactive	-	38
	Concentrated solar power + Thermal energy storage + Active	-	31

The operational CSP plants described in the present review were extracted from the SolarPACES database tool. Most of the information appearing in the profile of each CSP facility has been used throughout this manuscript. Some of the found TES CSP R&D projects: (i) contain duplicate information, or (ii) are out of scope, being related to topics such as photovoltaics or building air-conditioning. Thus, a total of 41 TES CSP R&D projects have been collected from CORDIS and SETO research tools for the present review.

2. Potential Integration of TES in CSP Plants

The typical configuration of an integrated TES CSP plant is illustrated in Figure 1, including the three main blocks of these systems: (i) solar field, (ii) power cycle and (iii) transport media/storage system [28]. This section provides a brief description of the solar collectors and thermal energy storage available technologies and a critical discussion of pros and cons of these technologies and their potential combinations.

Current operation of CSP plants is analogous to conventional thermal power plants, except for the use of solar radiation as a thermal energy source to produce electrical energy through an associated power cycle. A working fluid transfers the thermal energy, circulating between the solar field and the power block. The solar field is composed of concentrators, to improve the use of solar radiation, which is concentrated and projected onto a receiver to heat up at high temperature the working fluid [29]. The typical power block associated with a CSP plant is the steam Rankine cycle. Most of the existing operational CSP plants use a steam turbine for power generation [25]. However, the trend in recent research is to couple CSP with CO_2-based power cycles: Brayton [30,31] and supercritical (sCO2) [32], improving the overall efficiency of the CSP plant. Besides, the integration of TES in CSP plants will improve their dispatchability when solar radiation is only partially available or during the night [10]. More than half of the total CSP plants which are currently under operation around the world integrate TES systems. Commercial plants represent around 80% of the currently ongoing CSP facilities with TES. The rest of TES CSP facilities are divided among demonstration plants (13%), pilot plants (6%) and prototypes (1%) [9]. Both, the first and second generation of CSP plants have contributed to the development of current commercial CSP facilities, contemplating (i) the direct steam production in the receiver and (ii) higher volumes of molten salt-based storage. The next (third) generation of CSP plants will focus on the research of (i) new non-corrosive TES materials with high heat absorption and high operational durability, (ii) new HTFs with high-temperature and high-degradability resistance and (iii) more efficient power blocks, such as Brayton and supercritical [33].

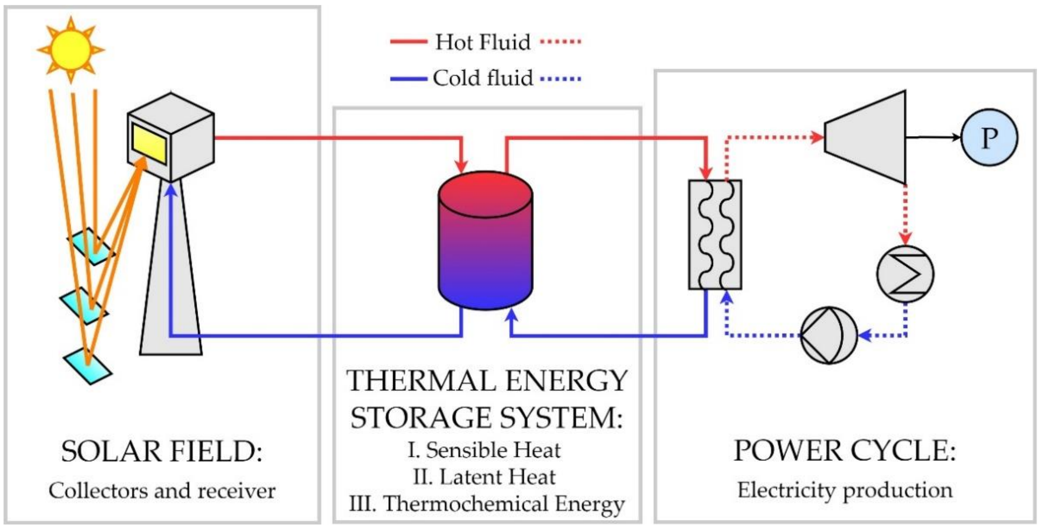

Figure 1. Main elements of an integrated TES CSP plant.

2.1. CSP Technologies

Table 3 shows the main characteristics of the most widespread concentrating solar technologies in CSP plants classified as: (i) parabolic trough collectors (PTC), (ii) linear Fresnel reflectors (LFR), (iii) solar power towers (SPT) and (iv) parabolic dish collectors (PDC), where PTC is the largest developed and established globally [10,24].

PTC and LFR concentrating technologies focus the solar radiation on a linear receiver, while PDC and SPT concentrating solar systems direct solar radiation to a focal point where the receiver is located [11]. The highest solar concentration ratio (up to 3000) is achieved by PDC and SPT [11], reaching high (i) operating temperatures (even above 1000 °C) [24], (ii) thermodynamic efficiencies for the CSP plant [34] and (iii) nominal power capacities (up to 280 and 377 MW, respectively) [9]. The most widespread concentrating solar technology is PTC (62%) followed by SPT (20%) and LFR (7%), within 141 CSP plants currently in operation and under construction. Meanwhile, CSP plants with concentrated solar power PDC technology are currently inoperative [25]. Thus, the development status of PTC and SPT is commercially available, both growing at the same rate in new construction facilities improving their performance, the TES and HTF media [13].

The high thermal efficiency of PDC and SPT, near 30%, and its high-temperature operation makes these emerging technologies very competitive with conventional PTC (18%, 400 °C) and LFR (12%, below 400 °C) applications. However, current TRL of these CSP technologies points out the commercial status of PTC and LFR, while wider experimental feedback, especially at large scale, is required to better know and define the disadvantages of the most efficient technologies. Given their tested characteristics, PTC presents a strong potential to become the leading CSP technology in the mid-term.

Table 3. Specifications and comparison between the main CSP technologies [11,12,24,25,28,34].

CSP Technology	PTC	LFR	SPT	PDC
Solar concentration ratio	70–80	60–100	1000–1500	1300–3000
Operating temperature (°C)	<400	<300	<1000	<1500
Nominal capacity (MW)	10–280	9–125	10–377	<1.5
Average specific cost (€/kW)	7399	5054	6052	-
Average LCOE (€/kWh)	0.24	0.16	0.15	-
Thermodynamic efficiency	↓↓	↓	↑	↑↑
Advantages	• Commercial scale. • Modularity. Good land-use factor	• Readily available. Low manufacturing cost.	• High conversion. High temperature storage. • Optimal for dry cooling.	• Good land-use factor. • With/out heat transfer fluid.
Disadvantages	• Fluid working temperatures up to 400 °C.	• Small plants. Recent entrance in market.	• Low land-use factor. • Larger-scale operation required.	• Further experimental feedback required.

The cost assessment of these technologies shows the highest average specific costs associated to PTC, although other technologies such as LFR or SPT with slightly lower specific costs present values of the same order of magnitude. The higher thermal efficiency of SPT mitigate the investment costs leading to the lowest average levelized cost of electricity (LCOE) among CSP technologies. The average specific cost and the LCOE of the CSP plants with SPT technology is 18% and 40% lower than CSP plants with PTC technology, respectively. The efficiency of PTC is not high enough to reverse the effect of the largest average investment costs and leads to the highest LCOE.

All the CSP plants which are currently under construction contemplate the use of TES instead of the possibility of increasing electricity production with fossil fuels [25]. This trend is driven by the reduction of annual operation and maintenance costs of TES compared to a fossil fuel support system. Moreover, the capacity factor is improved by increasing the electricity production and GHG emissions are minimized. The variability of the TES material annual costs from one year to the next is lower than fossil fuels, whose price trend is less predictable [35].

2.2. TES Technologies/Systems

Regarding the maturity (TRL level, Table 4), the most developed storage technology relies on sensible heat storage (SHS), followed by latent heat storage (LHS) and finally thermochemical energy storage (TCES).

Information on large experimental and industrial-scale plants is available for SHS operation. SHS is based on liquid or solid storage media, liquid medium being the most commonly used in CPS plants, such as water or molten salts [23,25]. LHS technology is still under development for later integration into CPS plants, being mainly at experimental and pilot scale. Although the TRL of LHS systems is somehow lower, LHS are also commercially available for some specific materials [36]. However, TCES is not currently available at commercial scale. Most of the TCES systems are still investigated at laboratory scale for their integration in CSP plants [37].

The energy density of the LHS media is higher than of SHS media, given the higher enthalpy related to the phase change [23]. However, TCES system has the highest energy density compared to other TES [37]. Several TCES materials are currently under development but not commercially available, while SHS materials are widely commercially available. The heat transfer mechanisms are slow for both LHS and TCES, since their materials present low thermal conductivities [24].

Table 4. Summary and comparison of different TES Technologies [23,24,36,37].

TES Technology	SHS	LHS	TCES
TRL	8–9	6–9	4–7
Energy density	Low	Medium	High
Heat transfer	Good	Slow	Slow
Materials costs	Low, except liquid metals and thermal oils	Low	Low, except design and installation of reactors
Required area	High	Medium	Low
Timescale	Hours–Seasonal	Days–Months	Hours–Years
Lifetime	Long	Limited	Depends on reactant
Storage temperature	High	High	Low
Flexibility	Fast switch charge/discharge	Fast switch charge/discharge	Slow switch charge/discharge
Advantages	• Large experimental and industrial feedback. • Easy implementation.	• Short distance transport. • Small volumes. • Constant temperatures for charge/discharge.	• Long distance transport. • Small volumes. • Long storage periods without losses.
Disadvantages	• High freezing point for liquid medium. • Variable and unstable discharging temperature. • Large volumes.	• Corrosivity of materials. • Large heat losses. • Formation of solid deposits on the heat exchange area.	• Complex technology. • High capital costs. • Technical issues: melting, incomplete reversibility, low reaction kinetics, sintering. • Storage of gases. • Required improvement of heat and mass transfer. • Low charging rate.

The lifetime of SHS materials (which can reach 20 years) is four times higher than that of LHS materials and even ten times higher than TCES materials [38]. The storage time of TCES materials exceeds that of LHS and SHS materials, even reaching a temporary scale of years.

Based on the information gathered in Table 4, strong R&D efforts in the development of TCES (TRL 4–7) must be conducted to overcome those drawbacks identified for this technology, since its potential to gain the leadership among TES-CSP technologies is extremely high. The accumulation of key advantages when compared to SHS and LHS technologies, such as the higher energy density, the smaller required volumes or the dramatic increase of the storage period without significant energy losses, makes TCES the most promising technology to couple with CSP plants in the long-term. However, efforts must be carried out to find materials with a long lifetime (avoiding melting/sintering issues, achieving complete reversibility, enhancing reaction kinetics) able to be in stored at low temperature. The improvement of heat and mass transfer mechanisms, together with the simplification of TCES operation, will also lead to a needed reduction of capital costs to become economically competitive.

TES systems can be classified by the materials and technology used, such as storage medium [39,40]. Figure 2 shows the main storage materials used by each TES technology: SHS, LHS and TCES.

2.2.1. Sensible Heat Storage (SHS)

Sensible heat storage (SHS) is the simplest method, based on the storage of thermal energy by raising the temperature of a liquid or solid storage medium (e.g., water, sand, molten salts, or rocks), without undergoing phase change over the temperature range of the storage process. SHS systems are cheap, commercial, simple and easy to control, but they present low energy density compared with LHS systems [37].

SHS systems use the heat capacity and the temperature variation of the storage medium during the process of charging and discharging. The amount of heat stored depends on (i) the specific heat of the medium, (ii) the temperature variation and (iii) the amount of storage material option [41,42] (Equation (1)).

$$Q_s = \int_{T_i}^{T_f} m \cdot c_p \, dT \cong m \cdot c_p \cdot (T_f - T_i) \quad (1)$$

where Q_s is the quantity of heat stored (J), m is the mass of heat storage medium (kg), c_p is the specific heat (J/(kg·K)), T_i is the initial temperature (°C) and T_f is the final temperature (°C).

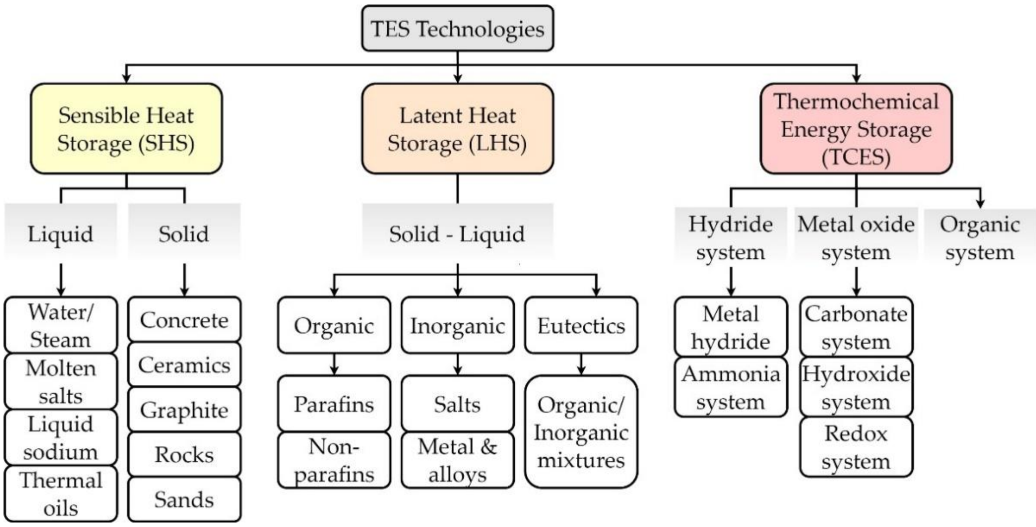

Figure 2. Main TES technologies classified according to the storage medium.

The most popular SHS materials withstand high temperatures (>500 °C), such as concrete, ceramics, graphite, rocks or sands [24,43]. Storage temperatures up to 1000 °C are mainly standby regenerator-type storage systems which transfer heat from gas directly to the solid material. Ceramics and concrete materials are being used in CSP operational facilities in demonstration, such as in the Jülich Solar Tower plant [44], or in CSP under development plants, such as in Huaqiang TeraSolar 15 MW Fresnel plant [25], given their good thermal and mechanical properties and low cost [45]. Among high temperature resilient materials, graphite is a suitable SHS candidate, given its high thermal diffusivity [46], whereas concrete and high alumina cement concrete blocks are identified as a potential SHS medium, given their low cost [43]. Furthermore, rocks are used as a SHS medium at the operational pilot plant Airlight Energy Ait-Baha, also given their low cost [25]. Natural rocks can be a sustainable option to improve energy dispatch in CSP plants located in regions with earth-abundant resources [47]. However, waste materials and byproducts are available as a SHS medium, entailing an environmental and economic benefit [48,49]. Experimental results show similar performances comparing a 100% recycled material and an alumina-based medium as SHS (i.e., net exergy considering thermal losses and pressure drop losses) [50].

The liquid materials used as SHS, such as molten salts, water, thermal oils and liquid sodium have already been tested in existing CSP plants [43]. Molten salts are the most widespread, since their thermal stability in the presence of air up to 500 °C [51,52], and other advantageous characteristics such as low vapor pressure, low freezing temperature for ternary mixed, low viscosity, high thermal conductivity and specific heat [53]. Almost 78% of the CSP plants currently under commercial operation or under construction use molten salts as a thermal storage medium [25]. Moreover, molten salts are also used as heat transfer fluid (HTF) in a large number of CSP commercial plants from Gemasolar CSP plant in Spain (2011) to the last operational CSP plant in China Qinghai Gonghe—50 MW Tower (2019), all of them using power tower technology [25,54]. Once the corrosion issue is solved, the next generation of molten salts will be based on chloride materials, given their resistance to high temperatures and low cost [55], keeping similar thermophysical properties as currently commercial molten salts [56]. Moreover, the inclusion of nanoparticles in molten salts will improve their thermophysical properties, enabling their use as HTF and TES [57].

Beyond molten salts, water is also commercially used as a thermal storage medium. The main advantages of water as TES are: its easy availability, non-toxicity, non-flammability and that it is completely harmless [23]. Water can be stored as saturated steam or pressurized water in a pressurized tank. When superheated steam is fed to the storage tank, the temperature and pressure increase, changing the saturation state. If saturated water enters the tank, the mass of water increases, keeping constant the pressure and temperature. During the discharge process, saturated steam is extracted from the storage tank as its pressure drops [36]. The main issue associated with water use in CSP plants is the scarcity if the plant is located in desert areas [58]. In addition, water can be use as a HTF and thermal storage medium, as in Puerto Errado 2 Thermosolar Power (PE2) [54] and Khi Solar One CSP plant [59,60].

Liquid metals used as thermal storage media, such as liquid sodium, are currently under development. They present safety problems related to its high combustibility in contact with water, in addition to discouraging higher costs than some molten salts. Currently, the Jemalong Solar Thermal Station pilot CSP plant in Australia, under operation from 2017, uses liquid sodium as HTF and as a thermal storage medium.

Other liquid media used for thermal storage by sensible heat are the thermal oils, although their usage is currently restricted to HTF in most CPS plants in operation [25]. The main advantage of thermal oils over water is their permanence in the liquid phase at temperatures higher than those of water, up to 250 °C at atmospheric pressure. Thus, thermal oils have a lower vapor pressure and, unlike molten salts, they do not need protection against freezing. However, thermal oils degrade and produce acids at temperatures above their operating range, accelerating the corrosion of containers and pipes [23,61]. Therefore, the possibility of using non-edible vegetable oils such as HTF and TES is being developed [61]. On the other hand, thermal oils at an experimental level are being used as a storage medium together with solid materials [62,63].

In summary, molten salt SHS TES have reached high commercial TRLs for high temperature applications, becoming the standard solution for dispatching solar thermal electricity at full load. However, their potential has not been fully developed in industrial applications (TRL 4–6). SHS TES solids regenerator-type storage systems are also commercially deployed in steel and glass industries for waste heat recovery, while their application in power plants is still being developed (TRL 6–7). Despite their TRLs, low cost and widely available natural rocks are very promising storage materials for large scale CSP plants when air is used as heat transfer fluid [11].

The cost of storage unit per high-temperature SHS systems is estimated to range between €20–70/kWh for liquid storage and between €15–40/kWh for solids storage [64]. Regarding the future economic feasibility of high-temperature SHS liquid storage, novel molten salts mixtures must be developed to expand the operating temperature range, together with the exploration of fully new materials with long-term reliability. Future efforts must focus on cost reductions of regenerator-type storage systems through (i) the development of low-cost materials from industry wastes or the use of natural rocks, (ii) less expensive pressurised vessels and (iii) the scale-up of regenerator-type storage technology.

For CSP application, the demonstration of novel SHS TES technologies at a relevant scale is still pending. Hence, pre-commercial small-scale demonstrations and pilot plants should be funded with a strong focus on increased flexibility through heat storage integration.

2.2.2. Latent Heat Storage (LHS)

Latent heat storage (LHS) materials are known as phase change materials (PCMs) with regard to the energy released or absorbed during a change in physical state. The heat is mainly stored in the phase-change process (at a quite constant temperature) and it is directly connected to the latent heat of the substance. Thus, charging and discharging phenomena occur during the phase change either from solid to liquid, liquid to gaseous, solid to gaseous or solid to solid [30]. However, since the storage of gaseous products is difficult, LHS technologies usually make use of solid to liquid phase transition rather than liquid to gas phase change [37] and they are considered to be an efficient alternative to SHS systems [45]. The use of a LHS system using PCMs is an effective way of storing thermal energy and has the advantages of medium energy storage density and the isothermal nature of the storage process [41].

The main advantage of using LHS over SHS is its capacity of storing heat at an almost similar temperature range. Initially, these materials act like SHS materials, in that the temperature rises linearly with the system enthalpy; however, later, heat is absorbed or released at almost constant temperature with a change in physical state [41] (Equation (2)).

$$\begin{aligned} Q_s &= \int_{T_i}^{T_m} m \cdot c_{ps}\, dT + m \cdot f \cdot \Delta q + \int_{T_m}^{T_f} m \cdot c_{pl}\, dT \\ Q_s &\cong m \cdot \left[c_{ps} \cdot (T_m - T_i) + f \cdot \Delta q + c_{pl} \cdot (T_f - T_m) \right] \end{aligned} \tag{2}$$

where Q_s is the storage capacity (J), T_m is the melting temperature (°C), m is the mass of PCM medium (kg), c_{ps} is the average specific heat of the solid phase between T_i and T_m (J/(kg·K)), c_{pl} is the average specific heat of the liquid phase between T_m and T_f (kJ/(kg·K)), f is the melted fraction and Δq is the latent heat of fusion (J/kg).

LHS is a nearly isothermal process, providing significantly enhanced storage quantities when compared to SHS systems of the same temperature range. Isothermal storage is an important characteristic because the solar field inlet and exit temperatures are limited due to (i) constraints in the HTF (ii) solar field equipment and (ii) the power cycle [36]. However, LHS systems present low thermal conductivity [37,65] and solid deposits may form on the heat transfer surfaces [38,45]. The latest research on PCMs focuses on the development of mechanisms to enhance their thermal conductivity, using metal foam, fins, heat pipes, mixtures of PCMs or embedded nanoparticles [66].

Generally, solid–liquid PCMs are the most interesting to be applied in a thermal storage and are classified into organic and inorganic materials [45].

Organic PCMs can melt and solidify many times without phase separation, so they have a high chemical and thermal stability, crystallize with little or no supercooling and are generally non-corrosive [41,67]. They also show some limitations such as a low enthalpy of phase change, low thermal conductivity and better thermal stability than inorganic PCMs [68]. Organic PCMs also can be classified into paraffins or non-paraffins compounds. Paraffins compounds are by-products of oil refinery [69,70], cheaper than other PCMs and compatible with all metal containers. However, they also have some disadvantages, such as large volume change with phase change [71]. On the other hand, non-paraffin compounds are the largest category for potential use as latent heat storage materials. However, they have different features based on each material [72], since this category is divided into fatty acids, alcohols, esters and glycols. Within the non-paraffin category, fatty acids have similar properties to paraffin compounds [71,72], but they are non-cost effective [73].

Inorganic PCMs show higher thermal conductivities compared to organic PMCs [74] but, in contrast, their maintenance is one of the most reported challenges due to their lack of thermal stability. They are frozen at low temperatures and they are difficult to handle at high temperatures, and they can be corrosive [41,67]. There are two large groups of materials within the inorganic PMCs: salts and metals and metal alloys. Salts, in general, have low heat conductivity, a relatively high degree of supercooling and cause degradation at high temperatures [75], while metals and metal alloys have high thermal conductivity and small volume change, therefore they could potentially be a good material, although they have low heat of fusion per unit weight [76].

Moreover, mixtures of different organic and inorganic materials can be generated [71], giving rise to eutectic materials with phase change almost always without segregation, high conductivities and thermal densities [41]. The lower melting temperature of eutectic mixtures than their constituents allows crystallization into a single crystal [77]. Thus, eutectic materials have the ability to melt and solidify consistently without appreciable phase segregation [73]. Depending on the mass fraction of each material, it is possible to vary the melting point of the resulting eutectic mixture [78]. They present low latent and specific heat capacities [79]. The development of high temperature eutectic materials above 500 °C grows in interest as stable thermal energy storage in CSP plants [18].

The main applications of PCMs have been developed for air-conditioning [67], heating and cooling [69,70] in buildings. Nevertheless, there is a potential use of PCMs as TES in CSP plants [68,80]. Up until now, only numerical and experimental research have been carried out, such as cascaded latent heat storage with alkali nitrate salts [81], the combination of SHS with LHS using stearic acid [82], the use of a eutectic mixture such as PCM [83], the use of pure $NaNO_3$ as PCM [84] for direct steam generation (DSG) in a CSP plant or the use of embedded nanomaterials in PCMs to improve the thermal stability during storage and the heat transfer [85].

In summary, latent heat energy density of storage unit ranges between 90–100 kWh/m^3 for high-temperature LHS systems for feasible sizes 10 kWh–10 MWh. High temperature LHS with variable phase-change temperatures between 140–300 °C have been constructed and demonstrated in the operational environment, while, high power systems are still under development with some demonstration projects (TRL 5–6) and high capacity storage systems are TRL 5–9 [64].

The cost of a storage unit per high-temperature LHS systems is estimated to range between €20–70/kWh [64]. These costs need to be reduced to be able to exploit the technological advantages of LHS in the market. This reduction should be mainly focused on the enhancement of heat transfer mechanisms and the development of low-cost PCM systems able to operate at 400–500 °C.

2.2.3. Thermochemical Energy Storage (TCES)

Thermochemical energy storage (TCES) systems are based on reversible chemical reactions [37]. In this way, the endothermic reaction generates the charging process, causing a reagent "A" to separate into two parts, giving rise to products "B" and "C", Equation (3), which can be stored independently and at ambient temperature until the discharge process is required, so that heat losses are practically non-existent [23]. The discharge process takes place with the exothermic reaction and therefore energy is released through the mixture of products "B" and "C" at the required pressure and temperature conditions [41].

$$\begin{array}{rl} \text{Charging (Endothermic reaction):} & A + \text{Heat} \rightarrow B + C \\ \text{Discharging (Exothermic reaction):} & B + C \rightarrow A + \text{Heat} \end{array} \tag{3}$$

The TCES system is the least investigated storage technology though it can potentially store higher amounts of energy than SHS or LHS systems due to (i) its high energy density [36] (almost 10 times higher than SHS and 5 times than LHS [86]) and (ii) its indefinitely long storage duration at ambient temperature [24]. The amount of heat stored (Q_s) in a chemical reaction depends on the heat of reaction and the extent of conversion given by Equation (4).

$$\begin{gathered} Q_s = m \cdot a_r \cdot \Delta H_r + \int_{T_i}^{T_f} m \cdot c_p \, dT \\ Q_s \cong m \cdot \left[a_r \cdot \Delta H_r + c_p \cdot (T_f - T_i) \right] \end{gathered} \tag{4}$$

where, a_r is the mass fraction reacted, ΔH is the heat of reaction (J/kg) and m is the amount of mass of the storage medium (kg), T_i is the initial temperature (°C), T_f is the final temperature (°C) and c_p is the average specific heat between T_i and T_f (J/(kg·K)).

TCES technology must overcome some challenges, due to limitations in heat transfer, cycling stability, reversibility and cost [36]. TCES technology is still in an immature stage and remains at the research level (TRL 3–4) [87,88].

The main technologies that are being studied as possible TCES medium are classified in hydride systems, metal oxide systems and organic systems. These systems are capable of working at high temperatures between 400 and 1000 °C [40,86]. Therefore, TCES technology use materials with higher operation temperature levels than those of the materials used for SHS, such as molten salts (500 °C). Therefore, heat recovery efficiency is greater due to larger operating time, i.e., it is possible to produce more power for the same operating time lapse as SHS.

Hydride systems are classified as metal hydride and ammonia systems. Among metallic hydrides, the most developed is the magnesium hydride (MgH_2) system, which does not generate byproducts. The products of the reaction are solid–gas, so they can be easily separated and have high cycles of reversibility. The ammonia system has important experimental feedback. However, their reaction kinetic is slow and requires high operating pressure, presenting also high costs [40,86].

Metal oxide systems are classified as hydroxide systems, carbonate systems and redox systems. Among hydroxide systems, there are materials with high energy density, good reversibility of the reaction operating at atmospheric pressure, but with low thermal conductivity. Carbonate systems are low cost and use very high energy density materials. The reaction products can be easily separated, but they show sintering problems and poor reactivity. Redox systems do not need a catalyst, they use oxygen as a reactant and the reaction products can be separated, but there are few experiment feedbacks and the systems produce an environmental impact [40].

Finally, organic systems, such as methane reforming, present high reaction enthalpy, but produce side reactions and have low reversibility [86].

Both hydride and carbonate systems are the most promising TCES systems, given their high energy storage density and low cost. Nevertheless, the cyclic degradability and storage requirement of the gas make the redox system the most suitable TCES option [89].

Around 95% of installed TCES systems based on chemical reactions are under research and development and reach TRL 4. In addition to the research on materials, the main challenge for TCES is this technology is related to global system issues such as reaction control, reactor design or process integration. A large room for research is found to increase the TRL of the reactive systems of TCES technology in very different aspects: (i) design of improved reactor concepts, (ii) better integration of gaseous reactants, (iii) material improvement (kinetics, stability) and (iv) optimisation of full reversibility.

Due to the advantages of TCES over LHS and SHS, new advances in research are focused on reducing costs of TCES systems while improving the stability of the cycles in the reversible reactions that occur, developing the design of reactors in which the reaction takes place, through charging/discharging rate, and its integration in the CSP plants [40].

A key aspect to boost their integration in CSP plants will be the enhancement of heat and mass transfers inside the reactor. Furthermore, attention should be paid to the capability of hybrid storage combining 2–3 TES technologies [11].

Current costs are not competitive, given the low TRL of this technology, but the target of cost of storage for TCES with chemical reaction ranges between €10–90/kWh [64]. Cost reduction will include the increase of reactor lifetime and the decrease of the cost of reactants.

2.3. TES CSP Integrated Configurations

Once the main characteristics of CSP and TES has been detailed in Sections 2.1 and 2.2; a revision of the best suited combinations of both technologies is elaborated in this section. As known, electricity production in conventional CSP plants is concentrated during the daily period with solar energy availability. The integration of a thermal energy storage system which makes the electricity production more flexible improves the economic feasibility of CSP plants. More than half of the CSP facilities (51%) currently operating in the world include TES systems [25], storing the energy surplus to be used during high demand periods. Moreover, conventional fossil fuel-based support systems are commonly associated with CSP plants becoming operational when the renewable alternative or the retrieval of stored energy is not enough [90]. However, the use of fossil fuels to satisfy the demand induces an increase in the cost and CO_2 emissions, further contributing to global warming [23].

Therefore, the use of TES in CSP plants implies an environmental and economic benefit, avoiding the loss of thermal energy by storing the excess heat produced to be used when required. The selection of the best TES system to each CSP technology must consider the following characteristics with regard to storage [14,41]:

- The heat storage capacity, which defines the thermal energy which can be stored in the system for a given process, medium and size of the storage system. The larger energy density of the storage medium (MJ/m^3), the smaller storage volume required.
- The storage/discharge rates related to the speed and time elapsed in each charge or discharge process.
- The period of time during which energy can be stored. It will depend on the storage medium, from hours to months.
- The chemical compatibility of the storage medium with the CSP plant. The storage medium must be mechanically and chemically stable, minimizing its degradation after each charge/discharge cycle.
- The energy storage efficiency which relates the energy retrieved from the storage medium and the energy required in the storage process, accounting for the energy losses between each charge/discharge cycle. Thus, excellent heat transfer must occur between the HTF and the storage medium to improve the energy efficiency above 95%. Besides, there must be high chemical compatibility between HTF, heat exchanger and storage medium, with minimum thermal losses.
- The compatibility with the power block associated to the CSP plant. The higher operating temperature of the storage medium, the greater overall efficiency of the CSP plant. Up until now, the Rankine power cycles have been the most widespread in CSP plants using molten salts as the storage medium. However, novel storage materials currently under development withstand operating temperatures above 700 °C and can improve the efficiency of the CSP system by coupling to Brayton cycles.
- The cost of the storage medium including capital and operation and maintenance costs. The longer lifetime and the lower cost of a storage medium, the better the economic and commercial feasibility.
- The storage medium must be safe and environmentally-friendly, considering its lifetime.

Despite the characteristics required to choose the thermal storage medium that best suits the CSP plant, the main configurations to integrate the TES system to the CSP plant must be accounted. The TES system can be classified as active or passive, considering the movement of the storage medium during its charging and discharging, as shown in Figure 3.

The advantages and limitations of the main TES CSP integrated configurations are shown in Table 5.

In active storage systems, the storage medium is a fluid capable of absorbing or emitting thermal energy through forced convection. If the storage medium is the HTF, the storage system is active–direct and no heat transfer mechanism is required. Solid particles will be a potential TES and HTF for the third generation of CSP plants, allowing operating temperatures above 800 °C to improve the thermal conversion efficiency of the associated power cycle [91]. However, if the storage medium is not the same as the HTF, a heat exchanger between both fluids is required. In addition, in the TES active systems, two separate tanks or a single tank can be used. When 2-tanks are used, one of them contains the storage medium charged with thermal energy, while the other contains the discharged material. When conventional molten salts are the storage medium in the 2-tank format, freezing is possible at high temperature (120–220 °C). The use of a single tank reduces the cost and the required volume for the storage tank. In this case, the stored heat may be stratified, creating a thermal gradient, but it is difficult to maintain the thermal stratification.

Another option is the accumulation of water as saturated steam or saturated liquid in a single pressurized tank, which does not require a heat exchanger if it is an active-direct system. Despite its low energy density and the high cost of pressurized tanks [24], the extensive use of water as steam in different applications makes it possible to store water in different saturation states, discarding the rest of the gases as storage media for sensible heat.

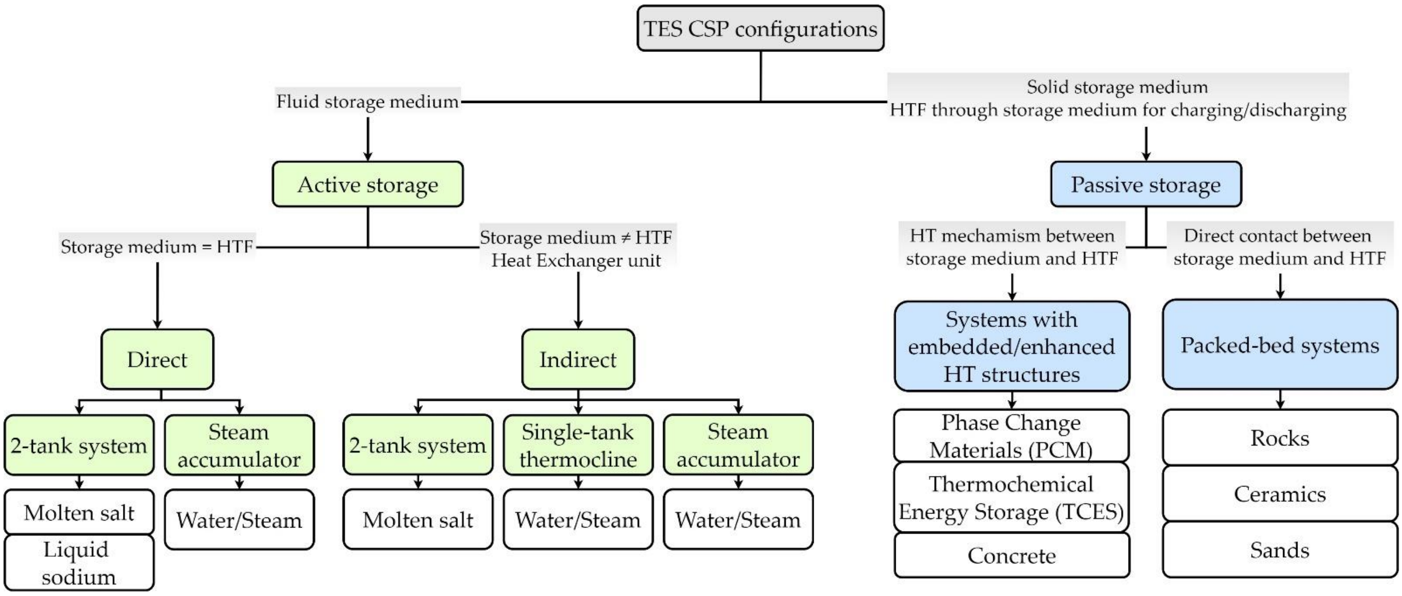

Figure 3. Main TES configurations implemented into CSP plants, according to the concept active/passive storage.

Contrarily, in passive storage systems, the storage medium is normally a low-cost solid material—simple and compact storage unit—and the HTF circulates through it stimulating the charging/discharging of thermal energy stored. Moreover, a heat exchange mechanism between the storage medium and the HTF may be necessary, although if direct contact between the medium storage and HTF is possible, the heat transfer may be better. The temperature during the discharge step is unstable under packed-bed systems. Nevertheless, the heat exchangers required under the embedded heat transfer structures raise the investment cost [24,36]. Among the passive storage systems, the packed-bed system is a promising alternative, given its wide operating temperature range [92].

The most widespread TES system in currently operative CSP plants is the 2-tank format within the active–indirect system (71%). The CSP technology associated with the 2-tank active–indirect TES system is PTC, using molten salts as storage medium and a thermal oil as HTF. The HTF, such as thermal oil, limits the maximum solar-field outlet temperature at 393 °C. The expected electricity production of this type of plants ranges from 158 to 944 GWh/year for CSP plants whose size is 50 MW and 250 MW, respectively. The plant capacity factor as the ratio between the expected production and the maximum possible production within a year is between 26 and 57%, considering a storage size from 3 to 10 h [25].

Additionally, the commercial CSP plant Puerto Errado 2 uses LFR CSP technology in conjunction with a single thermocline tank active–indirect TES system. The water is used as HTF, which reaches a solar-field outlet temperature of 270 °C. The storage size is 0.5 h with a capacity factor of 19% and a net power at nominal conditions of 30 MW [93]. Previously to the Puerto Errado 2 CSP plant, a prototype named Puerto Errado 1 evaluated the single tank thermocline system, with a 1.4 MW DSG power block [25].

Table 5. Main advantages and limitations of each possible TES configuration into a CSP plant [24,36].

TES CSP Integrated Configurations		Advantages	Limitations
Active Direct Storage	2-tank	• Separate hot/cold storage tanks • No heat exchanger required • (HTF = Storage medium)	• Suitable materials as HTF and storage medium required • Larger stored volume required • High cost and freezing point (<220°) for molten salts
	Steam accumulator	• Direct Steam Generation (DSG) • No heat exchanger required • (HTF = Storage medium)	• Low volumetric storage capacity • Expensive pressurized storage tanks
Active Indirect Storage	2-tank	• Commercial maturity • Separate hot/cold storage tanks	• Larger stored volume required • High cost and freezing point (<220°) for molten salts
	Single tank	• Smaller stored volume required • 35% cheaper than 2-tank system	• Complex filler material configuration to keep stratification
	Steam accumulator	• Direct use of stored steam in Rankine power cycle	• HTF such as synthetic oil is required • Low volumetric storage capacity • Expensive pressurized storage tanks
Passive Storage	Embedded HT structures	• Cheap solids may be used • High volumetric storage capacity • (PCMs and TCES)	• Low heat transfer rates • High investment cost for heat exchangers
	Packed-bed systems	• Cheap solids may be used • High heat transfer rates	• Discharge temperature may vary

The characteristics of the most widespread TES CSP configurations under currently operational commercial CSP facilities are listed in Table 6.

The second most commonly integrated TES system is the active–direct (24%) in both modalities: 2-tanks and steam accumulator [25]. Under each modality, the storage medium and the HTF is the same substance and the heat transfer is produced by forced convection [24]. The active–direct TES system is commonly integrated as SHS technology in SPT plants [25]. However, the CSP technology implemented in some operational demonstration plants is PTC, such as Archimede and ASE Demo Plant [94], or LFR (Lanzhou Dacheng Dunhuang (DCTC Dunhuang)—10 MW and 50 MW Fresnel CSP Plant [95]). The 2-tanks format use molten salts as storage medium and HTF, reaching a solar-field outlet temperature up to 565 °C [25]. Nevertheless, the Jemalong Solar Thermal Station operational pilot plant uses liquid sodium as HTF and storage medium [96], while the SUPCON Delingha 10 MW Tower CSP Plant operational demonstration facility adopts double heat transfer fluid as water and molten salt [97]. The expected electricity production ranges from 110 to 500 GWh/year for commercial CSP plants with a 2-tank direct system whose size is 20 MW and 150 MW, respectively. The storage size (6–15 h) improves the plant capacity factor up to 33–36%. Moreover, steam has been used as a storage medium and HTF since 2009, reaching a solar-field outlet temperature up to 530 °C, when the steam is stored as saturated steam, and between 250–300 °C for pressurized water. The expected electricity production ranges from 23.4 to 180 GWh/year for commercial CSP plants whose size is 11 MW and 50 MW, respectively. The plant capacity factor is between 24 and 41% considering a storage size up to 2 h [25].

Regarding passive storage TES CSP configuration, the Huaqiang TeraSolar 15 MW Fresnel CSP Plant uses concrete as TES and water as HTF [98]. The steam turbine net capacity is 14 MW, reaching an electrical production of 75 GWh/year. The storage capacity of 14 h allows a high plant capacity factor of 57% [25].

Table 6. Main characteristics of TES CSP configuration currently operating under commercial scale [25].

TES CSP Configuration	Active Storage				Passive Storage
	Direct		Indirect		Embedded HT Structures
	2-Tank	Steam Accumulator	2-Tank	Single-Tank	
CSP technology	SPT	SPT	PTC	LFR	LFR
TES medium	Molten salts	Water	Molten salts	Ruths tank	Concrete
HTF medium	Molten salts	Water	Thermal oil	Water	Water
T_{out} solar field (°C)	565	250–530	393	270	450–550
Expected production (GWh/year)	110–500	23–180	158–944	49	75
Nominal capacity (MWe)	20–150	11 to 50	50–250	30	15
Storage size (h)	6 to 15	1 to 2	3 to 10	0.5	14
Power block	Steam Rankine	Steam Rankine	Steam Rankine	Steam Rankine	Steam Rankine
Number of commercial TES CSP plants	8	3	32	1	1

The rest of the TES CSP facilities currently in operation use combinations of the previous ones, such as in the case of Dahan Power Plant [99] in which the steam accumulator system is combined with two indirect tanks; or passive storage systems, such as packed-bed systems in Jülich Solar Tower Plant [44], all of these being demonstration or pilot plants.

3. European and North American TES CSP R&D Projects Review

In the present section, a review of the completed and ongoing TES CSP R&D projects launched in the last decade (2011–2022) from Europe and North America, which analyze the full integration between CSP, TES and the associated power block, are detailed. Other R&D projects launched in the last decade and not focused on the integration of the full TES CSP system at large scale are not included in this review. These projects oriented to the development of new materials or components required for TES systems, whose application is at small scale or for building and district heating systems, are beyond the scope of the present review.

Before 2011, the CSP-based R&D projects were focused on the integration of SHS and LHS as TES [27]. Molten salts were the most developed storage medium within SHS system, even used as HTF in active direct storage systems configuration [100,101]. Furthermore, research based on molten salts was focused on strategies to minimize its main drawbacks: (i) increasing the storage temperature over 650 °C [102] and (ii) improving the specific heat with embedded ceramic particles [103]. Regarding the CSP TES passive storage configuration, SHS and LHS storage mediums were also investigated. Within SHS the most developed passive storage configurations were: (i) packed-bed system of sand [104] or concrete [105], and (ii) solid graphite modular blocks to achieve operating temperatures up to 1650 °C [106]. Additionally, since 2008, the development of PCMs as LHS increased, transferring the thermal energy by heat exchangers [107,108] or embedded thermosyphon heat pipes [109], even integrating nanoparticles into the PCM to improve the heat transfer efficiency [27].

3.1. Summary of R&D Projects (2011–2022): Timeline and TRL

This section summarizes and compares all the European and North American R&D projects, completed and ongoing, launched in the last decade. Table 7 gathers general information about these TES CSP R&D projects whose technical and economic data will be provided in the following subsections.

Table 7. TES CSP R&D projects from 2011 to the present.

TES	Project Name *	Location	Period	Coordinator *	Budget (M€)	Ref.
LHS	DDI-TES	Florida (USA)	2011–2012	USFl	0.7	[110]
TCES	TCS-Power	Germany	2011–2015	DRL	4.4	[111]
TCES	RESTRUCTURE	Greece	2011–2016	CERTH	3	[112]
TCES	STORRE	France	2012–2016	CEA	2.9	[113]
TCES	LCMH-TES	South Carolina (USA)	2012–2016	SRNL	2.5	[114]
LHS	HELH-TES	Illinois (USA)	2012–2018	ArNL	1	[115]
TCES	SC-TES	Florida (USA)	2014–2015	UFl	0.4	[116]
TCES	RC-TES	Alabama (USA)	2014–2016	SRI	0.8	[117]
TCES	ELEM-TES	Colorado (USA)	2014–2017	CSM	1	[118]
TCES	ISR-TES	New Hampshire (USA)	2015–2018	BE	2.6	[119]
TCES	BMC-TES	New Mexico (USA)	2015–2018	AlNL	3.4	[120]
TCES	CaL-TES	Alabama (USA)	2015–2018	SRI	2.8	[121]
SHS	NEXT-CSP	France	2016–2020	CNRS	4.9	[122–127]
Other	SOLSTORE	Spain	2017–2019	CIC	0.1	[128,129]
LHS	NPMSSES	United Kingdom	2017–2019	ULe	0.2	[130]
LHS	AMADEUS	Spain	2017–2019	UPM	3.2	[131]
TCES	SesPER	Spain	2017–2020	CSIC	0.2	[132]
SHS	NEXTOWER	Italy	2017–2021	ENEA	6.2	[133]
SHS + LHS	IN-POWER	Spain	2017–2021	LEITAT	5.8	[134]
SHS + LHS	NewSOL	Portugal	2017–2021	UEv	5.6	[135]
TCES	SOCRATCES	Spain	2018–2021	USe	4.9	[136,137]
LHS	THERMES	United Kingdom	2019–2021	UBir	0.2	[138]
SHS	LPP-SS	Colorado (USA)	2018-	NREL	8	[139]
LHS	TES-HE	New Hampshire (USA)	2018-	BE	1.1	[140]
SHS	CSP-ERANET (Newcline)	Spain	2019–2024	AGENEX	13.8	[141]
TCES	SS-TES	Michigan (USA)	2020-	MiSU	2	[27]
TCES	EWSCh-TES	Arizona (USA)	2020-	ArSU	2.9	[27]
TCES	EC-TES	South Carolina (USA)	2020-	SRNL	0.2	[27]
SHS	HTMS-TES	Tennessee (USA)	2020-	ORNL	0.1	[142]
SHS	FULL-TES	California (USA)	2020-	EDISUN	39	[27]
SHS	PB	Montana (USA)	2021-	MoSU	0.1	[27]

* Abbreviation of project's name and main coordinator. Full name appears in Appendix A.

The United States of America (USA) is the country with greatest development of TES CSP R&D projects, mainly focused on TCES technology. Meanwhile, Spain has launched the second highest number of TES CSP R&D projects in the last decade (Table 7). Both countries have a long record of developing CSP technology, concentrating the largest number of currently operating CSP facilities deployed in the world with and without TES (i.e., 17 in the USA [25] and 51 in Spain [7]). Figure 4 illustrates the distribution by countries and TES technology of the number of TES CSP R&D projects.

Figure 5 represents a timeline built with the TES CSP R&D projects within the scope of the present study. The upper part comprehends the ongoing TES CSP R&D projects, while the bottom part shows the TES CSP R&D projects already completed since 2011. In addition, the TRL of all the TES CSP R&D projects is shown through a colour scale from low (dark red—TRL 1) to high (dark green—TRL 9) technological readiness level by the end of the project.

The most widespread TES technology among the research projects (almost 55%) between 2011 and 2018 involve the integration of TCES with a CSP plant, reaching a TRL by the end of the project between four and eight; from experimental demonstration to near commercial scale. Within ongoing TES CSP R&D projects, SHS and TCES systems are the most extended with lower TRLs which range from two to six, except for a project which reaches a TRL of eight. Regarding research projects which include LHS as TES, the development level oscillates within lab and pilot scale (TRL 3–5). However, R&D projects involving SHS and LHS TES reached a development level at demonstration scale in the relevant environment (TRL 6).

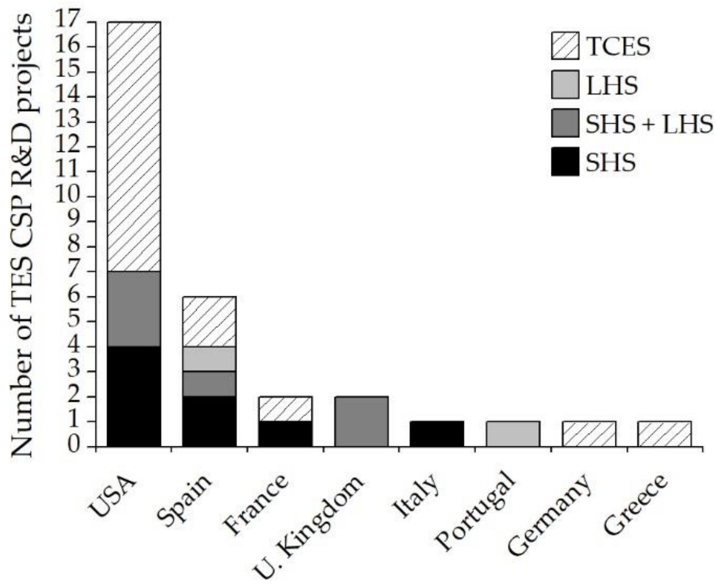

Figure 4. TES CSP R&D projects from 2011 distributed by country and TES technology.

3.2. TES CSP R&D Projects Completed between 2011–2022

This section gathers the technical and economic information of those TES CSP R&D projects finished from 2011 onwards within Europe and North America. Most of the analyzed projects focus on the complete TES CSP configuration. However, few research projects aim to only develop a specific block of the TES CSP system: storage medium, required equipment for the heat transfer between CSP-TES and TES-power cycle, or new storage concepts. Table 8 summarizes economic and technical data of the TES CSP R&D projects which assess the full integration of the TES with the CSP plant and the power block.

3.2.1. TCS-Power

The overall objective of the Thermochemical Energy Storage for Concentrated Solar Power Plants (TCS-Power) research project was to develop a new, efficient and economically viable TCES for CSP plants, minimizing electricity production costs. Two low-cost and long-term stable TCES systems were proposed within the TCS-Power project: redox and hydroxide. Manganese oxide is the storage medium selected as redox TCES to be integrated into SPT CSP plants, given the high operating temperature (>700 °C). The air is the fluid used as HTF and oxygen carrier for the redox reaction, while calcium oxide is the storage material used as hydroxide TCES integrated into PTC CSP plants, achieving a working temperature between 400 and 600 °C. Molten salts were selected as HTF within hydroxide TCES. However, the hydroxide TCES medium could be used as HTF and TES, given the possibility of the material conveying. Both TCES systems use charge/discharge reactors for the heat transfer between HTF and TES as passive storage TES CSP configuration. The power block associated with both TES systems was the steam Rankine, given its technological maturity. Both TCES systems were evaluated at lab and pilot scale to 10 kW (TRL 4–5). Furthermore, a techno–economic assessment evaluated the TCES up-scaling to commercial scale, being the obtained LCOE of €0.14 and €0.21/kWh under hydroxide and redox TCES systems, respectively. This European R&D project launched in 2011 was coordinated by Deutsches Zentrum für Luft—und Raumfahrt e.V. (DRL) from Germany [111].

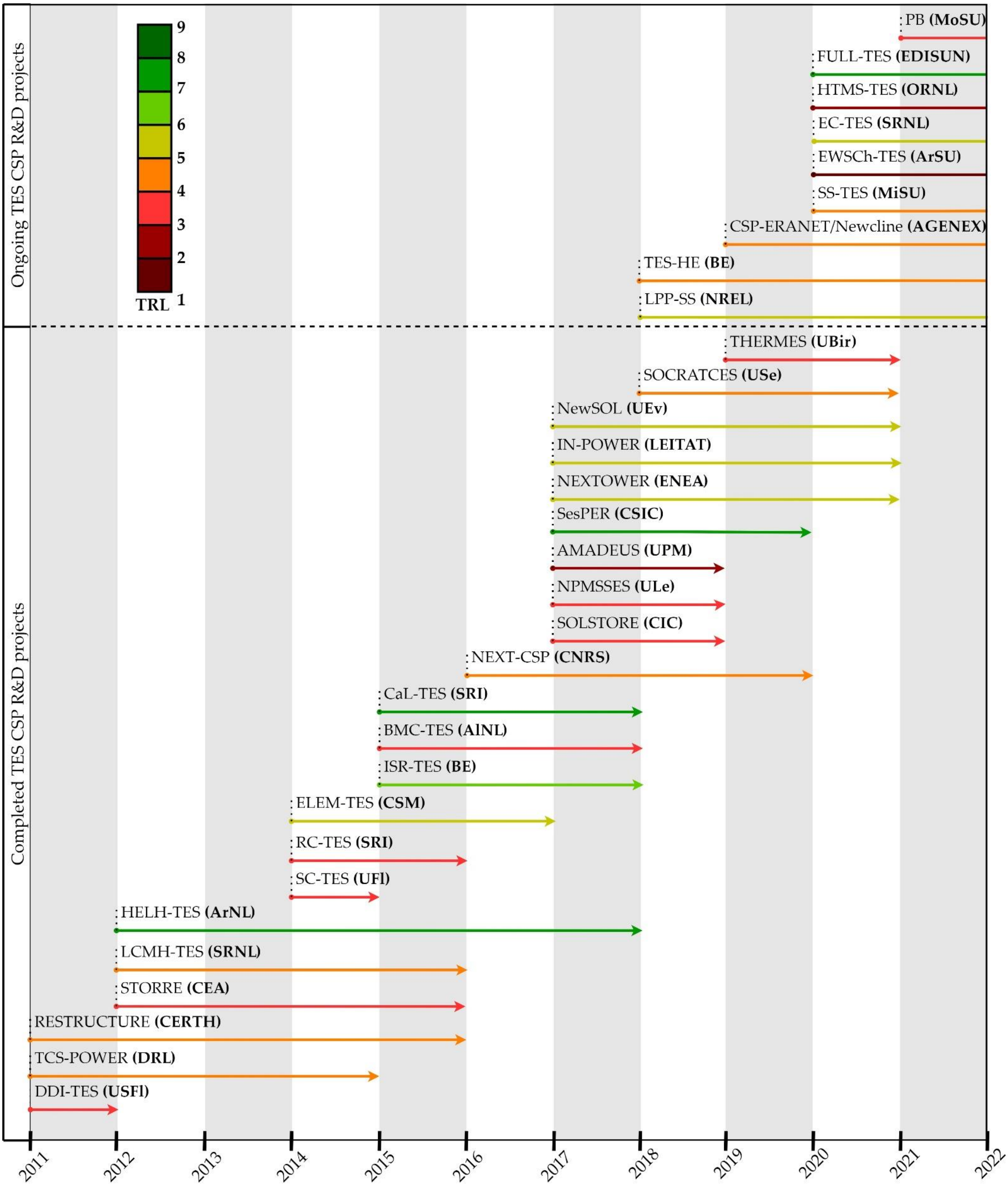

Figure 5. Timeline of TES CSP R&D projects from 2011 to the present.

Table 8. Technical and economical parameters of completed TES CSP R&D projects from 2011.

Project Name Abbreviation	TES CSP Configuration	TES Technology	Storage Size (h)	CSP Technology	HTF	T_{max} ¥ (°C)	Power Block	TRL §	LCOE * (€/kWh)	Ref.
TCS-Power	Passive storage	Redox TCES	up to 12	SPT	Air	400–600	Steam Rankine	4–5	0.14	[111]
		Hydroxide TCES		PTC	Molten salts				0.21	
RESTRUCTURE	Passive storage	Redox TCES	6 to 13	SPT	Air	up to 1000	Air Brayton CC	4–5	<0.15	[112]
STORRE	Active storage direct/indirect 2-tank	Hydroxide TCES	6 to 13	PTC, LFR	HTF = TES or HTF ≠ TES	300–550	Steam Rankine	3–4	-	[113]
CaL-TES	Passive storage	Carbonate TCES	-	SPT	sCO_2	720	Closed loop CO_2	7–8	0.06	[121]
NEXT-CSP	Active storage direct 2-tank	Solid particles SHS	up to 12	SPT	HTF = TES	650–750	Gas turbine, Subcritical steam, Air Brayton	5	0.1	[122–127]
NEXTOWER	Active storage indirect single-tank	Liquid metal SHS	-	SPT	Air	800	Gas turbine	6	-	[133]
IN-POWER	Active storage single-tank & Passive storage	Molten salts SHS & PCM LHS	-	LFR, PTC	Molten salts	600	DSG	6	0.1	[134]
NewSOL	Passive storage	Concrete module	-	PTC	Ca-ternary molten salt mixture	up to 550	Steam Rankine	5–6	0.1–0.12	[135]
	Active storage single-tank & Passive storage	Molten salts SHS & PCM LHS	8							
SOCRATCES	Passive storage	Carbonate TCES	days/months	SPT	HTF = TES	600–1000	Closed-loop CO_2 Brayton	5	0.07	[137]

* Expected LCOE under commercial up-scaling. § Expected TRL when project ends. ¥ Maximum temperature achieved in the process from TES to power block.

3.2.2. RESTRUCTURE

The Redox Materials-based Structured Reactors/Heat Exchangers for Thermo-Chemical Heat Storage Systems in Concentrated Solar Power Plants (RESTRUCTURE) research project aimed to develop a new heat transfer mechanism for the redox TCES systems based on monolithic structures, such as honeycombs or foams partially or totally made of redox materials. The STP CSP technology was selected to integrate the redox TCES system, reaching working temperatures of 1000 °C. The associated power block was a Brayton combined cycle (CC) using air as HTF. The projected storage period was between 6 to 13 h, considering an assessment of up-scaling to commercial scale (70.5 MWe). A LCOE below €0.15/kWhth was estimated through a commercial scale analysis. Before the up-scaling assessment, the redox TCES system was tested under pilot scale at Solar Tower Jülich/STJ research platform in Germany (TRL 4–5). The European R&D project launched in 2011 was coordinated by Ethniko Kentro Erevnas kai Technologikis Anaptyxis (CERTH) from Greece [112].

3.2.3. STORRE

The high temperature thermal energy storage by reversible thermochemical reaction (STORRE) research project aimed to develop the integration of a high-density TCES system in LFR and PTC CSP plants. The calcium hydroxide is the TES material, allowing high-working temperatures up to 550 °C and storage capacities of days. The TES CSP configuration selected is 2-tank active storage, being indirect if there is a HTF between the solar field and the TES or direct if the solid particles are heated into a solar receiver. The reactors required to perform de gas–solid reversible reaction of calcium hydroxide were tested at pilot scale (TRL 3–4). The power block for the up-scaling assessment up to commercial scale (85 MWe) was a steam Rankine with a storage capacity of 6 and 13 h. The European R&D project launched in 2012 was coordinated by Commissariat a l'Energie Atomique et aux Energies Alternatives (CEA) from France [113].

3.2.4. CaL-TES

The Demonstration of High-Temperature Calcium-Based Thermochemical Energy Storage System for Use with Concentrating Solar Power Facilities (CaL-TES) research project aimed to develop a low cost TCES system to couple with sCO_2 power cycles integrated into SPT CSP plants. A carbonate TCES system based on calcium oxide was selected to achieve high operating temperatures for the power block up to 720 °C. The same packed-bed reactor is used to perform the reversible reaction. Under the endothermic reaction, the HTF transfers heat to the reactor to decompose limestone into CaO and CO_2, diverting the gas to storage. The exothermic reaction occurs when CO_2 from storage reacts with CaO in the reactor to retrieve the stored energy and to be transferred to the HTF. Thus, the TES cSP configuration is a passive storage, considering (i) molten salts or liquid metal as HTF between the packed-bed reactor and an intermediate heat exchanger and (ii) sCO_2 as HTF between the intermediate heat exchanger and the power block. A demonstration up-scaling of 100 MWh will be expected beyond the project (TRL 7–8). The American R&D project launched in 2015 was coordinated by the Southern Research Institute (SRI) [121].

3.2.5. NEXT-CSP

The NEXT-CSP research project (High temperature concentrated solar thermal power plan with particle receiver and direct thermal storage) aimed to validate an industrial pilot plant (TRL5) tested at Thémis SPT experimental facility (France) for integrating new technology in CSP plants. The Centre National de la Recherche Scientifique (CNRS) in France coordinated the European R&D project launched in 2016 [122].

A fluidized particle in-tube concept, first published in 1980, was developed to design the solar receiver (scaling up to 50 MWth per single unit) to heat the TES up to 650–750 °C [123]. The solar receiver with fluidized particle recirculation was previously demonstrated at 150 KW in the CSP2 (Concentrated Solar Power in Particles) research project [124]. Silicon carbide solid particles were used as TES medium and HTF, as two-tank active direct TES CSP configuration. The cold and hot particles tanks were interconnected through a particle-pressurized air fluidized bed heat exchanger [123]. This novel storage configuration was coupled to a gas turbine reaching a power block efficiency of 46% [125]. However, the integration of subcritical steam or air Brayton power cycles also achieved good efficiencies (up to 41% [126] and 39% [127], respectively) with lower energy penalties. Additionally, the integration of supercritical steam or CO_2 cycles could minimize energy penalties and cost of the TES CSP plant. For future work, the large-scale facility (>100 MWe) using multiples SPTs will be developed and demonstrated [123].

3.2.6. NEXTOWER

The NEXTOWER research project (Advanced materials solutions for next generation high efficiency concentrated solar power (CSP) tower system) aimed to demonstrate the durability over 20 years of ceramic materials for large CSP air-based SPT (>5 MWe). The air is heated up to 800 °C in the solar receiver and the thermal energy is transferred to an innovative single tank thermocline with liquid metal as TES medium by an air–lead heat exchanger. The TES CSP configuration is an indirect active system using air as HTF. The liquid metal storage material is based on liquid lead stored in new non-corrosive alumina forming steels, which has been transferred from nuclear fission technology. The liquid lead as TES was installed and proved at demo scale TRL 6 (SOLEAD) in *Plataforma Solar de Almería* (Spain). The high temperature achieved by the storage medium extends the thermal applications of CSP plants. Regarding the association of high-temperature power blocks to the CSP plant, the easiest integration would be achieved with working fluids such as compressed gases or supercritical fluids. The European R&D project launched in 2017 was coordinated by Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) [133].

3.2.7. IN-POWER

The Advanced Materials technologies to QUADRUPLE the Concentrated Solar Thermal current POWER GENERATION (IN-POWER) European R&D project aimed to develop new technology solutions for LFR and PTC CSP plants to improve the efficiency and to minimize the costs. Regarding energy storage, a combination of SHS and LHS media is investigated. The TES CSP configuration is a molten salt (60% $NaNO_3$ and 40% KNO_3) single-tank thermocline active storage with encapsulated PCM (Aluminium silicon). The molten salts act as HTF to the PCM as passive storage TES CSP configuration. This new SHS-LHS hybrid TES system (i) minimizes the charge/discharge cyclical degradation and (ii) maximizes the storage capacity compared to the same volume of a classic molten salts single-tank thermocline system. Thus, the TES system could be reduced and also its cost (LCOE beyond 2020 €0.10/kWh), testing in LFR and PTC pilot plants (TRL 6) for DSG. The European R&D project launched in 2017 was coordinated by Acondicionamiento Tarrasense Asociación (LEITAT) from Spain [134].

3.2.8. NewSOL

The main objective of New StOrage Latent and sensible concept for high efficient CSP Plants (NewSOL) research project is to develop new materials for energy storage in (CSP) plants. Two innovative concrete storage media were investigated for integration into existing or new PTC CSP plants, reaching storage temperatures up to 550 °C. A concrete module tank is proposed as SHS medium for existing CSP plants, using a new Ca-ternary molten salt mixture as HTF circulating inside the embedded pipes (passive storage TES CSP configuration with a storage capacity of 1600 kWh_{th}). Under new CSP plants, a Ca-ternary molten salt single-tank thermocline with concrete walls and encapsulated PCMs is implemented as a SHS and LHS system within an active storage TES CSP configuration, using the new molten salt mixture as HTF for the PCM passive storage medium. Thus, the new thermocline system replaces classic steel walls with cement (i) to minimize cyclic thermocline degradation and (ii) to improve the storage performance. The new SHS-LHS TES system was implemented as a prototype at demo scale (TRL 5–6) in Évora Molten Salts Platform (Portugal), producing 8 additional hours of steam to the associated power block. The NewSOL European R&D project launched in 2017, led by Universidade de Évora (UEv) from Portugal [135].

3.2.9. SOCRATCES

The SOlar Calcium-looping integRAtion for Thermo-Chemical Energy Storage (SOCRATCES) research project focused on reducing the intermittency in electricity production of SPT CSP plants, using the advantages of calcium looping (CaL) compared to other types of technologies used as TCES, such as the low price of $CaCO_3$ (€10/ton) and its wide availability. In addition, the equipment used in the CaL system was previously developed as CO_2 capture technology. Solar energy decomposes limestone into CO_2 and CaO at calciner receiver to be later independently stored, even at ambient temperature. When electric demand is high, the stored products are fed to the carbonator reactor, retrieving thermal energy to the power block. The TES CSP configuration can be considered as passive storage, with heat exchangers needed between the storage tanks and the main reactors. The high working temperatures achieved (600 and 1000 °C) could improve the power block efficiency associated to a SPT CSP plant. Among the power cycles assessed, the best promising option for upscaling the CaL TCES system is the closed-loop CO_2 Brayton cycle, reaching overall efficiencies up to 45%. The CaL TCES system has been tested in the relevant environment at pilot scale (TRL 5). The LCOE expected will be lower than 0.07€/kWh at commercial scale [136]. The European R&D project launched in 2018 was led by University of Seville (USe) from Spain [137].

3.2.10. Other TES CSP R&D Projects (Materials, Concepts, Technology)

Since 2011, TES research projects focused on the development of concepts, materials or heat transfer technologies have also been investigated as an application to CSP plants. Regarding LHS TES systems, different structures to store PCM were researched. The University of South Florida (USFl) from the USA validated at lab scale encapsulated PCM into a packed-bed system as passive storage [110]. Furthermore, Argonne National Laboratory (ArNL) from the USA developed a 2-phase project from lab to demonstration scale to validate PCM using graphite foam to improve its thermal efficiency, infiltrating $MgCl_2$ into the graphite pores [115]. Moreover, the European NPMSSES research project (United Kingdom) researched the introduction of nanoparticles into a PCM (solar salt) to improve its thermo–physical properties at lab scale [130]. Another European R&D project (AMADEUS from Spain) developed synthetic PCM, demonstrating at proof of concept the thermal energy retrieval through a hybrid thermionic–photovoltaic converter to produce electricity [131]. Regarding the application of LHS TES system to low temperature solar fields, the European THERMES R&D project (United Kingdom) developed a microemulsion of PCM to act as HTF and TES at lab scale [138].

Additionally, the main developed TCES technologies were based on two systems: hydride and metal oxides. The Savannah River National Laboratory (SRNL) and Brayton Energy (BE) institutions (USA) validated a metal hydride TCES at bench scale to be integrated into a CSP with an associated high temperature sCO_2 power block [114,119]. Binary metal chalcogenide as TCES system in a modular reactor was developed by Los Alamos National Laboratory (AlNL) from the USA to achieve working temperatures up to 750 °C [120]. Regarding metal oxide systems, the carbonate one was developed at lab and bench scale by University of Florida (UFl) and Southern Research Institute (SRI) from the USA, respectively. The strontium carbonate TCES system reached temperature up to 1000 °C (UFl) [116], while the regenerative carbonate system developed by SRI operated at medium temperature (650–850 °C) [117]. Besides, new TCES materials as perovskites researched by Colorado School of Mines (CSM) from the USA [118] and SesPER R&D project (Spain) [132], achieving high storage temperatures (up to 1200 °C) at advanced TRL 6 to 8. However, new TES similar to SHS system have been developed by SOLSTORE R&D project (Spain), providing extra thermal energy by the enthalpy of a solid-state reaction [128,129].

3.3. Ongoing TES CSP R&D Projects Lauched between 2011–2022

This section gathers the ongoing TES CSP R&D projects launched from 2011 within the European and North American regions. The currently active TES CSP R&D projects focuses on (i) new SHS materials and (ii) the growing use of TCES technology. Table 9 summarized the main relevant data of the current active TES CSP R&D projects since 2011.

The National Renewable Energy Laboratory (NREL), from the USA, promotes a demonstration scale research project (TRL 6) with 2-tank indirect active storage TES CSP configuration, using new molten chloride salts as SHS medium (up to 12 h of storage capacity) and liquid-metal sodium as HTF to achieve a high temperature (740 °C) for the associated power block (sCO_2) to the SPT CSP plant [139]. The new molten chloride salts are also developed by Oak Ridge National Laboratory (ORNL), from the USA, in a single-tank thermocline TES CSP configuration to reduce costs [142]. The thermocline concept will be developed by NEWCLINE (CSP-ERANET) R&D project, using PCM at pilot scale (TRL 5) [141]. The integration of a sCO_2 power cycle is developed in other R&D projects, using as TES (i) composite PCM (Brayton Energy (BE), USA) [140], (ii) multiple TCES to suitably dispatch electricity (Arizona State University (ArSU), USA) [27] or (iii) solid material to be demonstrated at full scale (5 MW), such as packed-bed of rocks (EDISUN (USA)) [27]. Regarding the BE research project, the main objective is to test a new heat exchanger design, given as TES the graphite foam-based PCM developed by ArNL from 2012 to 2018. The development of TCES research projects continues to expand, increasing the working temperature up to 1300 °C with redox reactions (Michigan State

University (MiSU), USA) [27] or improving the storage capacity at ambient temperature of a new molten carbonate mixture (Savannah River National Laboratory (SRNL), USA) [27]. Finally, research on improving the heat transfer efficiency of packed-bed passive storage systems is developed by Montana State University (MoSU), from the USA [27].

Table 9. Technical and economical parameters of active TES CSP R&D projects from 2011.

Project Name Abbreviation	TES CSP Configuration	TES Technology	CSP Technology	T_{max} ¥ (°C)	Power Block	TRL §	LCOE * (€/kWh)	Ref.
LPP-SS	Active storage (2-tank indirect)	Molten chloride salts SHS	SPT	740	sCO_2	6	0.06	[139]
TES-HE	Passive storage	PCM LHS	SPT	>700	sCO_2	5	-	[140]
CSP-ERANET (Newcline)	Active storage indirect single-tank & Passive storage	Ceramics/PCM LHS	PTC, SPT	-	-	5	-	[141]
SS-TES	Passive storage	Redox TCES	-	up to 1300	-	5	-	[27]
EWSCh-TES	Passive storage	Multiple TCES	-	-	sCO_2	1–2	-	[27]
EC-TES	Passive storage	Carbonate TCES	-	-	-	5–6	-	[27]
HTMS-TES	Active storage indirect single-tank	Chloride salts SHS	-	-	More-efficient	3	-	[142]
FULL-TES	Passive storage packed-bed	Rocks SHS	SPT	600	sCO_2	7–8	<0.05	[27]
PB	Passive storage packed-bed	SHS	-	-	-	3–4	-	[27]

* Expected LCOE under commercial up-scaling. § Expected TRL when project ends. ¥ Maximum temperature achieved in the process from TES to power block.

4. Discussion and Conclusions

The problem of intermittency in energy production associated to the CSP facilities will only be solved by increasing the use of TES. More than a half of the currently operating CSP facilities have a TES system, mainly based on molten salts SHS medium. Despite molten salts having a high TRL for high-temperature applications, natural rocks will be a promising SHS medium given their low storage cost. Within LHS systems, high-temperature PCM has been tested in the operational environment, being one of the potential TES systems when its heat transfer ratio and storage cost are improved. Regarding the TCES system, issues such as the reactor design and the reaction control are being investigated at TRL 4. When a greater development of the chemical reactions involving TCES is reached, a lower storage cost is expected even below SHS and LHS materials.

Almost all of the European and North American TES CSP R&D projects completed before 2011 implemented the conventional configuration related to the first and second generation of CSP plants associated with a steam Rankine power block, including (i) molten salts as TES, (ii) thermal oil as HTF and (iii) PTC technology in solar fields. Firstly, even though LCOE of PTC technology is one of the highest, its advantageous properties proven on a commercial scale will boost its leadership in the CSP market. Secondly, despite the 2-tank indirect active storage system being the most commercially extended, the steam accumulator format within the active direct storage system allows direct use of steam generated in the solar field for storage and production of electrical energy through the steam power cycle. Moreover, savings of 35% of the cost of the TES system can be achieved by using a single tank. The major issue of the active storage systems are the limitations associated with the media currently used in commercial CSP plants, such as the high freezing point of common molten salts, the low thermal conductivity of water, as well as the high costs of conventional molten salts and pressurized water storage tanks. Thus, the R&D projects launched after 2011 in Europe and North America developed new TES, using TES CSP configurations based on passive storage and single tank thermocline active storage to minimize the LCOE of the CSP facilities, being able to use low-cost materials and achieving better heat transfer. Furthermore, one of the most important advantages is the inclusion of a thermocline system in the passive storage using molten salts and PCM, leading to a new storage configuration with lower LCOE. Regarding HTF, the use of TES as HTF or even air is advantageous over the use of conventional molten salts, minimizing the costs of electricity production. Nevertheless, since there is a high number of R&D projects with high-temperature TCES storage systems, the associated CSP technologies are mainly based on SPT and PTC. One of the limitations of high-temperature TCES storage systems focuses on the development of materials that can withstand these working temperatures. The USA and Spain are the leading countries in the implementation of research projects related to the integration of TES in CSP facilities with an associated power cycle for large-scale electricity production. Their great track record of technology development in CSP plants endorses both countries, accounting for almost 60% of the currently operating CSP plants.

Regarding SHS media, new molten salts allow to achieve operating temperatures up to 740 °C. In addition, novel storage media based on liquid metal or solids (i.e., particles or rocks) begin to develop from pilot to sub-commercial scale at the STP CSP plants. Similarly, the combination of SHS and LHS within LFR and PTC CSP facilities are under development at demo scale. The LHS system using different PCMs could increase the thermal energy that could be stored. Furthermore, new lab-scale research based on introducing nanoparticles improves the thermophysical properties of the PCM. The TCES-based R&D projects extended are related to hydroxide, carbonate and redox TCES systems, reaching working temperatures up to 1000 °C and a level of development from demo to sub-commercial scale.

The TCES systems have been the most investigated TES technologies in the last decade, given the low cost of the storage medium and the high temperatures achieved when retrieving the stored thermal energy. Thus, new high-temperature power blocks can be implemented into the TES CSP facilities to improve the overall plant efficiency, such as Brayton or supercritical CO_2 cycles. The main objective of the largest budget allocated to an ongoing TES CSP R&D project is to develop the sCO_2 power cycle associated with CSP plants on a commercial scale.

5. Future Directions

The next steps of research in TES CSP integration in the near future will be focused on the upscaling, from demo to commercial stage, the SPT and PTC CSP facilities, using (i) high energy density, low-cost TES materials for larger storage time with minimal energy losses (i.e., solid SHS as passive storage, combination of liquid SHS and PCM as LHS medium, carbonate or redox TCES systems) and (ii) high efficiency power blocks (i.e., supercritical or Brayton) to even minimize the LCOE of the CSP facility below 0.05 €/kWh. Solid particles or packed-beds of rocks, with SHS as passive storage, may be able to reduce the investment cost of the CSP facility. Among LHS systems, the newly developed PCMs together with the use of new low-freezing point molten salts will set a new configuration between the passive and active system, minimizing the storage size and therefore associated costs. Notably, the TCES systems will grow exponentially, leading the conversion of CSP facilities to base-load plants with safe and uninterrupted electricity production.

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Nomenclature

Symbols	
a	fraction reacted, -
c	specific heat, J/kg·K
f	melt fraction, -
m	mass of storage medium, kg
Q	heat, J
T	temperature, °C
ΔH	heat of reaction, J/kg
Δq	latent heat of fusion, J/kg
Subscripts and superscripts	
f	final
I	initial
m	melting
max	maximum
out	outlet
p	constant pressure
pl	liquid phase
ps	solid phase
r	reaction
s	storage/stored
Acronyms andabbreviations	
CC	Combined Cycle
CORDIS	Community Research and Development Information Service
CSP	Concentrating Solar Power
GHG	Greenhouse Gases
HT	Heat Transfer
HTF	Heat Transfer Fluid
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost Of Electricity
LFR	Linear Fresnel Reflectors
LHS	Latent Heat Storage
PDC	Parabolic Dish Collectors
PMCs	Phase Change Materials
PTC	Parabolic Trough Collectors
RES	Renewable Energy Sources
R&D	Research and Development
sCO_2	Supercritical CO_2
SETO	Solar Energy Technologies Office
SHS	Sensible Heat Storage
SPT	Solar Power Towers
TCES	Thermochemical Energy Storage
TES	Thermal Energy Storage
TRL	Technology Readiness Level
USA	United States of America

Appendix A. List of R&D Projects, Co-Ordinators and Abbreviations

Table A1. List of R&D projects name and abbreviations.

Abbreviation	Project Name
AMADEUS	Next GenerAtion MateriAls and Solid State DevicEs for Ultra High Temperature Energy Storage and Conversion
BMC-TES	Binary Metal Chalcogenides for High Temperature Thermal Storage
CaL-TES	Demonstration of High-Temperature Calcium-Based Thermochemical Energy Storage System for Use with Concentrating Solar Power Facilities

Table A1. *Cont.*

Abbreviation	Project Name
CSP-ERANET (Newcline)	Advanced thermocline concepts for thermal energy storage for CSP
DDI-TES	Development and Demonstration of an Innovative Thermal Energy Storage System for Baseload Power Generation
EC-TES	Eutectic Carbonates for Low Cost-Efficient Thermochemical Heat Storage System
ELEM-TES	Efficiently Leveraging Equilibrium Mechanisms for Engineering New Thermochemical Storage
EWSCh-TES	Economic Weekly and Seasonal Thermochemical and Chemical Energy Storage for Advanced Power Cycles
FULL-TES	Development, Build and Operation of a Full-Scale, Nominally 5MWe, Supercritical Carbon Dioxide Power Cycle Coupled with Solid Media Energy Storage
HELH-TES	High Efficiency Latent Heat Based Thermal Energy Storage System Compatible with Supercritical Carbon Dioxide Power Cycle
HTMS-TES	Simplified High-Temperature Molten Salt Concentrating Solar Power Plant Preconceptual Design
IN-POWER	Advanced Materials technologies to QUADRUPLE the Concentrated Solar Thermal current POWER GENERATION
ISR-TES	Integrated Solar Receiver with Thermal Storage for an sCO_2 Power Cycle
LMMH-TES	Low-Cost Metal Hydride Thermal Energy Storage System for Concentrating Solar-Thermal Power Systems
LPP-SS	Liquid-Phase Pathway to SunShot
NewSOL	New StOrage Latent and sensible concept for high efficient CSP Plants
NEXT-CSP	High Temparature concentrated solar thermal power plan with particle receiver and direct thermal storage
NEXTOWER	Advanced materials solutions for next generation high efficiency concentrated solar power (CSP) tower systems
NPMSSES	Nanoparticle Enhanced Molten Salts for Solar Energy Storage
PB	Efficient Thermal Energy Storage with Radial Flow in Packed Beds
RC-TES	Regenerative Carbonate-Based Thermochemical Energy Storage System for Concentrating Solar Power
RESTRUCTURE	Redox Materials-based Structured Reactors/Heat Exchangers for Thermo-Chemical Heat Storage Systems in Concentrated Solar Power Plants
SC-TES	Carbon Dioxide Shuttling Thermochemical Storage Using Strontium Carbonate
SesPER	Solar Energy Storage PERovskites
SOCRATCES	SOlar Calcium-looping integRAtion for Thermo-Chemical Energy Storage
SOLSTORE	Solid-state reactions for thermal energy storage
SS-TES	Solid State Solar Thermochemical Fuel for Long-Duration Storage
STORRE	High temperature thermal energy Storage by Reversible thermochemical Reaction
TCS-Power	Thermochemical Energy Storage for Concentrated Solar Power Plants
TES-HE	Integrated Thermal Energy Storage Heat Exchanger for Concentrating Solar Power Applications
THERMES	A new generation high temperature phase change microemulsion for latent thermal energy storage in dual loop solar field

Table A2. List of R&D project coordinators and abbreviations.

Abbreviation	Project Coordinator
AGENEX	Agencia Extremeña de la Energía
AlNL	Los Alamos National Laboratory
ArNL	Argonne National Laboratory
ArSU	Arizona State University
BE	Brayton Energy
CEA	Commissariat a l’Energie Atomique et aux Energies Alternatives
CERTH	Ethniko Kentro Erevnas kai Technologikis Anaptyxis
CIC	Centro de Investigación Cooperativa de Energías Alternativas
CNRS	Centre National de la Recherche Scientifique
CSIC	Agencia Estatal Consejo Superior de Investigaciones Científicas
CSM	Colorado School of Mines
DRL	Deutsches Zentrum für Luft-und Raumfahrt e.V.
EDISUN	Edisun

Table A2. *Cont.*

Abbreviation	Project Coordinator
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
LEITAT	Acondicionamiento Tarrasense Asociación
MiSU	Michigan State University
MoSU	Montana State University
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
SRI	Southern Research Institute
SRNL	Savannah River National Laboratory
UBir	University of Birmingham
UEv	Universidade de Évora
UFl	University of Florida
ULe	Univertisty of Leeds
UPM	Universidad Politécnica de Madrid
USe	Universidad de Sevilla
USFl	University of South Florida

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