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Development of Economical Solar Collector and Solar Storage for Combating Global Warming-A Review

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Abstract: The growing urgency to combat climate change has intensified the shift from fossil fuels to renewable energy sources, with solar energy emerging as a key solution due to its abundance and sustainability. This review critically examines Concentrated Solar Power (CSP) technologies—Parabolic Trough Collectors (PTCs), Linear Fresnel Reflectors (LFRs), Solar Power Towers (SPTs), and Parabolic Dish Concentrators (PDCs)—and their integration with Thermal Energy Storage (TES) systems. CSP systems capture and convert solar radiation into electricity, and TES technologies address the challenge of intermittency by storing thermal energy for later use. Sensible Heat, Latent Heat, and Thermochemical storage methods are compared in terms of efficiency, material properties, and economic viability. Although CSP requires significant initial capital investment, advancements in TES are improving system reliability and reducing the Levelized Cost of Electricity (LCOE). The review highlights that CSP-TES systems, particularly Solar Power Towers with molten salt storage, are poised to lead future market growth due to their high efficiency and dispatchability. With continued technological improvements and cost reductions, CSP combined with TES offers a promising pathway for sustainable energy generation and significant contributions to global decarbonisation efforts.

1. Introduction

In recent years, environmental concerns have taken centre stage as the world grapples with the repercussions of human activities. Agriculture, forestry, and land use practices alone account for about 25% of greenhouse gas emissions, intensifying the urgency to combat climate change. The rapid escalation of global temperatures, with a critical threshold of 1.5^{0}C degrees, demands immediate attention from policymakers and authorities worldwide. Such temperature increases trigger extreme weather events, jeopardizing both economies and human well-being (Ullah and Lin 2024). In this context, the over-reliance on fossil fuels by emerging economies aggravates environmental degradation, emphasizing the necessity of transitioning to renewable energy sources (Li *et al.* 2024). Solar energy emerges as a viable alternative, offering abundant, affordable, and clean energy solutions across various sectors (Chandrasekar and Senthilkumar 2021). The mounting pressure to adopt renewable energy sources, particularly solar power, underscores the imperative to mitigate global warming and reduce greenhouse gas emissions (Sarangi *et al.* 2024). Moreover, the depletion of finite fossil fuels and associated environmental consequences necessitates a shift towards renewable energy (Amalu *et al.* 2023). Solar PV (Photovoltaic), Solar PVT (Photovoltaic-Thermal), and CSP (Concentrated Solar Power) are examples of solar technologies that offer sustainable alternatives for energy production and environmental conservation (Hamidinasab *et al.* 2023; Byiringiro *et al.*, 2025a & 2025b). Leveraging solar energy for domestic applications such as electricity generation, water heating and other industrial applications, can help societies reduce reliance on conventional energy sources and mitigate environmental impacts (Herez *et al.* 2023). Furthermore, advancements in renewable energy storage, particularly for CSP, present promising strategies for efficient energy generation and use. The decreasing costs of generating electricity from renewable sources underscore the feasibility of transitioning from fossil fuels towards a decentralized and sustainable energy landscape (Baigorri, Zaversky, and Astrain 2023a). In light of these findings, this review explores the dynamic interplay between energy sources, environmental sustainability, and economic development, emphasizing the pivotal role of solar energy in addressing global environmental challenges and promoting a sustainable future.

2. Methodology

2.1 Review Strategy

A systematic search was conducted across Scopus, Web of Science, IEEE Xplore, and ScienceDirect databases, supplemented by technical reports from NREL, IEA, and SolarPACES. Search terms focused on CSP-TES integration, including "Concentrated Solar Power," "Thermal Energy Storage," “solar radiation” and specific technologies like molten salt and phase change materials.

2.2 Initial Screening

Initial screening applied three filters: (1) publication type (peer-reviewed articles, technical reports, case studies), (2) publication date (2010-2025), and (3) English language only. This eliminated outdated, non-English, or irrelevant studies (e.g., fossil fuel systems), yielding approximately 50 potential articles.

2.3 Final Screening

Final screening evaluated remaining studies for technical relevance to CSP-TES integration, prioritizing empirical data from operational plants and validated models. The process resulted in 34 high-quality references forming the review's foundation.

3. Literature Review

3.1 Types of Solar Collectors

The sun’s energy reaching earth in one hour is almost equivalent to our annual consumption of primary energy (Mena *et al.* 2019). The radiation entering the earth’s atmosphere from the sun comprises two components: *DNI (Direct Normal Irradiance)* and *DHI (Diffuse Horizontal Irradiance)*. DNI consists of sunlight striking the earth's surface perpendicularly (Merchán *et al.* 2022), (Singh and Kumar 2018) while DHI represents the radiation that is scattered or bounced around as a result of dust, clouds or aerosols. Both DNI and DHI radiation serve as the foundation for classification of solar collector technologies. Currently, solar collector technologies can be grouped broadly into two main categories: by method of capturing solar radiation: *Non-Concentrating and Concentrating collectors* (Belyakov

2019) and by method of tracking solar radiation: *Non-tracking*, *One-axis tracking*, *and Dual-axis tracking collectors* (Suman, Khan, and Pathak 2015). Concentrated solar collectors uses mirrors and a receiver, which can be fixed or mobile, to capture and harness the energy of the sun. Concentrated solar collectors are further sub – divided into *line focus* and *point focus* CSP system. In a line focus CSP system, solar radiation is concentrated along a line or linear receiver, whereas in a point focus CSP system, it is concentrated onto a single focal point. Solar energy from these technologies is converted into heat or steam, which is then utilised to generate electricity with a turbine generator similar to a thermal gas plant while non-concentrating solar technologies directly produces electricity as radiation falls on the collector. Non-tracking collectors are immobile, while tracking collectors follow the movement of the sun, ensuring that the incoming radiation is always perpendicular to the collector surface. Tracking collectors are typically designed to be either a single-axis or dual-axis tracking system. A single-axis tracking system is aligned along a north-south perpendicular line and follows the position of the sun from east to west. In contrast, a dual-axis tracking system rotates around two axes, perpendicular to each other: The primary axis is fixed relative to the ground, while the secondary axis rotates with respect to the primary axis (Suman *et al*. 2015). The non-concentrated and the non-tracking solar technologies encompass Flat Plate Collector (FPC), Evacuated Tube Collector (ETC), and Compound Parabolic Collector (CPC) while the Concentrated and the tracking solar collectors include Parabolic Trough Collectors (PTC), Linear Fresnel Reflector (LFR), Solar Power Thermal (SPT) and Parabolic Dish Collector (PDC)/Stirling Engine. However, this review will specifically focus on concentrated solar technologies. **Figure 1a** and **1b** shows a summary of the solar collector technologies used for CSP.

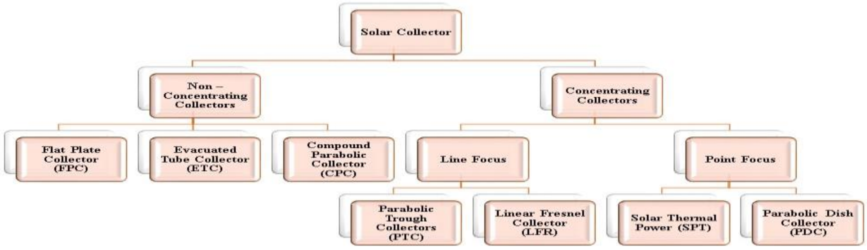

Figure 1a: Classification of Solar Collector by method of capture
Source: (Bonk et al. 2018)

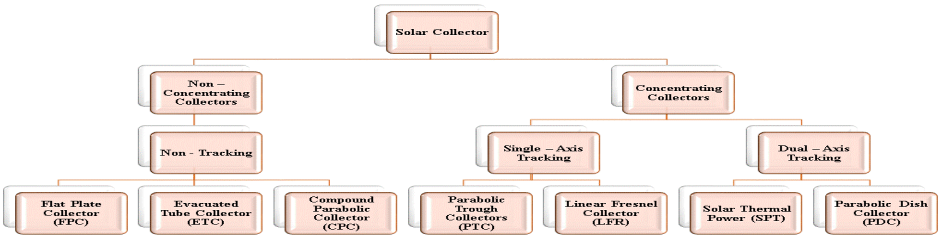

Figure 1b. Classification of Solar Collectors by Method of Tracking
Source:(Suman *et al.* 2015)

3.2 *Concentrated Solar Technologies*

The Direct Normal Irradiance (DNI) is a critical factor considered in the design and effective operation of CSP plants, both economically and commercially. Specifically, annual DNIs above 1800 Kwh/m^3 are ideal for CSP operations (Islam et al. 2018), while DNIs below this threshold are more suitable for solar PV or solar PV/T technologies (Alami *et al.* 2023). Countries located in Desert areas such as the Middle East and North Africa (MENA), South – Western part of USA, South – Western part of China, Border of China and Mongolia, West India, and South Africa, typically experience high annual DNIs ranging from approximately $2000 - 2800\ Kwh/m^3$ (Merchán *et al.* 2022),(Bonk *et al.* 2018),(Islam et al. 2018) as shown in **Figure 2.**

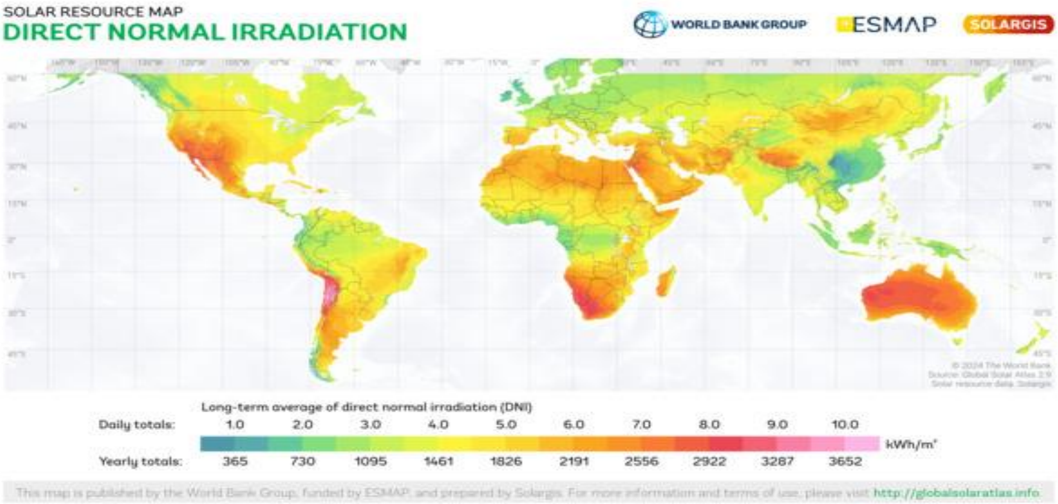

Figure 2. Areas of the World with high DNI
Source:(SolarGIS 2024)

3.2.1 *Parabolic Trough Collector (PTC)*

PTC consists of a non – linear mirror (parabolic) that focuses the energy of the sun in the focal line of the parabolic through where the absorber tube is positioned (Badran, Mamlook, and Abdulhadi 2012). The absorber tube is coated with glass to minimize heat loss via convection. Both the reflectors and absorbers track the sun's movement daily. Thermal fluids, typically oils, serve as Heat Transfer Fluids (HTF) to collect heat and transfer it to a steam generator via a Rankine cycle, which is then used for electricity production. **Figure 3** shows a $72MW$ PTC system installed in Boulder, Nevada.

Figure 3. A 72MW Nevada Solar One in Boulder, Neva USA
Source:(Taylan and Berberoglu 2013)

3.2.2 Linear Fresnel Reflector (LFR)

The LFR employs a linear reflecting surface to redirect sun rays onto a stationary receiver situated atop the mirrors. Like PTC, LFRs can track sunlight along a single axis. LFRs also utilize thermal fluids, either oil or water, as HTF to convey heat directly to the steam generator (Direct Steam Generation) or to a storage tank for later electricity production during peak demand periods. **Figure 4** shows a $30MW$ LFR system installed in Calaspara, Spain.

Figure 4. A 30MW Linear Fresnel Reflector System Puerto Errado 2 Thermo-Solar power plant (PE 2) at Calaspara Spain
Source:(Taylan and Berberoglu 2013)

3.2.3 Solar Power Thermal (SPT)

An SPT, or Central Receiver System (CRS), employs multiple reflectors or heliostats to focus (concentrate) reflected sun rays to a point on top of a tower with a central receiver. Heliostats can be positioned either at 180^0 or 360^0 around the tower based on the geographical location. The receiver absorbs heat, which is then conveyed to the power block for electricity generation or to a storage tank for later electricity production. **Figure 5** shows an $11MW$ and $20MW$ SPT system in Seville, Spain.

Figure 5. An $11MW$ and $20MW$ Solar Thermal Plant, Solar Platform, Sanluclar, La Mayor, Seville Province, Spain
Source:(Taylan and Berberoglu 2013)

3.2.4 Parabolic Dish Concentrator (PDC)

PDC systems concentrate sun rays at a focal point located above the centre of the dish. A Stirling engine at this focal point converts concentrated heat into mechanical energy, which is further converted into electricity. The system tracks the movement of the sun. PDC designs eliminate the need for a coolant such as water and are relatively expensive to construct and have limited adoption of storage facilities (Mena et al. 2019; Merchán *et al*. 2022; Singh *et al*. 2018; Zhang *et al*. 2013). **Figure 6** shows a 1.5 MW PDC system at Peoria, Arizona, USA.

Figure 6. A 1.5 MW Maricopa Solar Project at Peoria, Arizona, USA, **Source**:(Taylan and Berberoglu 2013)

3.3 Comparisons of CSP Technologies

Within CSP technologies, the PTC system holds a significant commercial share, closely followed by Solar Power Thermal (SPT) (Alami *et al*. 2023). Despite being costly, SPT projects are increasingly explored due to their potential for enhanced efficiency, reduced costs, higher energy densities, economical solar field setups, minimal maintenance requirements, and lower environmental impacts (Baigorri *et al*. 2023a). LFR systems offer simplicity and cost-effectiveness by eliminating the need for HTF; however, they exhibit lower efficiency compared to SPT, and Thermal Energy Storage (TES) integration poses challenges (Merchán *et al*. 2022). PDC systems are highly efficient, yet large-scale electricity production escalates costs, necessitating numerous installations for practical viability (Zhang *et al*. 2013). **Table 1** shows the comparisons between the available CSP technologies while **Table 2** shows recent CSP projects around the world.

Table 1. Comparisons between CSP Technologies

	CSP Technology			
Parameters	**Parabolic Trough**	**Linear Fresnel Reflector**	**Solar Power Thermal**	**Parabolic Dish Concentrator**
Concentrating Ratio	$70-80$	>60	>1000	>1500
Working Temperature (℃)	$200-400$	$50-300$	$300-1000$	$120-1500$
Typical Efficiency (%)	18	12	$25-28$	30
Peak Efficiency (%)	$14-20$	18	$23-35$	30
Capacity (MW)	$10-300$	$10-200$	$10-200$	$0.01-0.025$
Development Status	Commercially Available	Pilot Stage	Not Commercially available like parabolic trough	Demonstration Stage

Source: (Shahabuddin *et al*. 2021)

Table 2. Current CSP Projects Around the World

CSP Project	Location	Country	Status	Nominal Capacity (MW)	CSP Technology	Construction Start Year	Year Operational
China Shipbuilding New Power (CSNP)	Urat	China	In Operation	100 *MW*	Parabolic Trough	2017	2020
Atacama I / Dominador	Calama Antofagasta	Chile	100MW In Operation, 110 MW in Development	210 *MW*	Power Tower, Photovoltaic	2014	2021
Jinta ZhongGuang Solar	Jinta Juiquan Gansu	China	100 MW in Development, 600MW in Development	700 *MW*	Power Tower, Photovoltaic	2022	-
Noor Energy I / DEWA IV	Dubai	United Arab Emirates	717MW in Operation, 233 MW in Development	950 *MW*	Parabolic Trough, Power Tower, Photovoltaic	2018	2023
SOLINPAR Sicily Stromboli MS – LFR	Tranpali, Sicily	Italy	In Operation	4 *MW*	Linear Fresnel, Photovoltaic	2020	2021
Integrated Solar and Combined Cycle (ISCC)	Waad Al Shamal	Saudi Arabia	In Operation	1440 *MW*	Combined Cycle, Parabolic Trough	2014	2018
Redstone	Portmasburg, Northern Cape	South Africa	In Operation	100 *MW*	Power Tower	2021	2024
Huidong New Energy Akesai	Aksai, Juiquan, Gansu	China	In Operation	750 *MW*	Power Tower	2022	2024

Source:(SolarPACES 2024)

3.4 Parts of a CSP System

A CSP system consists of three major parts including the solar field, thermal energy storage unit and the power block as shown in **Figure 7.**

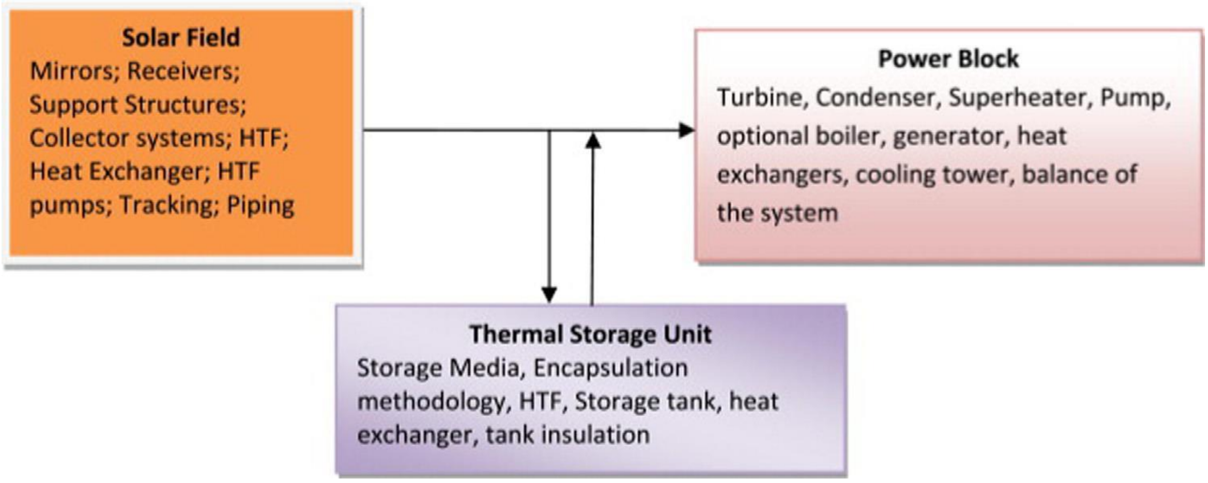

Figure 7. Parts of a CSP System, Source:(Islam *et al.* 2018)

3.4.1 *Solar Field*

Consists of an array of mirrors or reflectors that track, gather, and focus sun rays onto various mediums, such as a receiver tube for PTC, a fixed receiver for LFR, a receiver attached to a Stirling engine for PDC, and a central receiver tube for SPT (Singh *et al.* 2018). With the exception of PDC, all CSP technologies use HTF to absorb and transport thermal energy. Subsequently, this thermal energy is converted into mechanical energy, and used to generate electricity through the Rankine Cycle. The HTF may include water/steam, molten salts, synthetic oil or Nano - particles.

3.4.2 *Thermal Energy Storage Systems (TESS)*

TES systems include technologies designed to store excess Thermal energy (heat or cold) for use at later time whether for heating or generating electricity. Further exploration of various technologies within this domain will be conducted in subsequent sections.

3.4.3 *Power Block*

The power block primarily comprises turbines, generators, condensers, pumps, heat exchangers, and other components. This section of the CSP system is accountable for electricity generation.

3.5 *Energy Storage Systems (ESS)*

Over time, the capability to store surplus energy for future utilisation has heightened the appeal of CSP systems. Classification of ESS is dependent on the type of energy transformation *(mechanical, electrochemical, thermal, and electrical*) required in generating electricity. Because our focus is on capturing solar energy in the form of heat, we will specifically explore the various Thermal Energy Storage (TES) systems that can be combined with CSP systems. **Figure 8** illustrate the many types of TES systems.

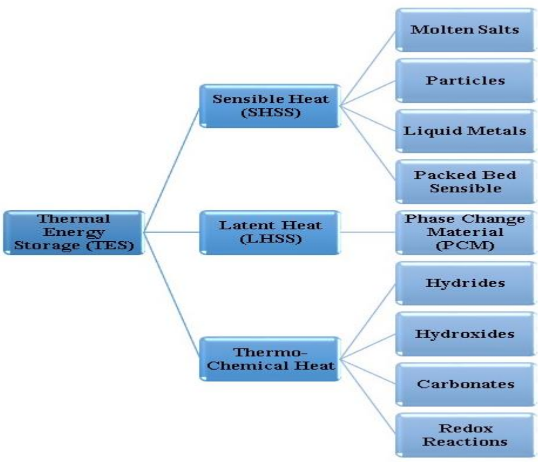

Figure 8. Types of TES systems

Integrating TES technologies with CSP systems enhances the overall system efficiency. In general, TES systems are classified into three categories*: Sensible heat, Latent heat, and Thermo-Chemical storage systems*. Sensible Heat Storage (SHS) Systems involves storing thermal energy through temperature changes in the TES material while Latent Heat Storage (LHS) Systems measure energy released or received during phase transitions from solid to liquid at a constant temperature (Dongellini *et al*. 2025),(Georgousis *et al*. 2025). Thermo-Chemical Storage systems involve the heat energy either absorbed or released during a chemical reaction.

3.5.1 Sensible Heat Storage Systems (SHSS)

SHS systems store energy by increasing the temperature of a substance, usually solid or liquid. During the storage procedure materials do not change phase change during the temperature range of the storage process. The efficiency of SHS relies heavily on the material's heat capacity (**ρC_p**), and thermal diffusivity ($k/\rho C_p$), which determines the rate of heat release and extraction (Steinmann 2022). The energy stored can be calculated using **Eqn 1.**

$$Q = mC_p\Delta T \qquad \textbf{Eqn. 1}$$

where Q is the stored energy, m is the mass of the storage medium, Cp is the specific heat capacity of the material, and ΔT is the temperature change during the storage process. SHSS systems include; *Molten Salts, Sensible Heat Particle (SHP), Packed Bed (Rocks), Liquid Metals, and Water/Steam Accumulators.*

3.5.1.1 Molten Salts

Molten salts are commonly used to store sensible heat because of their excellent thermophysical characteristics as a means of storing sensible heat. In CSP plants, molten salt systems typically operate on a two-tank system, with each tank maintained at different temperature levels, thereby establishing the temperature differential necessary for charging or discharging sensible heat. Molten salts generally exhibit an Energy Storage Density (ESD) ranging from $150 - 250\ kWh/m^3$. They are capable of maintaining stability at temperatures of up to 600℃, offering unpressurized storage, low viscosity, affordability, and a lifespan of approximately 30 years. However, molten salts face significant drawbacks, including decomposition at high temperatures and corrosiveness. Recent technological advancements have led to the discovery of Novel Molten Salts (NMS), characterized by thermal stability at higher temperatures of up to 850℃, natural abundance, affordability, and ESD values ranging from approximately $120 - 275\ kWh/m^3$. Despite their promising characteristics, NMS encounter similar challenges as conventional molten salts. As an avenue for research, these salts can be enhanced by incorporating nanoparticles to improve their thermal properties (Kuravi *et al*. 2013). **Figure 9** shows a schematic of SPT with two molten tanks for storage of heat.

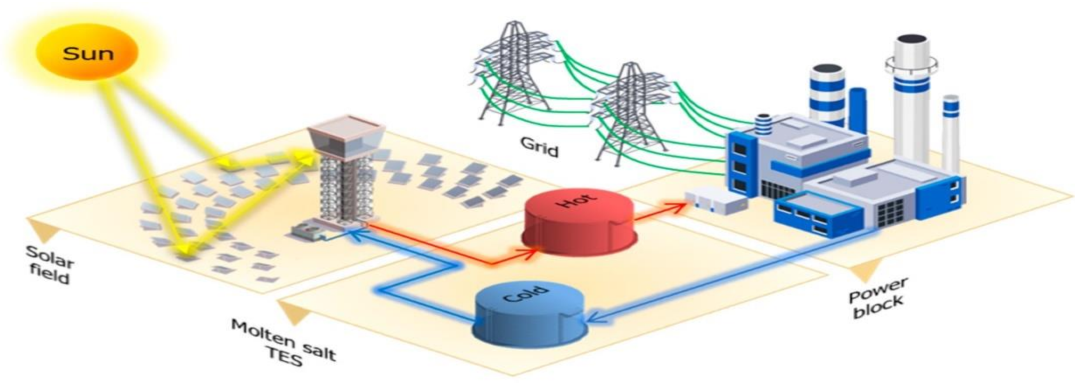

Figure 9. A Solar Tower with Two Molten Salt TES System
Source:(Prieto *et al*. 2023)

3.5.1.2 Sensible Heat Particle (SHP)

Also known as particulate solids, this technology utilizes silica sand, iron oxide, or silicon carbide as its medium for thermal energy storage. Particles like molten salts absorb solar heat and transfer it through a medium before entering a hot tank. When energy is required, these particles travel to the heat exchanger, where the heat is extracted and returned to the cold tank. SHP is an HTF with an ESD value of $150 - 200\ kWh/m^3$, making it ideal for use at temperatures above 800℃. However, disadvantages include a reduction in thermal efficiency due to particle loss, particle agglomeration, and sintering, which affect storage efficiency (Imran Khan, Asfand, and Al-Ghamdi 2022). **Figure 10** shows a schematic of an SPT with a Sensible Heat Particle.

3.5.1.3 Packed Bed (Rocks)

Utilizes non-toxic materials like slags, concretes, and rocks as storage media, while employing air or other substances as the HTF. The storage media remains permanently positioned within the storage tank and absorbs thermal energy conveyed by a heat carrier fluid. When heat is required, only air is conveyed to the power block. Packed bed's advantage lies in its simplicity, cost-effectiveness, low environmental impact, and thermal and chemical stability exceeding 1100℃, with an ESD value ranging from $150 - 200\ kWh/m^3$. Despite these favourable attributes, it still experiences thermocline degradation and fluctuating flow temperatures, both of which impact storage utilisation (Achkari and El Fadar 2020),(Baigorri, Zaversky, and Astrain 2023b). **Figure 11** shows a schematic of packed bed Storage System.

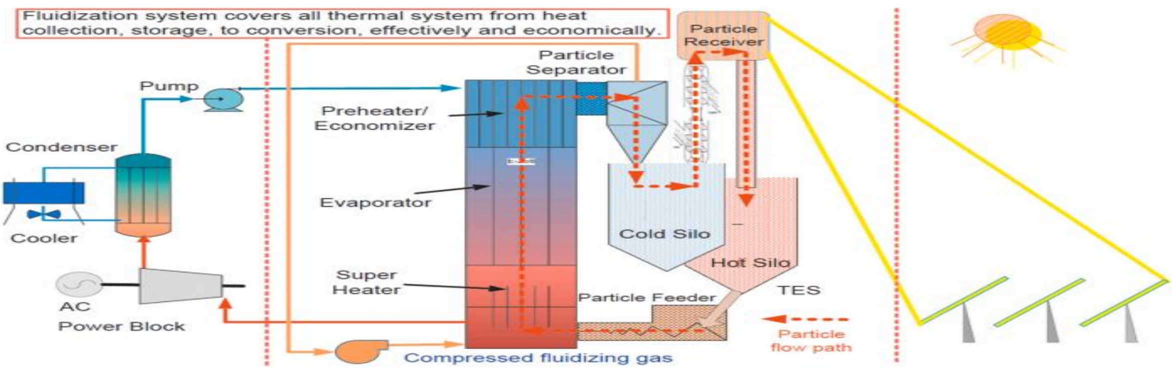

Figure 10. A Solar Tower CSP system with Sensible Participle Storage
Source:(Baigorri *et al.* 2023a)

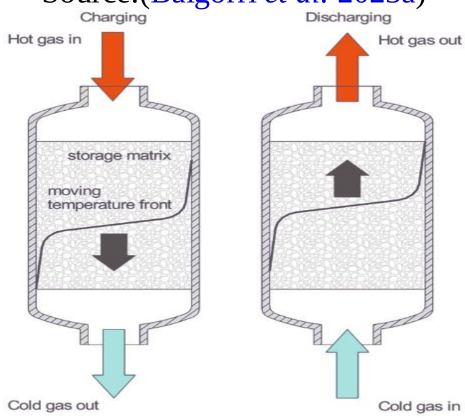

Figure 11. A schematic of a Packed Bed Sensible Heat TES
Source:(Steinmann 2022)

3.5.1.4 Liquid Metals

The utilisation of liquid metals such as Lead (Pb), Lead-bismuth ($Pb - Bi$), Sodium-Potassium alloy (NaK), and a ternary eutectic combination of Lithium, Sodium ($LiNaK$), and Potassium serves as HTF in CSP systems, which can adopt either a two-tank (direct system) or one-tank (indirect system) configuration. Liquid metals exhibit favourable characteristics such as effective operation at high temperatures exceeding 800^0C, excellent heat conductivity, mechanical reliability, and thermal efficiency. However, their propensity for high reactivity with water and oxygen can pose safety concerns, potentially leading to hazardous situations. Additionally, the materials required for liquid metal HTF systems tend to be costly, and their ESD value is limited to a range of $75 - 250\ kWh/m^3$. These factors should be carefully considered when evaluating the feasibility and practicality of employing liquid metals as HTF in CSP applications (Baigorri *et al.* 2023a).

3.5.1.5 Steam/Water Accumulator

Steam accumulators utilise pressurized saturated water (steam) as a means to store heat. The excess steam created by the Rankine cycle is channelled into a pressurised vessel containing water. As the steam condenses, it elevates the temperature and pressure of the liquid within the tank, and so serves as the storage medium. The storage vessels can either be horizontal or vertical reactors, with horizontal accumulators being the more commonly employed choice. The advantages of using water as an HTF include its high specific heat capacity, non-toxic nature, affordability, and widespread availability. However, drawbacks include issues related to vapor pressure and corrosion (Achkari and El Fadar 2020a). **Figure 12** shows a schematic of a steam accumulator TES system.

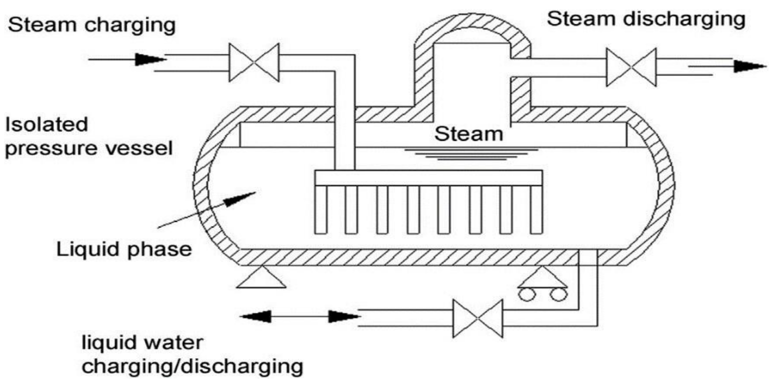

Figure 12. Schematic of a Steam Accumulator
Source:(Steinmann and Prieto 2021)

3.5.2 Latent Heat Storage Systems (LHSS)

LHS systems rely on PCMs', which have the unique ability to release or absorb energy during a change in physical state, typically between solid and liquid. As the material absorbs thermal energy, it melts, and when it solidifies, it releases the stored thermal energy. These materials are notable for their higher energy storage density compared to other technologies. They store thermal energy at a constant temperature, which enhances system flexibility and demonstrates good long-term reliability. Due to their latent heat capacity, PCMs can store between 5 - 100 times more energy than sensible heat systems of the same volume because of their latent heat capacity. According to (*Sharma et al.* 2009) ,the storage capacity with this medium can be calculated using equation 2;

$$Q = m\left[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)\right] \qquad \textbf{Eqn. 2}$$

Where $\boldsymbol{Q}$ is the Total Thermal Energy Stored in Joules., $\boldsymbol{m}$ is the Mass of PCM (Kg), $\boldsymbol{C_{sp}}$ is the Specific Heat Capacity of solid PCM in $J/kg \cdot K$, $(\boldsymbol{T_m} - \boldsymbol{T_i})$ represents the increase from initial temperature $(\boldsymbol{T_i})$ to melting point $(\boldsymbol{T_m})$, $\boldsymbol{a_m}$ is the Melt fraction (0 – 1, where 1 fully melted), $\Delta\boldsymbol{h_m}$ is the Latent Heat of Fusion (J/Kg), $(\boldsymbol{T_f} - \boldsymbol{T_m})$ represents the temperature increase from melting point $(\boldsymbol{T_m})$ to final temperature $(\boldsymbol{T_f})$, $\boldsymbol{C_{lp}}$ represents Specific Heat Capacity of the liquid PCM (J/Kg).

3.5.2.1 Phase Change Materials (PCM)

PCMs are a technique that uses heat storage through a phase change, usually from solid to liquid, while keeping the temperature constant. PCMs are typically categorized into Organic and Inorganic Compounds. Inorganic PCMs are the optimal choice for LHS due to their high ESD values of approximately $700\ kWh/m^3$. However, a fundamental issue with PCMs is their low heat conductivity and high reactivity with metals, particularly after prolonged thermal cycling, especially when encapsulated (Achkari and El Fadar 2020a),(Baigorri *et al.*, 2023b). **Figure 13** shows a schematic of PCM TES system.

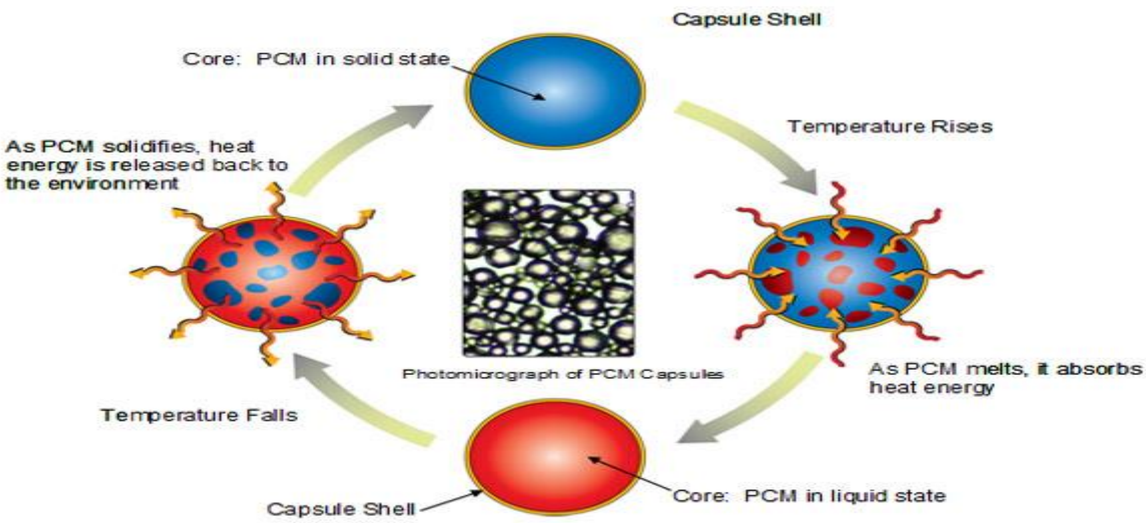

Figure 13. A Schematic of a PCM TES System
Source:(RAHA Parrafin Co 2025)

3.5.3 Thermo – Chemical Systems

Utilises chemical reactions as a method to store thermal energy. Solar receiver-derived heat drives an *endothermic* reaction (a process where heat is absorbed from the environment), breaking a chemical reactant into two distinct products during the charging process. Later, when energy is required, an *exothermic* reaction (a process where heat is released to the environment due to a chemical reaction) recombines these two products. These reactions are typically reversible.

$$A + \Delta H_r \rightleftharpoons B + C$$

3.5.3.1 Hydrides

$$M_xH_y(s) + \Delta H_r \rightleftharpoons xM(s) + \frac{y}{2}H_2(g)$$

Hydrides have the capability to absorb hydrogen at elevated temperatures ranging from approximately $350 - 1000\ ℃$, while hydrogen and thermal energy can be released through the combination of hydrogen with the metal. The ESD value of hydrides is approximately 580 kWh/m^3. Among hydrides, alkali and alkaline earth metal-hydrides are favoured due to their high reversibility and ESD. Challenges associated with hydrides include low heat conductivity, hydrogen embrittlement, diffusion, permeation, and scaling issues (Shahabuddin *et al*. 2021),(Baigorri *et al*. 2023b).

3.5.3.2 Hydroxides

$$M(OH_2)(s) + \Delta H_r \rightleftharpoons MO(s) + H_2O$$

Metal hydroxides store energy through dehydration (charging process) and rehydration (discharging process). During charging, alkaline metal oxides decompose into metal oxides and steam. In the discharging phase, the metal oxide is moisturised with steam, which releases stored energy. This technology boasts an ESD value ranging from $260 - 437\, kWh/m^3$ and is cost-effective. However, challenges include low thermal conductivity and critical agglomeration.

3.5.3.3 Carbonates

$$MCO_3 + \Delta H_r \rightleftharpoons MO(s) + CO_2(g)$$

Metal carbonates store energy through decarbonation (charging process) and carbonation (discharging process). During decarbonation, heat from the surroundings is absorbed to decompose a metal carbonate into metal oxide and CO_2. The carbonation process occurs when the metal oxide reacts with CO_2, releasing heat. Calcium looping with $\frac{CaCO_3}{CaO}$ is a prominent chemical compound due to numerous advantages it offers, including low cost, high operating temperatures ($650 - 1000$°C), absence of side reactions, high density storage of approximately $700\, kWh/m^3$, non-toxicity, non-corrosiveness, abundant availability of reactants, and incorporation of carbon capture. Major challenges include particle agglomeration/sintering, which reduces carbonation rate, and cyclic stability (Achkari and El Fadar 2020a), (Palacios *et al*. 2020), (Baigorri *et al*. 2023b).

3.5.3.4 Redox – Reactions

$$M_xH_y(s) + \Delta H_r \rightleftharpoons M_xO_{y-z}(s) + \frac{z}{2}O_2$$

$$ABO_3(s) + \Delta H_r \rightleftharpoons M_xO_{3-\delta}(s) + \frac{\delta}{2}O_2$$

Metal oxides store energy through reduction (charging process) and oxidation (discharging process). Heat from the environment is utilised to reduce the oxidation state of the oxide, which releases lattice oxygen during the reduction process. During the discharging phase, the storage medium transitions into the oxidised state, releasing the thermal energy stored in the reaction. A significant advantage of this technology is the elimination of gas storage requirements, as ambient air can serve as both HTF and reactant, resulting in reduced overall costs. The ESD value for Redox reactions ranges between $295 - 400\ kWh/m^3$, depending on whether stoichiometric oxides or perovskites are used. They can also operate within temperatures ranging from $400 - 1100$°C. The primary challenge appears to be the cost of materials (Palacios *et al*. 2020).

3.6 Comparisons of TES for CSP Plants

SHS systems are widely used and commercially available, with water, inorganic salts, thermal oils, and ceramics being the most common materials. Recently, natural rocks have shown promising potential for utility-scale CSP plants. However, SHS systems are constrained by the specific heat capacity of the storage medium, which necessitates larger installations to store greater amounts of energy, leading to larger systems. LHS systems provide higher storage capabilities, capable of storing and releasing heat at nearly constant temperatures. Despite their advantages, LHS technologies are still under development, particularly due to their low thermal conductivity, which poses a challenge for efficient energy transfer. Thermo-Chemical Storage offers even higher storage capacities than both SHS and LHS. Although this technique has only been explored in labs, its large volumetric energy storage capacity and chemical stability make it an intriguing possibility for future energy storage (Achkari and El Fadar 2020b). **Table 3** shows the different CSP projects incorporated with TES.

Table 3. Current CSP Projects and their TES Technologies

CSP Project	Location	Country	Technology	HTF	TES Type	Storage Capacity	Power Cycle
China Shipbuilding New Power (CSNP)	Urat	China	Parabolic Trough	Molten Salt	2 – tank direct	8 hours	Steam Rankine
Atacama I / Dominador	Calama Antofagasta	Chile	Power Tower, Photovoltaic	Molten Salt	2 – tank direct	17.5 hours	Steam Rankine
Jinta ZhongGuang Solar	Jinta Juiquan Gansu	China	Power Tower, Photovoltaic	Molten Salt	2 – tank direct	9 hours	Steam Rankine
Noor Energy I / DEWA IV	Dubai	United Arab Emirates	Parabolic Trough, Power Tower, Photovoltaic	Molten Salt/Thermal oil/Organics	2 – tank direct	11 / 15 hours	Steam Rankine
SOLINPAR Sicily Stromboli MS – LFR	Tranpali, Sicily	Italy	Linear Fresnel, Photovoltaic	Molten Salt	2 – tank direct	16 hours	Steam Rankine
Integrated Solar and Combined Cycle (ISCC)	Waad Al Shamal	Saudi Arabia	Combined Cycle, Parabolic Trough	Thermal Oil/Organics	-	-	Steam Rankine
Redstone	Portmasburg, Northern Cape	South Africa	Power Tower	Molten Salt	2 – tank direct	12 hours	Steam Rankine
Huidong New Energy Akesai	Aksai, Juiquan, Gansu	China	Power Tower	Molten Salts	2 – tank direct	8 hours	Steam Rankine

Source:(SolarPACES 2024)

3.7 Economic Considerations of CSP

Presently, the Capital Expenditure (CAPEX) required for investing in CSP technology is substantial; however, it is anticipated that the Levelized Cost of Electricity (LCOE) will significantly decrease with technological advancements in CSP. The variable nature of solar energy necessitates for the integration storage technologies to ensure a dependable power supply (Singh *et al*. 2018). (Mena *et al*. 2019) highlighted that among various storage technologies, TES stands out as the most economical. According to (Alami *et al*. 2023), integrating TES with CSP enhances efficiency and reduces LCOE. (Merchán *et al*. 2022) projected that LCOE correlates with the TES capacity of the plant, indicating that larger TES capacity further diminishes the LCOE of CSP plants. Regions with high DNI are prime locations for CSP plants and can address limited grid capacity issues in developing nations (Mena *et al*. 2019). Integration of CSP with existing power systems must prioritize economic and technical efficiency to prevent waste and cost overruns (Mena *et al*. 2019). Despite the scalability and dispatchability advantages of CSP technologies over other renewables, they have not achieved cost competitiveness or significant market penetration like solar PV, primarily due to complexity and limited viability for small-scale projects. Regulatory and political risks also pose challenges to CSP technologies (Mena et al. 2019). However, CSP-TES integration offers substantial potential for cost reduction and performance enhancement. It is anticipated that SPT with TES will lead the market in the near future, underscoring the importance of optimal sizing for balancing cost and reliability (Merchán *et al*. 2022). Additionally, hybridizing CSP plants with fossil fuels or solar PV offers avenues for cost reduction. When developing CSP plants, careful consideration of various costs such as capital expenses, operations and maintenance, land and water requirements, and minimum DNI thresholds is imperative. Despite economic challenges, the potential for efficient, dispatchable renewable energy generation with CSP, especially with TES integration, renders it a promising option for the future, particularly in suitable geographic locations (Islam *et al*. 2018).

Conclusion

PTCs, LFRs, SPTs, and PDCs represent the primary technologies utilised in CSP Plants. Among these, PTCs have achieved a higher degree of commercialization, followed by SPT. Despite the significant capital investment required for SPT projects, they are progressively being developed due to their potential to lower costs and enhance efficiency, especially when integrated with TES systems in CSP installations. The development of CSP plants necessitates consideration of capital expenses, operational and maintenance costs, land prerequisites, solar irradiance, and crucially, adherence to economic and technical standards to avoid cost overruns. While SPT has not yet gained widespread market penetration, it is anticipated that SPT will emerge as the market leader in the foreseeable future, given its potential for cost reduction and efficiency enhancement.

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