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SOLAR TOWER CSP USING MOLTEN SALTS: A REVIEW

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Abstract. *An increase in population growth has been observed, that combined with the increase in consumption levels, has considerably elevated global energy demands. In addition, it has already been demonstrated that a strong connection exists between energy consumption and environmental impacts, with fossil fuels being the largest contributor to climate change due to the emission of greenhouse gases. Currently, the total primary energy supply is essential based on fossil fuels. As such, it is necessary to employ renewable energy sources to reduce atmospheric emissions and increase global energy safety. In this context, solar energy stands out as a clean, renewable and abundant source. In Concentrating Solar Power (CSP), a series of mirrors concentrate solar radiation in a receiver and convert it to heat, which can be used to drive an electricity-generating plant or an energy source for an industrial process. There are currently four CSP technologies: Linear Fresnel reflectors and parabolic trough collectors, which concentrate sunlight on a linear receiver; and central tower receiver and parabolic dish systems, which concentrate sunlight on a focus point. The latter technologies are capable of achieving higher concentration ratios but require more effort in tracking accuracy. In 2013, plants based on PTCs were the most widely installed CSP technology, but central towers are increasing in number and power delivered. The first generation of CSP plants did not integrate a thermal energy storage (TES) system, and therefore couldn't produce dispatchable electricity. To increase the competitiveness compared to conventional power plants, new CSP plants are being developed with TES. Nowadays, molten salts are used as both the primary heat transfer fluid and TES medium in many CSP plants, to increase the maximum operating temperatures and plant efficiency. This paper intends to summarize the current status of concentrating solar power using central towers and molten salts.*

Keywords: *CSP, solar tower, molten salts, solar energy.*

1. INTRODUCTION

The use of solar energy has been increased in recent years due to its abundant availability and potential alternative to replace fossil fuels, avoiding unnecessary pollution and also a complete collapse of this source. Efficiency and general costs remain as challenges to overcome to a complete replacement to be achieved.

Therefore, continuous research has been conducted to obtain more promising results. Even though the earth is located 150 million km from the sun, around $1.08x10^{14}kW$ of energy emitted by the sun reaches the surface of the planet. In other words, what is consumed in terms of energy for the whole year, the earth receives from the sun in 1 hour (Thirugnanasambandam et al., 2010).

Solar energy can be exploited to generate electricity by using photovoltaic panels (PV) and concentrated solar power plants (CSP). Even though simple operations, as well as government subsidies, have enhanced the installation of PV panels, CSP plants offer the possibility to be also efficient during night time when storage systems are utilized, while PV panels can only produce electricity during daytime (IEA, 2010).

Potential locations for CSP around the world are generally identified by using the global distribution of Direct Normal Irradiance (DNI). Commercially viable CSP plants should maintain a DNI of at least 2000–2800 kW h/m^2/year. However, it is also argued that a DNI value higher than 1800 kW h/m^2/year is suitable for CSP plant development (Islam et al, 2018). The latitude is also another factor that determines the suitability of installing a CSP plant, where values between 15 and 40° in both hemispheres are suggested. North Africa, the Middle East, the Mediterranean, and vast areas in the United States including California, Arizona, Nevada, New Mexico are known as the Sun Belt, where greater solar radiation is available from the sun.

The development path of the concentrated solar power can be considered to have started in 1982 with the Solar One project established in California, based on a power tower plant capable of generating 10 MW (Scott et al. 2012). Next, the first operational dish system capable of generating 7.5 kW was established, followed by a drop in fossil fuel prices which resulted in a policy dismantling in favor of CSP by the governments, followed by CSP newer technologies, capable of reaching up to 6.7 GW using newly developed concepts of thermal energy storage. Lastly, as shown by Palacios et al. (2019), the mark of 10 GW operational is expected to be reached in 2022.

Figure 1 shows a schematic of the CSP evolution and expected operational capacity from 1980 to 2030.

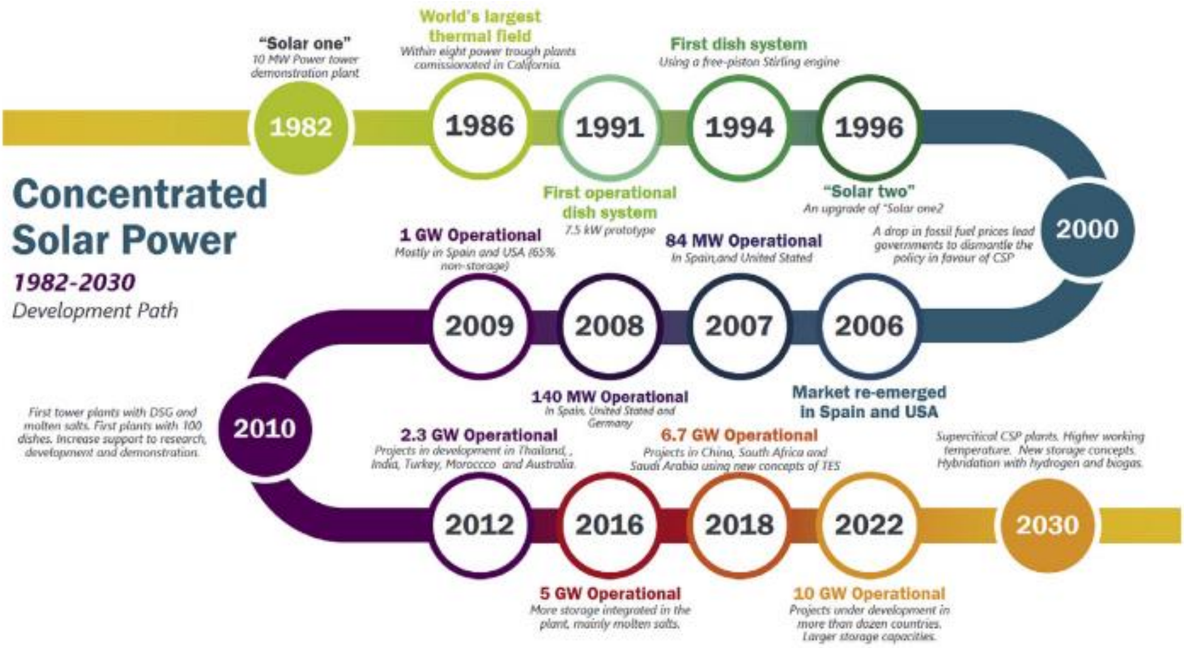

Figure 1. CSP development from 1982 to 2030 (Palacios et al., 2019)

Four generally accepted CSP technologies are characterized by concentrating sunlight by reflection onto a receiver. Linear Fresnel reflectors (LFRs) and parabolic trough collectors (PTCs) are line-focus solutions that concentrate sunlight on a linear receiver. Solar Power Tower (SPT) and parabolic dish systems are point-focus solutions that can achieve far higher concentration ratios but require proportionally more effort in tracking accuracy (Fernández et al, 2019). The main objective of this work is to review and discuss CSP technologies, emphasizing SPT using molten salts as heat transfer and/or thermal storage fluid.

2. SUN TRACKING CSP TECHNOLOGIES

Concentrated solar power (CSP) technologies convert part of the heat from the sun irradiation into electricity. CSP plants consist of mirrors connected with a tracking system distributed over an open field to track the sun's movement throughout the day. The incident solar radiation is reflected onto a receiver filled with a heat transfer fluid (usually oil or molten salt) that flows through pipes along the system holding the absorbed heat and subsequently reaches a turbine where the electricity is generated.

Presently, four technologies are categorized as part of CSP systems, as illustrated in Figure 2. The technologies are classified in line and point focus solutions. Parabolic Trough Collectors (PTC) and Linear Fresnel Reflectors (LFR) are line focus solutions, using a linear tube receiver to concentrate the reflected sunlight. Solar Power Tower (SPT) and Parabolic Dish Systems represent point focus solutions in which the achieved accumulated heat is usually higher due to the reached temperatures as already stated by Gauché et al. (2017) and Gil et al. (2010).

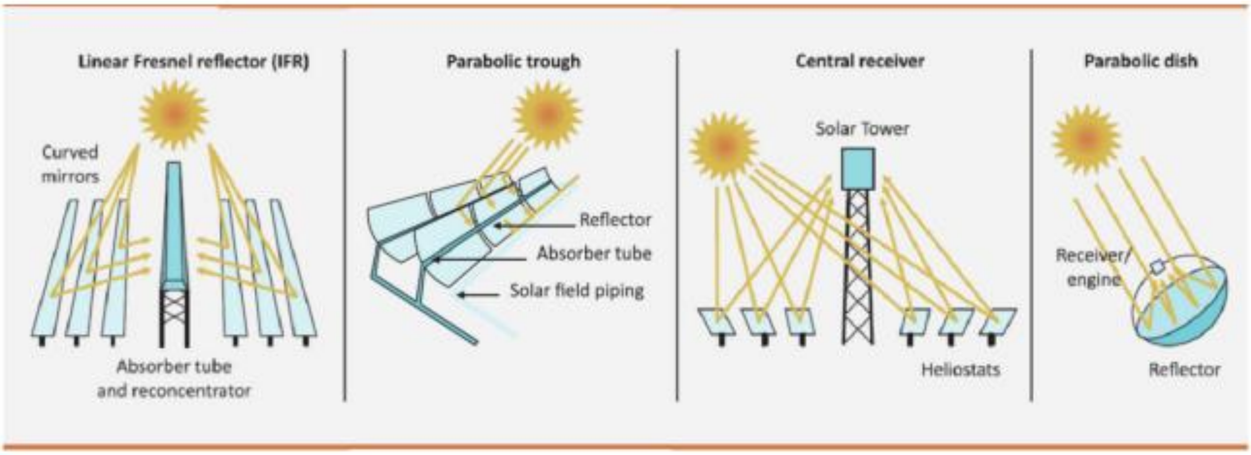

Figure 2. CSP available systems (Gil et al., 2010, Fernández et al., 2019)

Spain and the United States are the global leaders in cumulative CSP capacity in operation, with 2.3 GW at the end of 2020. CSP markets grew slowly in 2020 as a result of increasing cost competition from solar PV, the expiry of CSP incentive programs, and operational issues at existing facilities. Worldwide CSP capacity increased only 1.6% in 2020, reaching 6.2 GW. It was considered one of the lowest annual market growths in the latest years, as shown in Figure 3. More than 1 GW of CSP projects was under construction during 2020 in the United Arab Emirates, China, Chile, and India, although no new projects commenced construction during the year. China was the only country to add new CSP capacity in 2020 (REN, 2021).

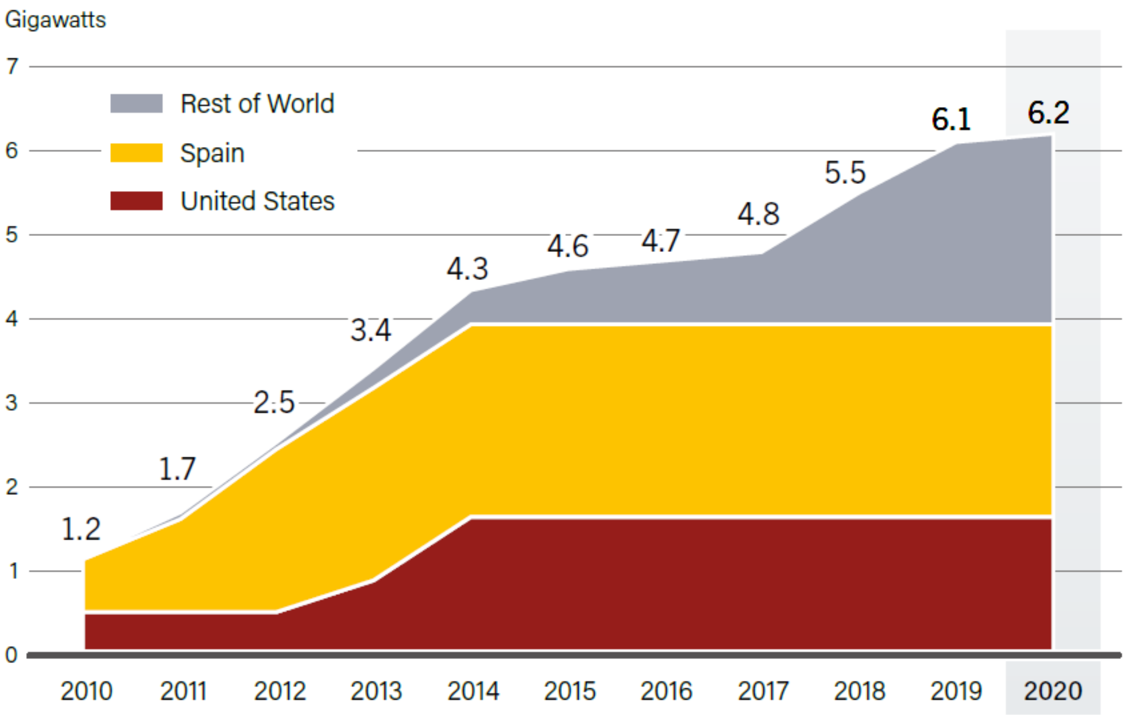

Figure 2 – CSP global capacity over the decade (REN21, 2021)

2.1 Parabolic Trough Collectors

Parabolic through collectors (PTC) plants use parabolic-shaped mirrors assembled in a linear tube. This assembly moves to track the sun's movement from sunrise until sunset in one axis, with the mirrors reflecting the sunlight onto the absorbing tube (Hachicha et al., 2013). The typical layout for this system is represented in a parallel pattern. Usually, synthetic oil is used for this system, which means that a maximum temperature of 400°C can be reached for the thermal cycles, limiting its achievable efficiency to approximately 38% (Guo al., 2016). Recent studies utilizing water as HTF have been conducted, achieving approximately 15% (Bhargav et al., 2021).

The PTC system is the most widely used CSP technology, due to the more advanced technology. At present, globally, there are 77 operational parabolic-trough power plants and most of them are located in Spain and the United States (Islam et al. 2018). In 2013, plants based on PTCs were the most commercially attractive and widely installed CSP technology, It presents longer commercial operational experience and less technical and financial risks (Achkari and El Fadar, 2020). But today, both PTC and SPT technologies dominate the market (Fernández et al. 2019), due to the higher efficiency of the SPT systems.

2.2 Linear Fresnel Reflectors

Linear Fresnel reflectors (LFR) system is composed of an array of flat or semi-flat mirrors and a receiver. The reflectors are responsible for tracking the sun movement reflecting the direct solar straight to the receiver, which remains fixed. Since the number of collectors is higher than the receivers, the concentration of light occurs at the rate of these two areas (Qiu et al., 2015).

When compared with PTC, the optical efficiency is smaller, since the transversal component of the radiation collides with the receiver tubes when the sun is distant from the zenithal position. Slight optical errors can also be expected since the distance from the mirrors to the focal point contribute to harm the optical performance (Abbas et al., 2013; Abbas, 2017).

To achieve better performance without potential harm due to cost/manufacturing, different configurations for this system have also been created. Compact linear Fresnel collectors, for instance, with smaller blocking optical losses with two parallel receivers assembled in each mirror, pointing to different receivers depending on the incidence angle of the direct solar radiation (Pino et al., 2013).

2.3 Parabolic Dish Collector

Parabolic Dish Collector (PDC) system utilizes parabolic dishes fitted with a two-axis tracking system and a receiver. Inside the receiver, a heat exchanger works transferring the heat to the working fluid. Its particular design allows positioning them either grouped or separated, being applicable for limited or wide fields.

This application is considered costly due to the high manufacturing cost, high precision required, and also extra handling and transportation issues (Suman et al., 2015). Even though the dishes produce electricity independently, the power capacity for each is considered low (around tens of kW), which means that a considerable amount is required to be installed to achieve the usual energy built with other CSP technologies (Barley et al, 2011).

2.4 Solar Power Tower

Solar power tower (SPT) consists of a central tower with a receiver, surrounded by thousands of mirrors called heliostats having individual two-axis tracking systems. The incident sunlight is concentrated by the heliostat field on the receiver located at the top of the tower. These plants usually utilize water, molten salt, and pressurized air as working fluids (Suman et al., 2015). A comprehensive analysis of solar power towers is given in item 5.

3. THERMAL ENERGY STORAGE

Solar energy is a clean, free, abundant, and inexhaustible energy source. However, it is intermittent and of unpredictable nature. To overcome its drawbacks and ensure a balance between supply and demand at all times and everywhere, thermal energy store (TES) techniques have become more and more unavoidable (Achkari and El Fadar, 2020). According to Fernández et al. (2019), most new CSP plants are being developed with TES, resulting in more affordable costs, compared to batteries (Ghirardi et al. 2021).

CSP is unique among renewable energy recently sources since it can be coupled with thermal energy storage (TES) as well as commercial fuels, making it highly dispatchable (Zhang et al., 2016). The converted solar thermal energy can be used to run a thermodynamic cycle and the excess thermal energy can be stored in a TES system. The energy stored can be used to produce electricity even after sunset. Furthermore, the fluctuations in incident weather can be supplemented by energy stored. The TES augments the capacity utilization factor of the plant and the value of the generated electrical energy (Awan et al., 2020).

The benefits yielded by TES systems are (Fernández et al., 2019): a cutback in real-time net power variability in the event of pool solar radiation, an extension of the whole production period, and a possible rearrangement of production toward high-price periods increasing the CSP power dispatchability.

High-temperature storage concepts for SPT can be classified as active or passive systems (Gil et al., 2010, Palacios et al., 2020). An active storage system is characterized by the storage media circulating through a heat exchanger, using one or two tanks as the storage media. If the storage medium is a heat transfer fluid (HTF), the system is direct-active; on the other hand, if the storage medium and the HTF are different, the active system is indirect. When the storage medium is solid, the HTF flows through the storage material only for charging and discharging, thus being classified as a passive type. Figure 4 presents both systems previously mentioned.

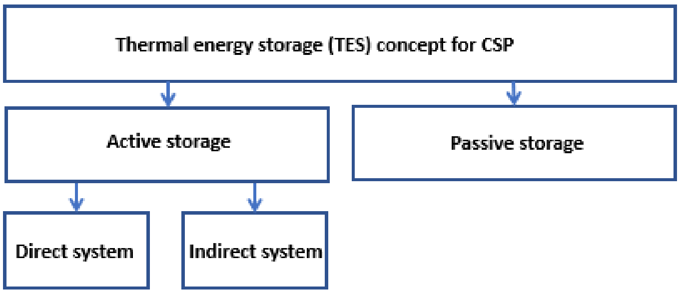

Figure 4. Categorization of TES for CSP plants (Gil et al.,2010)

The first large-scale power plants utilizing the indirect storage concept, with synthetic oil as HTF and solar salt as a storage medium, were Andasol 1, 2, and 3 (all producing around 50 MW_e), installed in 2008, 2009, and 2011, respectively. The plants were built in Granada, Spain, and can be operational for over more than 7h by the thermal energy provided by the indirect storage unit (Kelly et al., 2007). Direct storage in mineral oil (e.g. *Helisol*® 5A or Therminol VP-1) temperatures reaching up to 300°C have been utilized in the PTC SEGS-1 power plant built in California in 1984 (Kroizer, 1984). SEGS I is one of the nine Solar Electric Generating Station plants in California's the Mojave Desert. The combined electric generating capacity of these plants, which use parabolic trough technology, is more than 350 MW (NREL, 2021).

Thermal energy can be stored in three different forms: sensible heat, latent heat, and thermochemical heat, as can be seen in Figure 5. The simplest way of storing thermal energy is within sensible heat thermal energy storage systems, to which a temperature gradient is applied by heating or cooling the material. This technology is considered as a mature technology already implemented in different applications and commercially available since it is cost-effective and technically simple but presents low storage capacities in comparison with the other two technologies. The second one is the latent heat thermal energy storage system, which takes advantage of the heat involved during a phase change transition of the material. The main advantage is that these systems can store more than the sensible heat storage systems while keeping the complexity of the system design at hand. The last technology is thermochemical storage systems, which can absorb/release the heat produced during a reversible chemical reaction. TCS is the most promising and efficient way of storing thermal energy but is technically complex (Palacios et al., 2020). Latent heat and thermochemical technologies have presented low deployment, while sensible heat technology is the most used in CSP plants.

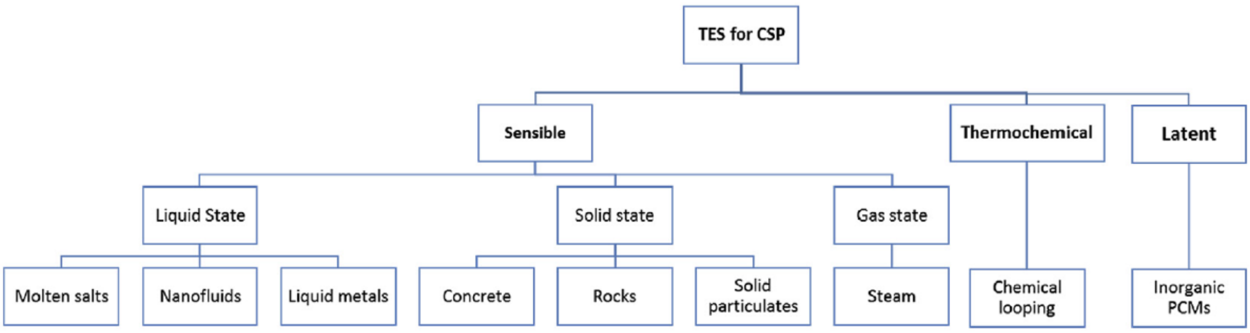

Figure 5. TES for CSP classified by TES systems. (Palacios et al., 2020)

The choice of the optimal storage material is a great challenge. A variety of materials have been studied, analyzed, and used for sensible heat storage systems; they are classified as liquid heat storage or solid heat storage materials. The main thermophysical properties desired for TES materials in CSP are specific heat, thermal conductivity, melting/solidification enthalpy and temperature, and viscosity. However, other properties such as degradation temperature, thermal stability, density, vapor pressure, and thermal expansion coefficient are necessary when looking for TES materials and designing the CSP plant implementing those materials (Fernández et al., 2019). Among the choices, water is the best candidate for domestic and low temperatures applications (between 25 and 90°C). For the high-temperature SHS applications, molten salts remain are most mature and widely used storage media in CSP plants (Achkari and El Fadar, 2020). The next section discusses the molten salts.

4. MOLTEN SALTS

At the end of 2020, an estimated 21 GWh of thermal energy storage was operating in conjunction with CSP plants across five continents, with more than 95% of global TES capacity based on molten salt technology (REN, 2021), due to their favorable thermophysical properties. Compared to water vapor, molten salts have a higher energy density, higher melting point, higher capacity of heat, and higher lifetime (Palacios et al., 2020; Ashour et al. 2021). Due to the higher operating temperatures, higher thermal to electric conversion efficiencies can be achieved. They are also cheaper than other types of heat transfer fluids such as organics or thermal oils. The main drawbacks addressed by the use of molten salts as HTF or TES media are corrosion issues and low specific heat capacity (Ibrahim et al., 2019). The corrosion is mainly related to the high operating temperatures reached by the molten salts (Vignarooban et al. 2015).

The prevention of high-temperature corrosion mitigation is required for the plants to operate for a long time. Several papers have studied the corrosion in molten salts in CSP. Fernández and Cabeza (2020a) studied thermal treatments for corrosion mitigation in a eutectic ternary chloride molten salt. Later, the same authors used the thermal treatment to analyze different container materials to be used in the new generation of CSP plants containing chloride molten salts (Fernández and Cabeza, 2020b). The use of nanoparticles is also being considered to enhance thermal properties and reduce corrosivity (Ibrahim et al., 2021).

New molten salts have been extensively studied, most of them derived from solar salt. The main reasons for the solar salt popularity are its relatively low cost, inflammability, and the fact that it is not toxic and has reasonable material compatibility, which allows its interface with stainless steel without extreme corrosion rates as previously observed by Mehos et al. (2017) and Walczak et al. (2018).

The following characteristics must be taken into account when selecting a heat transfer or thermal storage fluid:

- Specific heat capacity: Improves TES system efficiency, since it controls the capacity of the temperature rise that can be stored or transported (Fernández et al., 2019).
- Liquidus Temperature: This is defined as the temperature at which the solid is completely molten. Relates to operation on maintenance costs, since higher temperatures for this requires anti-freezing protection (Pfleger et al., 2015).
- Thermal stability and maximum operating temperature: Maximum working temperature that can be reached without causing degradation to the fluid (Kosmulski et al., 2004)
- Thermal conductivity: Related to the heat transfer rates. Higher values can be translated into higher heat exchange efficiency.
- Density: Relates the amount of energy per unit of volume that a selected TES can store. For an HTF at working temperature, the amount of heat carried directly relates to the density of a material and its specific heat capacity.

Recently (Caraballo et al. 2021) have investigated these properties for nitrate, chloride, fluoride, and carbonate-based molten salts eligible as TES materials, which can be seen next briefly discussed.

4.1 Nitrate Salts

Considered the most popular TES material in CSP, the non-eutectic mixture of 60% $NaNO_3$-40% KNO_3 (wt%), known as Solar salt, has been investigated since the 1980s according to Bradshaw et al (2008) and Glatzmaier et al (2010). The main reasons for its popularity are its good chemical safety, relatively low cost, and moderate material compatibility with other materials, such as stainless steel without having unexpected corrosion rates. The main drawbacks for this type of salt are their high crystallization temperature (around 240 °C) and maximum operational temperature (565 °C), thus having degradation reactions beyond this limit (Bradshaw et al, 1990; Sau et al, 2016). Hitech XL molten salt has been extensively studied, however, its viscosity and uncertainties related to the crystallization point remain as challenges to overcome.

4.2 Chloride Salts

Chlorides are considered good TES materials due to their natural abundance, high thermal stability, however, their melting point remains a drawback, but still lower than fluoride and carbonate-based TES materials. (Mohan et al. 2019).

Recently, research focusing on the development of multicomponent mixtures of lithium, sodium, magnesium, calcium, and other chlorides to decrease the melting point has been performed. However, even though this target could be successfully achieved, their high-cost impacts as a major drawback (Mohan et al, 2018; Mohan et al, 2019; Badenhorst et al, 2018).

4.3 Fluoride and Carbonate-based Salts

Fluoride has been used in the nuclear industry due to its relatively high specific heat capacity, thermal conductivity, and thermal stability in comparison with other molten salts (Forsberg et al, 2006; Le Brun, 2007), although previous studies for carbonate-based salts have shown its thermal stability operating between 600-700°C (Lageraaen et al, 1995).

The main challenge of using fluoride-based molten salt is its corrosion rate, which can be considered higher than carbonate and chloride salt mixtures (Forsberg, 2006; Frangini, 2008). Although some studies have shown that carbonates are less corrosive than fluorides, their viscosity is their main disadvantage, which can result in pumping issues (Keblinski et al, 2005).

4.4 Molten Salts Improvement

The addition of nanoparticles into molten salts has been extensively studied to enhance their properties, creating a nanofluid (Shin et al, 2011). Nanoparticles are usually used to increase the specific heat capacity, which is considerably low in comparison with water or other liquid metals, therefore, increasing the overall CSP efficiency. However, the addition of particles may result in a viscosity increase, compromising the performance of the system.

5. SOLAR TOWER

Among the CSP plant configurations, the SPT is the option with the highest potential, because the 2-axis tracking system allows reaching higher operating temperatures, and consequently a higher steam cycle efficiency (Ghirardi et al., 2021). This CSP technology can reach temperatures above 1000°C (Awan et al., 2020).

Although PTC technology is implemented in 80% of the operational plants (i.e. 83% of the installed capacity), given the recent growth in SPT technology, this ranking can quickly be changed. 45% of the CSP projects that are currently under development (i.e. 60% of the installed capacity) have been chosen as SPT plants versus 42% of projects for PTC (i.e. 37% of the installed capacity). SPT is mainly driven by its strength to achieve higher temperatures compared to PTC (Achkari and El Fadar, 2020). Moreover, SPT performs better than linear devices like PTC in isolated or weekly interconnected grids (Ghirardi et al, 2021). Nowadays, central tower technologies have been dominating the CSP market (Vasallo et al., 2017). Figure 6 represents CSP worldwide capacity under construction and development for each technology.

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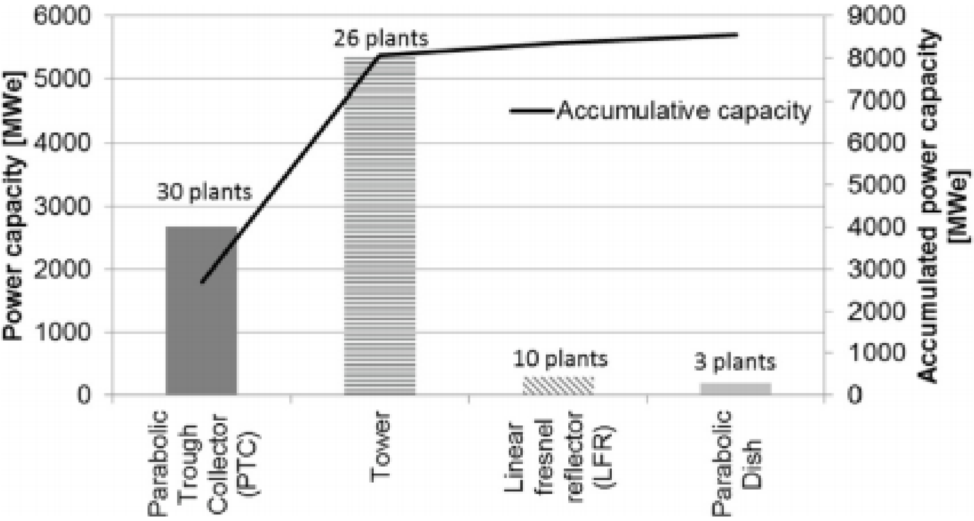

Figure 6. CSP power capacity under construction as a function of technology (Vasallo et al., 2017)

Comparing the four technologies previously presented, SPT can be advantageous in terms of temperature levels and overall efficiency. The efficiency can be based on a relation between the central receiver (tower) and the heliostat's capability of reflecting the solar radiation onto the receiver. Therefore, a drive system is required to keep the heliostats moving, covering both azimuth and elevation angles, resulting in a challenge to develop efficient drive system designs at a low cost. Since heliostats represent about 40% of the total cost of a power plant, the reduction of the heliostat cost may result in a substantial reduction in the SPT overall cost (Larmuth, 2015).

The efficiency of the plants can be increased by combining them with other energy sources. SPT including PV, CSP, and hybrid PV-CSP has attracted much interest in recent years and studies have yielded relevant findings (Behar et al. 2021). The hybridization with geothermal energy is also a good option, due to the large potential and geographical coincidence of geothermal resources with high solar irradiation areas (Boukelia et al., 2021). Different configurations for the heliostat have also been investigated, attempting to reduce shadowing caused by them. Further investigations to optimize the overall efficiency of the heliostat field have also been carried out. Belaid et al (2020) concluded that the yearly overall efficiency can be increased from 69.65% utilizing rectangular shapes to 70.96% and 71% for the octagon and circular shapes, respectively.

6. CONCLUSIONS

This paper, it was reviewed CSP systems, with a special focus on SPT systems using TES and molten salts. Although parabolic trough collectors are a more widely installed technology, new plants are being constructed using solar power tower technology. They are economically proven, have increased efficiency, and can produce electricity even in the absence of the sun. The major drawback of the CSP is its temporal intermittency. A thermal energy storage system can be integrated into the plants to store the excess thermal energy ad provide a continuous supply of heat for power generation. Most of the new CSP plants are being developed with TES.

The heat transfer fluid and the TES media used in CSP plants need to be carefully selected, based on thermophysical properties, temperatures, and corrosion issues. About 95% of global TES capacity was based on molten salts, due to their favorable thermophysical properties. The major drawbacks are the corrosion issues and the low specific heat capacity, both being extensively studied by researchers.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Abbas, R., A comprehensive optical characterization of linear Fresnel collectors by means of an analytic study, Appl. Energy 185 (2017) 1136e1151.

Abbas, R., Muñoz-Anton, J., Valdés, M., Martínez-Val, J.M; High concentration linear Fresnel reflectors, Energy Convers. Manag.t vol. 72 (2013) 60e68,

Achkari, O., El Fadar, A., Latest developments on TES and CSP technologies – Energy andenvironmental issues, applications and research trends, Applied Thermal Engineering 167 (2020) 114806

Antoni, G., Medrano, M., Martorell, I., Lazaro, A., Dolado, P., Zalba, B., Cabeza, L.F., State of the art on high temperature thermal energy storage for power generation. Part 1dconcepts, materials and modellization, Renew. Sustain. Energy Rev. 14 (2010) 31e55.

Ashour, A.I., Almitani, K.H., Abu-Hamdeh. N. "Developing and improving a prototype scale concentrating solar power tower-system", Sustainable Energy Technologies and Assessments, v. 45, 101105, 2021

Awan, A.B., Moulu, K.V.V.C., Zubair, M. "Performance enhancement of solar tower power plant: A multi-objective optimization approach". Energy Conversion and Management, v. 225, 113378, 2020.

Badenhorst, H.; Böhmer, T. Enthalpy of fusion prediction for the economic optimisation of salt based latent heat thermal energy stores. J. Energy Storage 2018, 20, 459–472

Barlev, D, Vidu R, Stroeve P., Innovation in concentrated solar power. Solar Energy Materialls & Solar Cells 2011;95(10);2703-25

Behar, O., Sbarbaro, D., Moran, L. "Which is the most competitive solar power technology for integration into the existing copper mining plants: Photovoltaic (PV), Concentrating Solar Power (CSP), or hybrid PV-CSP?", Journal of Cleaner Production, v. 287, 125455, 2021.

Belaid, A, Filali, A., Gama, A., Bezza, B., Arrif, T., Bouakba, M., Design optimization of a solar tower power plant heliostat field by considering different heliostat shapes. Int J Energy Res. 2020;44:11524–11541.

Bhargav, H., Upadhyay, Amitkumar J., Patel, Kishor Kumar Sadasivuni, J.M. Mistry, P.V.Ramana, Hitesh Panchal, Deepalekshmi Ponnamma, F.A. Essa. Design, development and techno economic analysis of novel parabolic trough collector for low- temperature water heating applications

Boukelia, T.E., Arslan, O., Bouraoui, A. "Thermodynamic performance assessment of a new solar tower-geothermal combined power plant compared to the conventional solar tower power plant". Energy, v. 232, 121109, 2021.

Bradshaw, R., Meeker, D. High-temperature stability of ternary nitrate molten salts for solar thermal energy systems. Sol. Energy Mater. 1990, 21, 51–60.

Bradshaw, R.W.; Siegel, N.P. Molten nitrate salt development for thermal energy storage in parabolic trough solar power systems. In Proceedings of the ASME 2008 2nd International Conference on Energy Sustainability, Jacksonville, FL, USA, 10–14 August 2008; ASME International: New York, NY, USA, 2008; pp. 631–637

Caraballo, A.; Galán-Casado, S.; Caballero, Á.; Serena, S. Molten Salts for Sensible Thermal Energy Storage: A Review and an Energy Performance Analysis. Energies 2021, 14, 1197. https:// doi.org/10.3390/en14041197

Carling, R., Mar, R., Sand81-8020: Industrial use of molten nitrate/nitrite salts. Tech. Rep. Sandia National Laboratories; 1981.

Fernández, A.G., Gomez-Vidal, J., Oró, E., Kruizenga, A., Solé, A., Cabeza, L. "Mainstreaming commercial CSP systems: A technology review". Renewable Energy, v. 140, p. 152-176. 2019.

Fernández, A.G., Cabeza, L.F. "Corrosion evaluation of eutectic chloride molten salt for new generation of CSP plants. Part 1: Thermal treatment assessment", Journal of Energy Storage, v. 27, 101125, 2020a

Fernández, A.G., Cabeza, L.F. "Corrosion evaluation of eutectic chloride molten salt for new generation of CSP plants. Part 2: Materials screening performance", Journal of Energy Storage, v. 29, 101382, 2020b

Flueckiger, S. M., Yang, Z., & Garimella, S. V. (2012). *Thermomechanical Simulation of the Solar One Thermocline Storage Tank. Journal of Solar Energy Engineering, 134(4), 041014.* doi:10.1115/1.4007665

Forsberg, C.W.; Peterson, P.F.; Zhao, H. High-Temperature Liquid-Fluoride-Salt Closed-Brayton-Cycle Solar Power Towers. J. Sol. Energy Eng. 2006, 129, 141–146

Ghirardim E., Brumana, G., Franchini, G., Perdichizzi, A. "Heliostat layout optimization for load-following solar tower plants", Renewable Energy, v. 168, p. 393-405, 2021.

Glatzmaier, G.N.; Siegel, N.P. Molten Salt Heat Transfer Fluids and Thermal Storage Technology Sandia Technical Report; SAND2010- 3826C; Sandia National Laboratories: Albuquerque, NM, USA, 2010.

Hachicha, A.A., Rodríguez, I., Capdevila, R., Oliva, A., Heat transfer analysis and numerical simulation of a parabolic trough solar collector. Appl Energy 2013;111(11):581–92

Ibrahim, A., Peng, H., Riaz, A., Basit, M.A., Rashid, U., Basit, A., "Molten salts in the light of corrosion mitigation strategies and embedded with nanoparticles to enhance the thermophysical properties for CSP plants", Solar Energy Materials and Solar Cells, v. 219, 110768, 2021.

International Energy Agency, IEA, Paris 2010. Technology Roadmap Concentrating Solar Power France.

Islam, M.T., Huda, N., Abdullah, A.B., Saidur, R. "A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends". Renewable and Sustainable Energy Reviews, v. 91, p. 987-1018, 2018

Kaplan, G.M., Understanding Solar Concentrators, Volunteers in Technical Assistance, Arlington, VA, 1985.

Keblinski, P.; Eastman, J.A.; Cahill, D.G. Nanofluids for thermal transport. Mater. Today 2005, 8, 36–44.

Kelly, B., Price, H., Brosseau, D., Kearney, D., Adopting nitrate/nitrite salt mixtures as the heat transport fluid in parabolic trough power plants. In: Proc. ASME energy sustainability, long beach, CA; 2007

Kosmulski, M., Gustafsson, J., Rosenholm, J.B., Thermal stability of low temperature ionic liquids revisited. Thermochim Acta 2004;412(12):47–53

Kroizer I., Design of a 13MWe parabolic trough plant at daggett, California. Design and performance of large solar thermal collector arrays - proceedings of the international energy agency workshop; 1985534–6

Lageraaen, P.; Patel, B.; Kalb, P.; Adams, J. Treatability Studies for Polyethylene Encapsulation of INEL Low-Level Mixed Wastes. Treatability Studies for Polyethylene Encapsulation of INEL Low-Level Mixed Wastes; Final Report (No. BNL-62620); Brookhaven National Laboratory: Upton, NY, USA, 1995.

Larmuth J.N, "Heliostat cost reduction methods applied to a small heliostat,"2015 Univ. Stellenbosch, MS, no. December 2015.

Le Brun, C. Molten salts and nuclear energy production. J. Nucl. Mater. 2007, 360, 1–5.

Mehos, M., Turchi, C., Vidal, J., Wagner, M., Ma, Z., Ho, C., Kolb, W., Andraka, C., Kruizenga, A., Concentrating Solar Power Gen3 Demonstration Roadmap; (No. NREL/TP-5500-67464); National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2017. 49.

Mohan, G.; Venkataraman, M.; Gomez-Vidal, J.; Coventry, J. Assessment of a novel ternary eutectic chloride salt for next generation high-temperature sensible heat storage. Energy Convers. Manag. 2018, 167, 156–164.

Mohan, G.; Venkataraman, M.B.; Coventry, J. Sensible energy storage options for concentrating solar power plants operating above 600 ◦C. Renew. Sustain. Energy Rev. 2019, 107, 319–337

NREL, 2021. "Concentrating Solar Power Projects by country." [Online]. Available: https://solarpaces.nrel.gov/by-country.

Palacios, A., Barreneche, C., Navarro M.E., Ding, Y., Thermal energy storage technologies for concentrated solar power e A review from a materials perspective

Pfleger, N., Braun, M., Eck M, B.T., Assessment of novel inorganic storage medium with low melting point. Energy Procedia 2015; 69:988–996

REN21. 2021. Renewables 2021 Global Status Report (Paris: REN21 Secretariat). ISBN 978-3-948393-03-8

Sau, S.; Corsaro, N.; Crescenzi, T.; D'Ottavi, C.; Liberatore, R.; Licoccia, S.; Russo, V.; Tarquini, P.; Tizzoni, A. Techno-economic comparison between CSP plants presenting two different heat transfer fluids. Appl. Energy 2016, 168, 96–109.

Shin, D.; Banerjee, D. Enhancement of specific heat capacity of high-temperature silica-nanofluids synthesized in alkali chloride salt eutectics for solar thermal-energy storage applications. Int. J. Heat Mass Transf. 2011, 54, 1064–1070

Steinmann., W-D. Advances in thermal energy storage systems - methods and applications; chap. Thermal energy storage systems for concentrating solar power (CSP) technology. Woodhead Publishing; 2015. p. 511–31.

Suman, S., Khan, M. K., and Manabendra P., 2015 "Performance Enhancement of Solar Collectors – A Review." Renewable and Sustainable Energy Reviews 49: 192–210.

Thirugnanasambandam, M., Iniyan, S., and Goic, R., 2010. "A review of solar thermal technologies". Renewable and Sustainable Energy Reviews 14: 312–322.

Vasallo, M.J., Bravo, J.M., Cojocaru, E.G., Gegúndez, M.E., Calculating the profits of an economic MPC applied to CSP plants with thermal energy system, Sol. Energy 155 (2017) 1165e1177.

Vignarooban, K., Xu, X., Arvay, A., Hsu, K., Kannan, A.M. "Heat transfer fluids for concentrating solar power systems – A review". Applied Energy, v. 146, p. 383-396, 2015.

Walczak, M., Pineda, F., Fernández-Ángel, G., Mata-Torres, C., Escobar, R.A., Materials corrosion for thermal energy storage systems in concentrated solar power plants. Renew. Sustain. Energy Rev. 2018, 86, 22–44.

Zhang, H., Baeyens, J., Caceres, G., Degr eve J, Lv Y. Thermal energy storage: recent developments and practical aspects. Prog Energy Combust Sci 2016; 53: 1–40.

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