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Thermal Energy Storage Systems for Concentrating Solar Power Plants

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Abstract

This chapter presents the relevance and integration of TES for CSP technologies. A TES system consists of the storage material, heat transfer equipment, and storage tank. The TES material stores the thermal energy either in the form of sensible heat, latent heat and thermochemical energy via chemical reactions. There are several requirements that must be considered to ensure optimal storage dynamics and longevity in a TES. These requirements are analysed and discussed. A broad spectrum of storage technologies, materials and methods are explored for the selection of suitable TES for CSP technologies. Materials for heat transfer fluid and material for energy storage that are generally used in TES are presented. Various limitations and problems of TES systems, such as high temperature corrosion with their proposed solutions, as well as successful implementations are reported. Further, storage media and storage type selection for CSPs based on their stability, material characterization and compatibility of materials are explained. Various available CSP technologies such as parabolic trough collector technology, linear Fresnel collector technology, solar tower technology, Stirling dish technology, etc., are discussed in detail and compared. Factors to be considered at different hierarchical levels for each CSP technologies with TES are explained.

Keywords: Solar thermal, thermal energy storage, parabolic trough collector, solar tower, stirling dish technology

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1.1 Introduction

According to the International Energy Agency (IEA) in 2019, global energy demand will rise by 1.3% each year to 2040. Non-renewable energy takes up a major percentage of the global energy sector. The awareness and use of renewable energy is one of the ways to meet sustainable energy goals and to alleviate the associated environmental problems including carbon emission. Also, the development on renewable energy is significantly slow-paced as observed in the last few decades. The development of renewable energy is seen only in very few countries. The most popular renewable energy sources currently under consideration are wind energy, solar energy, tidal energy, geothermal energy, hydro energy, etc. Due to many benefits including ready availability, the larger proportion of interest is taken by solar energy among various types of renewable energy sources (Regin *et al.*, 2008). However, the momentum of renewable energy technologies is not as significant as is needed with the expansion of the global economy and growth of population.

In the solar energy field, two major breakthrough technologies that have attracted significant attention in many countries are Solar Photovoltaic (PV) power generation and Concentrated Solar Power (CSP) plants. In solar PV plants, the solar energy is directly converted to electricity by using solar cells (Muhammad and Arshad, 2020; Jain *et al.*, 2020; Khajepour and Ameri, 2020; Ahmed *et al.*, 2020; Zhang *et al.*, 2013). The solar energy to electrical energy conversion efficiency of a commercial grade PV is observed to be less than that of CSP systems and power dispatch is not possible in PV-based solar power production. Other than larger energy efficiency, one of the major advantages of CSP is its ability to provide electrical power at nighttime and during cloudy hours. This can be made possible by incorporating Thermal Energy Storage (TES) system. The capacity to dispatch power is more in a CSP system than that of a PV-based solar power system.

1.2 Concentrating Solar Power (CSP) Technology

Solar energy is the most viable and abundant renewable energy source. The Concentrating Solar Power (CSP) technology is promising especially for countries having an abundance of solar resources. Implementation of CSP technology can secure the energy supply and reduce carbon footprint, resulting in achieving sustainable development goals. A Concentrating Solar Power (CSP) system includes a concentrator (to concentrate solar radiation), a receiver (converts solar radiation to thermal energy) and a power block (with the turbine to convert thermal energy to electrical energy). A CSP system receives and concentrates sunlight followed by converting solar radiation to thermal energy (Shouman and Khattab, 2015; Tian and Zhao, 2013; Cavallaro, 2009; Barlev *et al.*, 2011; Desai *et al.*, 2014; Islam *et al.*, 2018). The thermal energy is then carried by a fluid called Heat Transfer Fluid (HTF) to the power block for power generation.

The CSP concept materialized on an industry scale in the 1980s in California where nine separate Solar Electric Generating Systems (SEGS) based on parabolic trough receiver, totalling 354 MWe of installed capacity were constructed. These systems used oil as the HTF involving parabolic trough receivers based on steam turbines for power generation. As observed from the data provided by NREL, the growth of solar power plants based on CSP concepts has been led predominantly by Spain followed by the United States. New and ongoing CSP projects are also being developed in other countries as shown in Figure 1.1. As per the data provided by NREL,

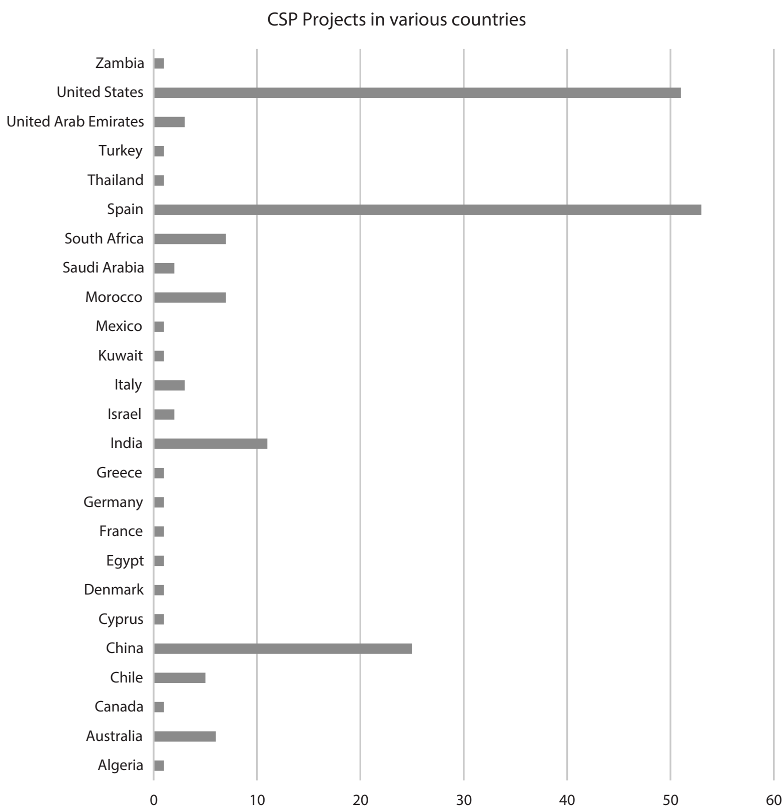

Figure 1.1 Number of CSP projects in various countries (source: NREL).

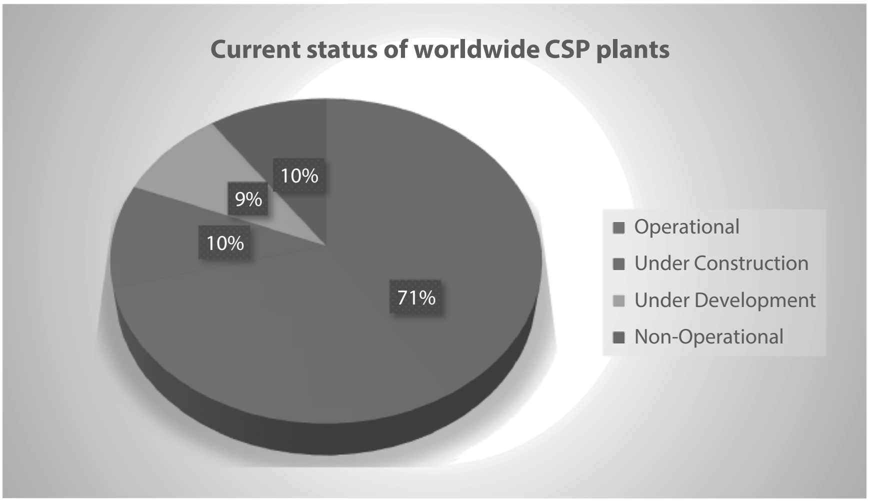

Figure 1.2 Current status of worldwide CSP plants (data source: NREL).

currently 188 worldwide CSP-based power plants are documented, out of which 71% are operational [see Figure 1.2].

1.2.1 CSP Receiver Concepts

There are two ways by which the solar radiation is concentrated from the solar panel: line focusing and point focusing systems. In the line focusing system, solar collectors concentrate the radiation along a focal line. In the point focusing system, solar radiation is concentrated on a single focal point. A single axis tracking system is needed to follow the sun during the day for the line-focusing systems. On the other hand, two axis tracking systems are needed for the mirrors in point focusing systems. Based on the focusing concepts and receiver geometry, currently four design concepts are used, such as parabolic trough system, linear Fresnel system, power towers and parabolic dish systems. A summary of these receiver concepts is illustrated in Figure 1.3 and briefly explained below.

1.2.1.1 Parabolic Trough System

In parabolic trough systems, solar radiation is focused to a receiver tube located at the focal point using mirrored parabolic troughs to focus. The receiver tube carries the HTF which can be heated up to a temperature of

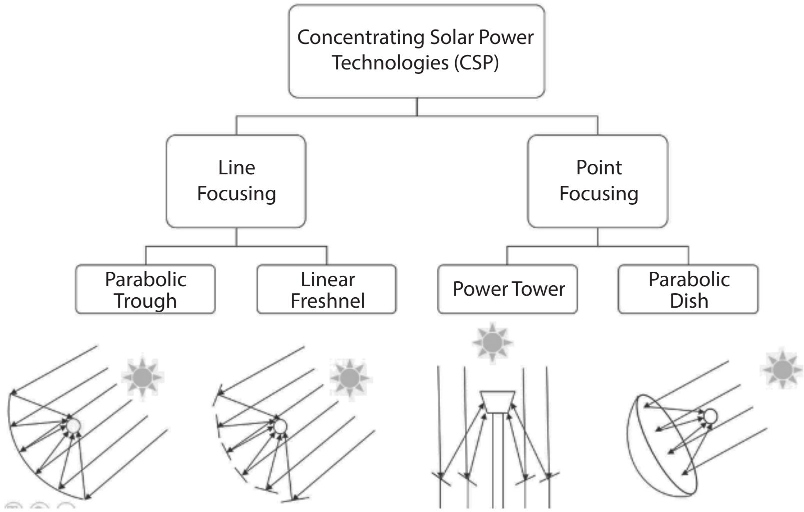

Figure 1.3 CSP receiver concepts.

390°C. The HTF is then pumped through a heat exchanger where superheated steam at high pressure is produced. Further, the steam is fed into a steam turbine connected to a generator to produce electricity. Synthetic oil, direct steam and molten salt are a few examples of HTF used in parabolic trough systems. The parabolic shaped reflectors implement a line-focusing system.

Parabolic trough systems are one of the promising technologies and most preferred configurations of CSP in the solar energy market. Most of today's commercial CSP plants are based on this concept, making up 65% (101 out of 188) of total CSP plants [Figure 1.4]. There are a good number of research works found in the literature on the parabolic trough system (Herrmann and Kearney, 2002; Herrmann *et al.*, 2004; Tamme *et al.*, 2004; Llorente *et al.*, 2011; Kolb, 2011).

1.2.1.2 Linear Fresnel Reflector Systems

Linear Fresnel reflector systems use a field of narrow long mirrors. The mirrors are rotated independently to concentrate solar radiation on a stationary receiver tube. The mirrors are either flat or curved that track the sun and focus solar radiation [Figure 1.3]. The fixed absorber tube allows for easier Direct Steam Generation (DSG). Due to direct DSG, the operating temperature for such systems can be larger. This system also works with line focusing concept.

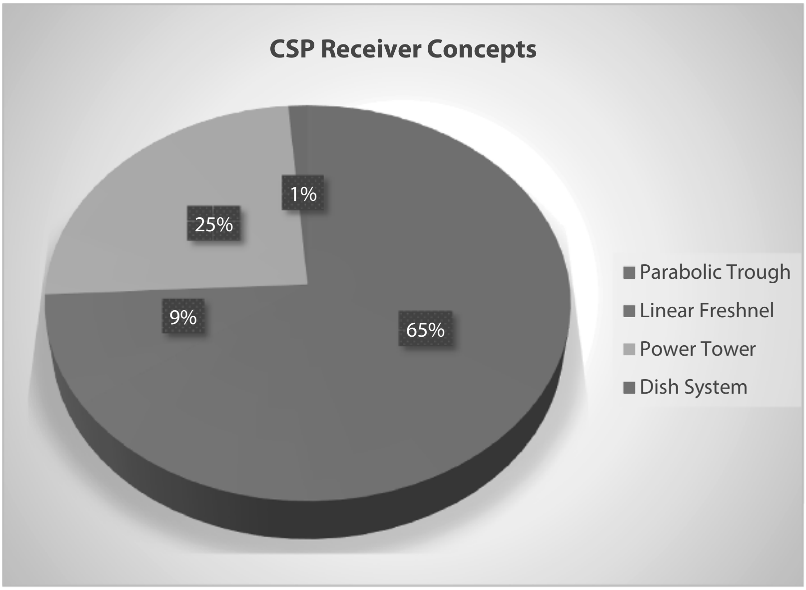

Figure 1.4 CSP receiver concepts as used worldwide.

One of the major advantages of such systems is the simple design of the reflector leading to lesser capital cost. Overall, Linear Fresnel CSP receiver system offers lowest start-up and maintenance cost. In addition, cheap and simple flat mirrors allow high reflectors density per square meter. However, linear Fresnel receivers have the lowest solar-to-electrical efficiency compared to other receivers due to high optical loss. Now 9% of all CSP plants opt for such collector concept [Figure 1.4]. As observed from the literature, there is a good amount of fundamental and academic research work going on to enhance the performance of the CSP system with linear Fresnel receiver (Desai and Bandyopadhyay, 2015; Mills *et al.*, 2000; Morin *et al.*, 2012; Xie *et al.*, 2011).

1.2.1.3 Central Receiver Plants

A circular array of large mirrors with sun-tracking motion (called heliostats) reflect direct sunlight onto an absorber system in central receiver. Such systems are also called power tower as the receiver is mounted on the top of a tower [Figure 1.3]. This is a point focusing system and the two axis tracking allows a higher concentration ratio and temperature. The receiver collects radiation as thermal energy and a HTF carries the energy from the receiver to the power block. Central receiver configuration allows high plant size due to its design. Currently, 25% of the installed CSP configurations are central receiver plants [Figure 1.4]. Research works on central receiver systems are reviewed and presented by Behar *et al.* (2013), Ho and Iverson (2013), and Avila-Marin (2011).

1.2.1.4 Dish System

In dish systems, dish-shaped parabolic mirrors are used as reflectors to concentrate and focus the solar radiation on a receiver [Figure 1.3]. The receiver is generally mounted above the dish. The receiver absorbs the thermal energy and transfers it to the Stirling engine or steam engine. Dish systems are also point focusing concept like solar towers. There were two thermal power plants with dish systems constructed [Figure 1.4]. In addition, very few works on dish systems are available in the literature (Zapata, 2015; Poullikkas *et al.*, 2010; Affandi *et al.*, 2015). Currently, dish systems have not been operational since the 1990s after the deployment of other configurations. The disadvantages of such systems are that they are expensive with a lower collection temperature.

1.3 Thermal Energy Storage in CSP

The intermittent and uncertain nature of solar energy are critical issues which cause a mismatch between source availability and energy demand. As a consequent, this results in ripples in the deployment and market penetrability of CSP technologies. Use of a backup system that uses non-renewable energy is one of the solutions of such problems. In addition, another cleaner solution to this problem is use of a Thermal Energy Storage (TES) system. The TES system can store energy when solar radiation is abundant. The stored energy can be released during periods without the solar radiation. This results in uninterrupted electricity generation during nighttime or on a cloudy day. Since the last few years, TES has been an explicit and significant component of CSP plant with the ability to drive the turbine almost continuously. Thus, electricity can be generated continuously at night and during cloudy hours when sunlight is not available. In addition, CSP with TES provides utility-scale and dispatchable electricity to the power grid. Also, TES allows CSP plants to generate electricity during evening hours when electricity is highly valued, offering better cost effectiveness. The integrated TES system can also result in shorter start-up time of the absorber systems. The TES system can be installed after the receiver system as illustrated in the block diagrams of Figure 1.5.

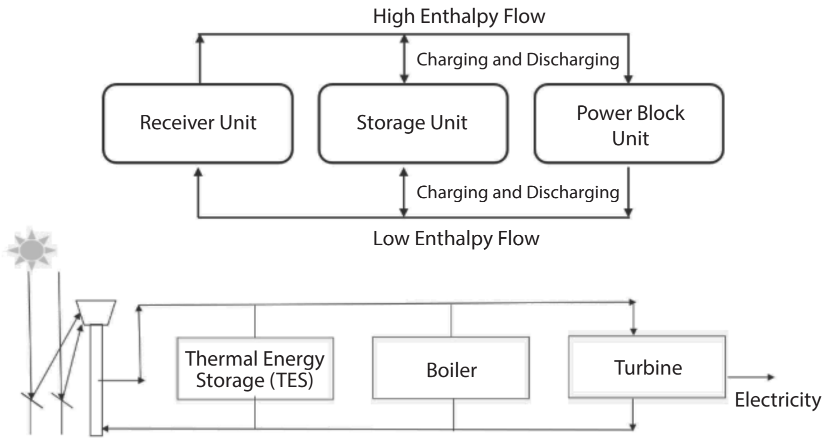

Figure 1.5 Integration of thermal energy storage systems to a CSP plant.

The possibility of integrating the TES system is one of the most distinct advantages of the solar energy field with CSP over other renewable energy fields. There are many storage technologies being developed that can be integrated into CSP plants. To accelerate the development of solar energy power generation in terms of economy and operation, an efficient and cost-effective TES system is important. Many earlier research works have studied the importance of TES on CSP and this results in an energy-efficient power plant (Guo *et al.*, 2018; John *et al.*, 2013; Prasad and Muthukumar, 2013; Adinberg, 2011; Powell and Edgar, 2012; Tamme and Laing, 2004; Tian and Zhao, 2013).

Thermal energy storage concepts for CSP plants can be classified as active or passive systems. In an active TES system, the thermal energy storage material itself circulates through a heat exchanger. Active systems can be divided into direct or indirect TES systems. In the commercial CSP plants, only active TES systems are used. Commercial active direct thermal energy storage systems are molten salt systems and steam accumulators. A second medium is used for storing the thermal energy in an active indirect system. A heat exchanger is used to transfer thermal energy from HTF to the second medium.

Two different materials for heat storage and circulation are used for passive storage systems which are dual medium storage systems. The HTF passes through the thermal storage system only for charging and discharging a TES material. The TES material can store energy in terms of sensible or latent heat. Passive TES systems are still under major research and they

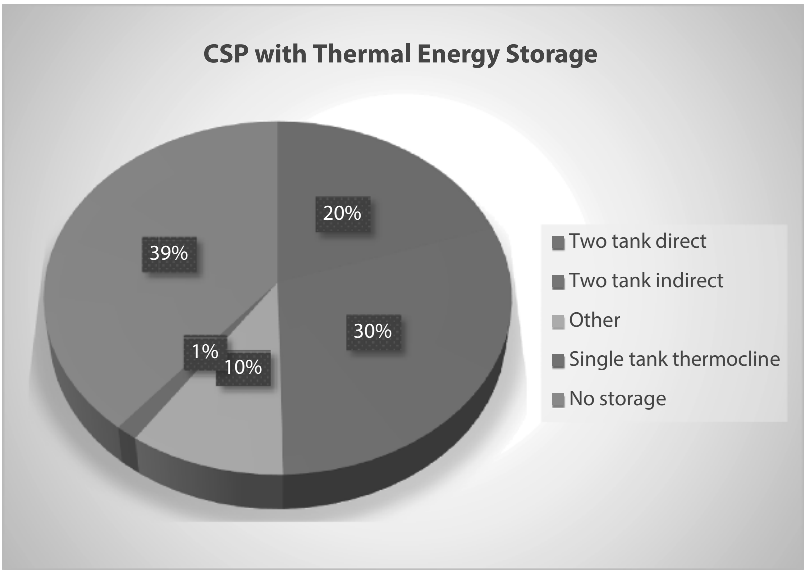

Figure 1.6 Reported integration of thermal energy storage systems in worldwide CSP plants.

have not yet reached the commercial CSP plant level. A brief discussion about different TES systems [Figure 1.6] as incorporated in commercial CSP follows below.

1.3.1 Active Two-Tank System

In an Active two-tank system, one tank holds hot HTF and another tank holds cold HTF. The hot HTF and cold HTF do not interact with each other. Major advantages of such systems are there will be no interaction between the fluids. Thus, heat loss is less and temperatures of the fluids in the tanks are almost uniform with time and position. However, two separate tanks of equal volumes are needed for such systems and tanks of the walls are subjected to daily cycles of molten salts. Thermal CSP plants with two-tank-based molten salt system are well documented by Kelly and Kearney (2004) and Herrmann *et al.* (2004). This concept can be used as direct or indirect storage systems.

1.3.1.1 Active Two-Tank Direct

In an active two-tank direct system, solar radiation is converted to thermal energy and the thermal energy is stored in the same fluid which was used

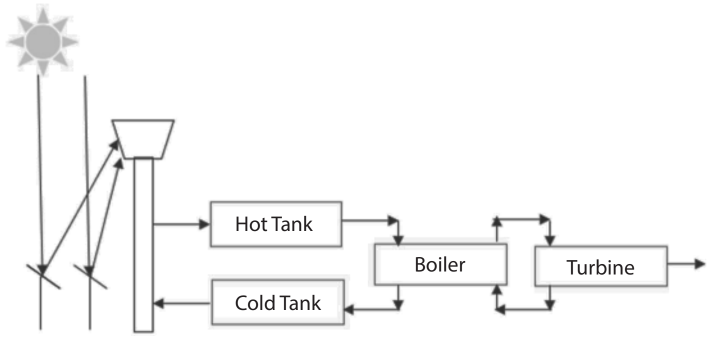

Figure 1.7 Active two-tank direct thermal energy storage.

to collect it. The fluid is stored in two tanks, one at high temperature and the other at low temperature. Fluid from the low-temperature tank flows through the receiver and gets heated to a high temperature [Figure 1.7]. Thereafter the hot fluid flows to the high-temperature tank for storage. Fluid from the high-temperature tank flows through a heat exchanger. In the heat exchanger the fluid loses heat to generates steam which is further used for electricity production. The cold fluid exits the heat exchanger and returns to the low-temperature tank to continue the cycle.

Concentrating solar power (CSP) projects that use parabolic trough systems such as Archimede, ASE Demo Plant, Chabei, Gansu Akesai, Solar Electric Generating Station I (SEGS I) use active two-tank direct thermal energy system [see Table 1.1]. Dacheng Dunhuang Molten Salt Fresnel project used two-tank direct storage with a storage capacity of 13 hours and Molten Salt as the heat transfer fluid. Such storage systems have attracted a great deal of attention from power tower receiver concept. Power tower projects such as Atacama-1, Aurora Solar Energy Project, Copiapó, Crescent Dunes Solar Energy Project (Tonopah) implement two-tank direct storage system. Currently, 20% of the commercial plants use two-tank direct TES system for energy storage, and the summary of all plants is listed in Tables 1.1, 1.2 and 1.3.

1.3.1.1.1 Active Two-Tank Indirect

In two-tank indirect systems, different fluids are used as the HTF and storage material. In cases when HTF is expensive or HTF is not well suited to be used as storage materials, such a system can be implemented. The storage material from the low-temperature storage tank flows through an extra heat exchanger. The fluid is heated by the high-temperature HTF in the

Table 1.1 CSP projects with parabolic trough receiver concepts integrated with thermal energy storage systems (data collected from NREL).

Parabolic trough CSP projects	Thermal energy storage (TES)	Thermal energy storage capacity	Storage description and material
Airlight Energy Ait-Baha Pilot Plant	Packed bed	5 hour(s)	Packed-bed of rocks
Andasol-1 (AS-1)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Andasol-2 (AS-2)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Andasol-3 (AS-3)	2-tank indirect	7.5 hours	Molten salts
Archimede	2-tank direct	8 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Arcosol 50 (Valle 1)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Arenales	2-tank indirect	7 hours	Molten salt 60% sodium nitrate and 40% potassium nitrate.
ASE Demo Plant	2-tank direct	4.27 MWh-t	Molten salt
Ashalim (Negev)	2-tank indirect	4.5 hours	Molten salts

(*Continued*)

Table 1.1 CSP projects with parabolic trough receiver concepts integrated with thermal energy storage systems (data collected from NREL). (*Continued*)

Parabolic trough CSP projects	Thermal energy storage (TES)	Thermal energy storage capacity	Storage description and material
Aste 1A	2-tank indirect	8 Hours	Molten salts 60% sodium nitrate and 40% potassium nitrate
Aste 1B	2-tank indirect	8 Hours	Molten salts 60% sodium nitrate and 40% potassium nitrate
Astexol II	2-tank indirect	8 Hours	Molten salt 60% sodium nitrate and 40% potassium nitrate
Bokpoort	2-tank indirect	9.3 hours	Molten salt
Casablanca	2-tank indirect	7.5 hours	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Chabei 64MW Molten Salt Parabolic Trough project	2-tank direct	16 hours	Molten salt
Delingha 50MW Thermal Oil Parabolic Trough project	2-tank indirect	9 hours	Molten salt
DEWA CSP Trough Project	2-tank indirect	15 hours	Molten salt

(*Continued*)

Table 1.1 CSP projects with parabolic trough receiver concepts integrated with thermal energy storage systems (data collected from NREL). (*Continued*)

Parabolic trough CSP projects	Thermal energy storage (TES)	Thermal energy storage capacity	Storage description and material
Diwakar	2-tank indirect	4 hours	Molten Salt
Extresol-1 (EX-1)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Extresol-2 (EX-2)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Extresol-3 (EX-3)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Gansu Akesai 50MW Molten Salt Trough project	2-tank direct	15 hours	Molten salt
Gujarat Solar One	2-tank indirect	9 hours	Molten salt
Gulang 100MW Thermal Oil Parabolic Trough project	2-tank indirect	7 hours	Molten salt
Ilanga I	2-tank indirect	5 hours	Molten salt
Kathu Solar Park	2-tank indirect	4.5 hours	Molten salt
KaXu Solar One	2-tank indirect	2.5 hours	Molten salts
KVK Energy Solar Project	2-tank indirect	4 hours	Molten salt

(*Continued*)

Table 1.1 CSP projects with parabolic trough receiver concepts integrated with thermal energy storage systems (data collected from NREL). (*Continued*)

Parabolic trough CSP projects	Thermal energy storage (TES)	Thermal energy storage capacity	Storage description and material
La Africana	2-tank indirect	7.5 hours	Molten salt 60% sodium nitrate and 40% potassium nitrate.
La Dehesa	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
La Florida	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Manchasol-1 (MS-1)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Manchasol-2 (MS-2)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
NOOR I	2-tank indirect	3 hours	Molten salt
NOOR II	2-tank indirect	7 hours	Molten salt
Rayspower Yumen 50MW Thermal Oil Trough project	2-tank indirect	7 hours	Molten salt

(*Continued*)

Table 1.1 CSP projects with parabolic trough receiver concepts integrated with thermal energy storage systems (data collected from NREL). (*Continued*)

Parabolic trough CSP projects	Thermal energy storage (TES)	Thermal energy storage capacity	Storage description and material
Shagaya CSP Project	2-tank indirect	9 hours	Molten salt
Solana Generating Station (Solana)	2-tank indirect	6 hours	Molten salt
Solar Electric Generating Station I (SEGS I)	2-tank direct	3 hour(s)	Molten salt
Termesol 50 (Valle 2)	2-tank indirect	7.5 hour(s)	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Termosol 1	2-tank indirect	9 hours	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Termosol 2	2-tank indirect	9 hours	Molten salt 60% sodium nitrate and 40% potassium nitrate.
Urat Royal Tech 100MW Thermal Oil Parabolic Trough project	2-tank indirect	10 hours	Molten Salt
Xina Solar One	2-tank indirect	5 hours	Molten salt
Yumen 50MW Thermal Oil Trough CSP project	2-tank indirect	7 hours	Molten salt

Table 1.2 CSP projects with linear Fresnel receiver concepts integrated with thermal energy storage systems (Data collected from NREL).

Linear fresnel CSP projects	Thermal energy storage (TES)	Thermal energy storage capacity	Storage description and material
Dacheng Dunhuang 50MW Molten Salt Fresnel project	2-tank direct	13 hours	Molten salt
eCare Solar Thermal Project	Other	2 hours	Steam drum
eLLO Solar Thermal Project (Llo)	Other	4 hours	Steam drum
IRESEN 1 MWe CSP-ORC pilot project	Other	20 minutes	Buffer
Puerto Errado 2 Thermosolar Power Plant (PE2)	Single-tank thermocline	0.5 Hours	Ruth's tank
Urat 50MW Fresnel CSP project	2-tank indirect	6 hours	Molten salt
Zhangbei 50MW DSG Fresnel CSP project	Other	14 hours	Solid state formulated concrete
Zhangjiakou 50MW CSG Fresnel project	Other	14 hours	Solid state formulated concrete

Table 1.3 CSP projects with central receiver (power tower) concepts integrated with thermal energy storage systems.

Power tower CSP projects	Thermal energy storage (TES)	Thermal energy storage capacity	Storage description and material
Atacama-1	2-tank direct	17.5 hours	Molten salt
Aurora Solar Energy Project	2-tank direct	8 hours	Molten salt
Copiapó	2-tank direct	14 hours	Molten salt
Crescent Dunes Solar Energy Project (Tonopah)	2-tank direct	10 hours	Molten salt
Dahan Power Plant	Other	1 hour	Saturated steam/oil
DEWA CSP Tower Project	2-tank direct	15 hours	Molten salt
Gemasolar Thermosolar Plant (Gemasolar)	2-tank direct	15 hour(s)	Molten salt
Golden Tower 100MW Molten Salt project	2-tank direct	8 hours	Molten salt
Golmud	2-tank direct	15 hours	Molten salt
Greenway CSP Mersin Tower Plant	Other	4 MW/h	Molten salt
Hami 50 MW CSP Project	2-tank direct	8 hours	Molten salt

(*Continued*)

Table 1.3 CSP projects with central receiver (power tower) concepts integrated with thermal energy storage systems. (*Continued*)

Power tower CSP projects	**Thermal energy storage (TES)**	**Thermal energy storage capacity**	**Storage description and material**
Huanghe Qinghai Delingha 135 MW DSG Tower CSP Project	2-tank indirect	3.7 hours	Molten salt
Jemalong Solar Thermal Station	2-tank direct	3 hours	Liquid sodium
Jülich Solar Tower	Other	1.5 hours	Ceramic heat sink
Khi Solar One	Other	2 hours	Saturated steam
Likana Solar Energy Project	2-tank direct	13 hours	Molten salt
MINOS	2-tank indirect	5 hours	Molten salt 60% sodium nitrate and 40% potassium nitrate
NOOR III	2-tank direct	7 hours	Molten salt
Qinghai Gonghe 50 MW CSP Plant	2-tank direct	6 hours	Molten salt
Redstone Solar Thermal Power Plant	2-tank direct	12 hours	Molten salt
Shangyi 50MW DSG Tower CSP project	2-tank indirect	4 hours	Molten salt

(*Continued*)

Table 1.3 CSP projects with central receiver (power tower) concepts integrated with thermal energy storage systems. (*Continued*)

Power tower CSP projects	**Thermal energy storage (TES)**	**Thermal energy storage capacity**	**Storage description and material**
Shouhang Dunhuang 10 MW Phase I	2-tank direct	15 hours	Molten salt
Shouhang Dunhuang 100 MW Phase II	2-tank direct	11 hours	Molten salt
SUPCON Delingha 10 MW Tower	2-tank direct	2 hours	Molten salt
SUPCON Delingha 50 MW Tower	2-tank direct	7 hours	Molten salt
Tamarugal Solar Energy Project	2-tank direct	13 hours	Molten salt
Yumen 100MW Molten Salt Tower CSP project	2-tank direct	10 hours	Molten salt
Yumen 50MW Molten Salt Tower CSP project	2-tank direct	6 hours	Molten salt

heat exchanger. The high-temperature storage material then returns back to the high-temperature storage tank. The HTF exits the heat exchanger at a low temperature returning to the receiver system to absorb heat again to continue the cycle. As observed in a two-tank direct system, storage material from the high-temperature tank is further used to generate steam. In contrast to the direct system, an extra heat exchanger is needed in an indirect system, making this system costlier.

Gujarat Solar One (Technology Parabolic Trough), a commercial plant developed by Cargo Solar Power, operates at a temperature range of 293°C-393°C and 9 hours storage capacity involving molten salt. Extresol-1, a commercial plant in Spain, developed by ACS/Cobra Group, uses storage system of capacity 7.5 hour(s). The storage material is a combination of various materials with 60% sodium nitrate and 40% potassium nitrate. Similarly, a large number of concentrating solar power (CSP) projects with all receiver concepts (except for dish system) use an active two-tank indirect storage system. The summary is listed in Tables 1.1, 1.2 and 1.3.

1.3.2 Active Single-Tank Thermocline

In a thermocline system, a single tank is used where warm fluid is above colder fluid. These kinds of systems are less expensive than two-tank systems [Figure 1.8]. The heat loss is more in such systems as the hot and cold

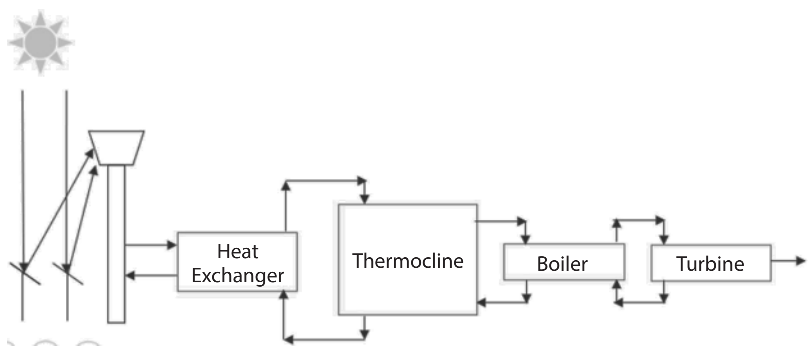

Figure 1.8 Active single tank thermocline thermal energy storage.

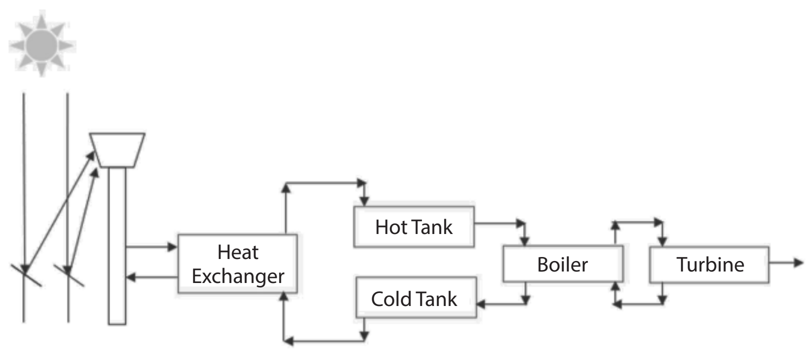

Figure 1.9 Active two-tank indirect thermal energy storage.

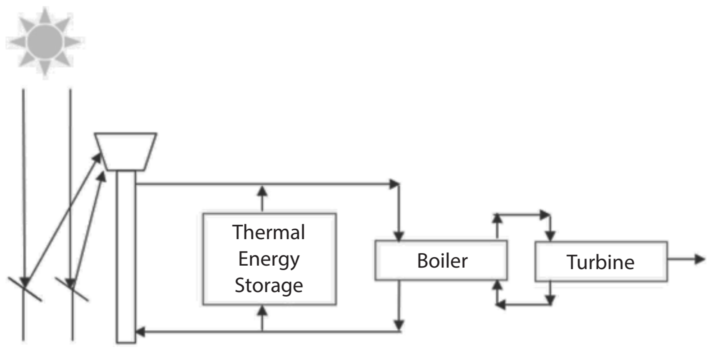

Figure 1.10 Passive thermal energy storage.

fluids are in direct contact. The hot and cold temperature regions are separated by a temperature gradient resulting in a thermocline. The density difference in the fluid thermally stratify the fluid in the tank. Buoyancy effects create thermal stratification of the fluid within the tank, which helps to stabilize and maintain the thermocline. Van Lew *et al.* (2011), Bayón and Rojas (2014), and Biencinto *et al.* (2014) carried out theoretical and experimental work on thermocline energy storage system for CSP plants.

High-temperature HTF flows into the top of the thermocline and leaves the bottom at low temperature. The thermocline moves downward and adds thermal energy to the system for storage. The thermocline moves upward and removes thermal energy from the system to generate steam and electricity if the flow is reversed. Puerto Errado 2 Thermosolar [see Table 1.2] operated by Novatec Solar España uses linear Fresnel reflector system currently operational in Calasparra, Spain, and has implemented a single-tank thermocline thermal energy storage system. This plant is operated at a temperature range of 140°C-270°C. Other plants also use this type of thermal systems and are listed in Tables 1.1, 1.2 and 1.3. Active two tank indirect thermal energy storage is also given in Figure 1.9 and passive type thermal energy storage in built with solar tower technology is given in Figure 1.10.

1.3.3 Other TES Systems

1.3.3.1 Packed-Bed Storage System

Other types of thermal energy storage system include packed-bed and passive system. Only power plants use a packed-bed system as the storage method is Airlight Energy Ait-Baha Pilot Plant. This plant uses Parabolic Trough Technology at temperature range of 270°C-570°C with 5 hours storage capacity.

1.3.3.2 Passive Thermal Storage System

In the passive type TES systems, thermal storage material is fixed and it does not flow, which is in contrast to the active system. The thermal storage material is used only to store thermal energy which can be transferred to and from the heat transfer fluid via thermal charging and discharging. A passive-type thermal storage system can be a solid material (example: concrete), fluid (example: water) or phase change material (example: PCM). In such systems, the heat transfer fluid transfer energy to the thermal storage material where the material stores energy which can be further transferred to the heat transfer fluid. Such systems have not been integrated in solar thermal power plants till date. The works on passive thermal energy storage system are on the laboratory and fundamental level. A good number of research works can be found in literature on the passive thermal energy storage system.

1.3.4 Types of Thermal Energy Storage (TES)

There are three types of TES mechanisms that can be applied to CSP and other applications: sensible energy storage, latent energy storage and thermochemical energy storage. An overview of these technical concepts and their states of development are presented below.

1.3.4.1 Sensible Energy Storage

The sensible thermal storage system stores thermal energy with increases in the temperature of the TES material. The principle of the sensible thermal storage system is simple and it has been widely applied in CSP as well as other applications. The TES material undergoes temperature change during energy storage and release. The physical and chemical changes of storage material is not observed. Sensible thermal energy storage method is simple and inexpensive. One of the disadvantages of sensible thermal energy storage material is low thermal conductivity. This results in lesser energy storage and release capacity. Also, the sensible heat transfer materials have low energy storage density. This further leads to large sizes of the storage devices.

The amount of energy stored in the material (Q) can be calculated as

$$Q = mC_p\Delta T$$

Where m is the mass of the material, C_p is the specific heat of the material at constant pressure and ΔT is the temperature difference.

Common sensible storage materials include water, steam, synthetic oil, molten salt, gravel, etc. [see Table 1.4]. As seen from Tables 1.1, 1.2 and 1.3, molten salt is widely used for sensible energy storage. Sensible thermal storage systems are mainly seen for low-temperature applications.

Research on sensible thermal storage is comparatively mature and has been developed to a commercially exploitative level. As the density of sensible thermal storage is low, sensible thermal devices typically have certain limitations due to their large sizes. Lucentini (2014) presented thermal storage of sensible heat using concrete modules in solar power plants. Tiskatine *et al.* (2017) carried out a detailed study on suitability and characteristics of rocks for sensible heat storage in CSP plants. For high-temperature sensible energy storage for CSP systems, the selection and analysis are done by Khare *et al.* (2013).

Table 1.4 Typical materials used in sensible heat TES storage (Mehling and Cabeza, 2008; Navarro *et al.*, 2012).

Material	Density (kg/m^3)	Specific heat at constant pressure (J/kg K)
Clay	1,458	879
Brick	1,800	837
Sandstone	2,200	712
Wood	700	2,390
Concrete	2,000	880
Glass	2,710	837
Aluminium	2,710	896
Iron	7,900	452
Steel	7,840	465
Gravelly earth	2,050	1,840
Magnetite	5,177	752
Water	988	4,182

1.3.4.2 Latent Heat Storage

Latent heat storage systems including phase change-based systems have attracted more attention in fundamental research as well as in industrial applications. During latent thermal storage, the storage material is heated until it changes phase at constant temperature conditions. Latent heat energy storage allows efficient storage of thermal energy by minimizing the entropy generation in isothermal processes like evaporation or condensation. Latent heat storage systems employ the enthalpy change of a substance passing through a phase change. In CSP technology the development of absorbers directly generating steam have sparked interest in latent heat storage systems.

Latent energy storage systems have high energy density resulting in easily structured, small and flexible designs. The material that is used for latent heat storage systems is called Phase change material (PCM). Latent heat can be absorbed (charging) as well as can be released (discharging) through phase change of the PCM. The amount of latent heat stored in the material (Q) can be calculated as follows:

$$Q = m\Delta h$$

Here m is the mass of the material and Δh is the enthalpy of phase change.

Even though there are many advantages of latent heat storage system compared to sensible heat storage system, the major disadvantages of PCM are incongruent phase change, high cost, corrosiveness and less thermal stability. As a result, such materials are still in the research stage and it has not been used by industry for CSP-TES applications. There are many materials that can be used as latent heat storage materials and a list with a few important properties is presented in Table 1.5.

Raul *et al.* (2018) studied modelling and experimental study of latent heat TES with encapsulated Phase change materials for CSP applications. Soares *et al.* (2013) reviewed passive PCM latent heat TES systems. Agyenim *et al.* (2010) reviewed materials, heat transfer and phase change issues for latent heat TES systems. Rathod and Barnerjee (2013) carried out a comprehensive study on thermal stability of PCM used in latent heat TES systems. Further, Cárdenas and León (2013) studied design considerations and performance enhancement procedures for high-temperature latent heat TES systems.

Table 1.5 Typical materials used in latent heat TES systems (Mehling and Cabeza, 2008; Navarro *et al.*, 2012).

Material	Melting temperature (°C)	Melting enthalpy (MJ/m³)
Water-salt solutions	−100–0	200–300
Water	0	330
Clathrates	−50–0	200–300
Paraffins	−20–100	150–250
Salt hydrates	−20–80	200–600
Sugar alcohols	20–450	200–450
Nitrates	120–300	200–700
Hydroxides	150–400	500–700
Chlorides	350–750	550–800
Carbonates	400–800	600–1,000
Fluorides	700–900	> 1,000

1.3.4.3 Thermochemical Energy Storage

Although chemical reaction thermal storage has multiple advantages, the chemical reaction process is complex. It sometimes requires catalysers and has certain safety requirements, and there are other difficulties such as a huge one-time investment and low overall efficiency. Thus, it currently remains in the small-scale experimental stage with plenty of problems yet to be solved before any large-scale application.

The theoretical option to store energy at higher densities compared to latent heat or sensible heat storage concepts and the advantage of storing the reactants at ambient temperature make thermochemical storage systems a promising solution for longer term energy storage. On the other hand, thermochemical storage systems show a higher complexity than concepts for sensible heat storage or latent heat storage. The long-term reversibility of the reactions is an important issue. Currently, these systems are at an earlier stage of development, and there have been no commercial applications so far.

1.4 Corrosion Problem in TES-CSP System

The use of TES provides round the electricity generation. However, as seen from the literature, most of the CSP plants use TES involving molten salts at high temperatures. Such materials are highly corrosive which can damage the components of CSP. It is impossible to prevent corrosion in molten salts altogether. The effect of corrosion may be reduced by using protective coating or corrosion resistant material. To use proper and effective coating, the material must have good adhesion properties with the structural material. The coating should be uniform and less porous (Liu *et al.*, 2014). Another way to supress the effect of corrosion is by application of a cathodic potential (Schwandt and Fray, 2014). Failure due to corrosion is a major issue and such risk of failure of TES system must always be taken into account. Such cost is a function of the costs of HTF and of materials used (Liu *et al.*, 2016).

1.5 Conclusion

Integration of TES in CSP plants is important for improving environmental issues as well as alleviating the global energy crisis. This chapter provides a comprehensive discussion on the integration of Thermal Energy Storage systems (TES) in Concentrating Solar Power plants (CSP) plants worldwide. Different TES technologies and their implementation in commercial-level CSP plants are discussed. It was observed from the discussion that CSP technology is already developed for commercialization. A good number of well-established CSP plants are producing electricity worldwide, led by Spain and the United States. In addition, a good number of commercial CSP plants are under construction or in the project state hinting towards a development of the renewable energy sector in the future.

The integration of TES into CSP plants is one of the major design changes that results in significant benefits including uninterrupted electricity production even during a day without the sun radiation or nighttime. Such systems will make the CSP plant more sustainable as well as more economically competitive and dispatchable. Even though a good number of CSP plants have been using TES, fast progress is needed in the TES technologies. As observed from the current state of the art, a large number of CSP plants implement sensible thermal energy storage systems. This is due to the reliability, low cost and large data owing to sensible energy storage. However, based on the disadvantages like low energy storage density, new ways like latent and thermochemical energy storage systems may be considered for future CSP plants. Latent and thermochemical energy storage systems have larger energy storage density which might lead to a bright future for CSP-TES technology. However, more research efforts are needed to overcome the disadvantages of latent and thermochemical energy storage systems.

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