Review on Sensible Thermal Energy Storage for Industrial Solar Applications and Sustainability Aspects

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Abstract

Industry is one of the leading energy consumers with a global share of 37%. Fossil fuels are used to meet more then 80% of this demand. The sun's heat can be exploited in most industrial processes to replace fossil fuels. Integration of a thermal energy storage system is a requisite for sustainability in solar heat for industries. Currently there are only 741 solar heat industrial plants operating with an overall collector area of 662,648 m² (567 MW_{th}) that cover very small share of total global capacity. This is only the tip of the iceberg- there is a huge potential that is eager to be exploited. The challenges of increasing cost-effective solar heat applications are development of thermal energy storage systems and materials that can deliver this energy at feasible economic value. Sensible thermal energy storage, which is the oldest and most developed, has recently gained interest due to demand for increased sustainability in energy use.

This paper attempts to review these latest trends in sensible thermal energy storage systems and materials that are used in solar industrial applications with a special focus on sustainability. The aim is to provide information for further research and development that shall make solar heat a cost-effective method to meet the increasing energy demand of the industrial sector.

Keywords: Sensible thermal energy storage, sensible thermal energy storage materials, solar industrial applications

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1.Introduction

Energy has always played a major role in the processing of resources to meet human needs. Global total energy consumption is increasing rapidly with the rise in consumption trends of society. Economies are growing with more industrialization. The Earth's energy consumption has doubled in the last 40 years. Industries consumed 37 % of the total final energy consumption that was 9.6 Gtoe in 2016 (IEA, 2018a). Current energy systems are generally based on burning fossil fuels, which are non-renewable, distributed around the world and critically unsustainable (Salunkhe and Krishna, 2017) to deliver. Most of the carbon emissions that cause global warming threatening future of the world are produced from burning fossil fuels. CO_2 emissions from fuel combustion were 32.3 Gt in 2016. Industrial sector is responsible for 19% of these CO_2 emissions (IEA, 2018a, 2018b).

The long-term goal of the Paris Aggreement is "keeping the rise in global mean temperature to "well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above preindustrial levels." (UNFCCC, 2015). According to the agreement signed with the participation of 130 countries, existing high levels of CO_2 emisions are the main cause of global warming (Gibb et al., 2018). These ambitious goals can only be met by ubiquitous use of renewable energy resources everywhere around the world. The share of renewables in world energy supply is constantly increasing, but remains at only 4.2% (IEA, 2018a, 2018b, 2018c).

Solar energy is an abundant source that generates about 1575 to 49,837 EJ per year (Alva et al., 2018). It is the ultimate source of all the other energy sources including other renewables and fossil fuels on Earth. Geothermal energy from the magma of the Earth is not produced by the sun. The solar energy falling on Earth is much more than our total global energy supply of 13800 Mtoe. The sun is an unlimited and clean source that shall provide energy efficient solutions that reduce CO_2 emissions (Atkins et al., 2010). According to United Nation's Environment Program (UNEP) 2015 report, depending on the location, a 1.4 MWth (2000 m²) solar system could each generate a saving of around 175 metric tons of CO_2 emission (UNEP, 2015).

Integration of solar energy in industrial processes is one effective solution to reduce fuel cost and CO_2 emissions and improve market competitiveness. Today, solar thermal applications are mainly used in buildings. According to IEA Solar Heat Worldwide 2019 report, there are only 741 industrial plants using solar heat with an overall collector area of 662,648 m² (567 MW_{th}) (IEA, 2019). Most of the industrial processes require continuous energy flow for 24 hours, 365 days a year. This cannot be met continuously with solar energy. Although solar thermal applications are limited in industries, their technology readiness levels (TRL) for other applications are high (Farjana et al., 2018a; Jia et al., 2018; Kylili et al., 2018). Energy from the sun can be better utilized during daytime in sunny days. The excess solar energy from day-time or summer needs to be stored for use during nights or winter (Boda et al., 2017).

Thermal energy storage (TES) methods offer flexible solutions that render solar energy systems sustainable and further reduce CO_2 emissions (Cabeza et al., 2015; Paksoy, 2007). We cannot stop the earth's rotation, so TES is the key candidate for solving this problem of intermittent energy supply from the sun.

Integrating TES into existing heating and cooling systems shall produce significant savings and increase energy efficiency. TES uses the internal energy of materials to store sensible, latent and thermo-chemical heat (Romaní et al., 2019; Xu and Wang, 2019). In sensible heat storage method, thermal energy due to temperature change in the storage material is utilized. In latent heat storage method, energy is stored during the phase transition process of the materials, so called Phase Change Materials (PCM). Thermochemical storage method uses reversible chemical reactions and physical sorption processes to store heat (Liu et al., 2016; Tao and He, 2018). Usage period, cost, temperature range, storage capacity, availability of storage material, heat loss rates and installation area are key criteria to select suitable storage method (Almendros-Ibáñez et al., 2018; Li, 2016; Romaní et al., 2019; Socaciu, 2011).

Thermal energy storage can also be classified according to the "usage period" as short-term storage (day/night) and seasonal storage (summer/winter). According to temperature range, it can be heat storage, cold storage or both heat and cold storage. Seasonal TES systems store heat in summer to be used in winter, or to store cold in winter and to meet cooling demand in summer. Short-term storage systems provide heat daily for cloudy periods or nighttime or sometimes for shorter durations of time (Stutz et al., 2017).

Solar energy can be utilized in many industrial processes, especially in low temperature applications. Here, variability of sunlight is the main barrier for continuous process (EESI, 2011). Solar energy systems are not efficient during nights- unless near the poles- or cloudy days without the use of TES technologies (Alonso et al., 2016). If solar energy is not used with a proper storage technology, it cannot meet the expected energy demands. This requires consumption of non-renewables by back-up systems with high environmental burden and additional energy costs (Lauterbach et al., 2012).

In recent years, the number of solar heat applications in industry has increased due to new advances in TES systems. There are several studies that review TES for solar thermal power plants or concentrated solar power (CSP). Only few studies are dedicated to industrial processes (IP) as shown in Table 1.

Table 1. Recent review articles on solar heat TES for CSP and industrial process (IP) applications

Solar heat application	TES method	Temperature range (°C)	Reference
CSP	Latent heat	Up to 1000	(Xu et al., 2015)
CSP	Thermochemical heat	400-1200	(Andre et al., 2016)
CSP	Latent Heat	NA	(Mao, 2016)
CSP	Sensible and Latent Heat	Above 250	(Liu et al., 2016)
CSP	Thermochemical heat	Up to 1500	(Prieto et al., 2016a)
CSP	Thermochemical heat	200-1000	(Pelay et al., 2017)
CSP	Sensible heat	150-600	(Roubaud et al., 2017)
CSP	All	Up to 1100	(Almendros-Ibanez et al., 2018)
IP	Latent heat	140-400	(Crespo et al., 2019)
CSP	Sensible heat	Above 600	(Mohan et al., 2019)
IP	All	20 - 260	(Kumar et al., 2019)
CSP	Thermochemical heat	Above 300	(Prasad et al., 2019)

There is an urgent need to adopt low carbon technologies in industrial energy systems. This mandates using cost-effective and sustainable TES systems in solar heat industrial applications. Sensible TES (STES) system in packed-beds (TRL: 8-9) is the simplest and economically viable way to store heat for industrial applications compared with latent TES (TRL: 5-9) and thermochemical TES (TRL <4) (Palacios et al., 2020). Also, STES is the most economic heat storage system for high temperature industrial applications due to low cost and abundant storage materials such as rock, bricks, sand, soil, industrial or municipal wastes etc. (Becattini et al., 2017; Khare et al., 2013; Koçak and Paksoy, 2019a). Latent heat, and thermochemical with higher storage capacities than sensible heat is not yet cost-effective to be applicable for secure uninterrupted supply of solar heat in the industrial scale.

There is renewed interest in sensible heat storage for industrial applications with new concepts, materials and systems. This paper focuses on reviewing sensible TES for industrial solar heat applications for all temperature ranges. The objective is to demostrate the potential, sustainability and future trends in TES for industrial solar applications. In the light of this review study, industries can get extensive information on the current situation and be motivated to implement solar heat with low cost and high efficient sensible TES systems. Expected benefits are increasing share of the solar energy use in industrial processes instead of fossil fuels, avoiding environmental problems, meeting obligatory climate change targets and increasing global competitiveness.

2.Potential Industrial Processes

Energy is used in the industrial sector for a wide range of activities, such as processing and assembly, process heating and cooling, space conditioning, and lighting (Oyelaran et al., 2016; Ramos et al., 2014). Process heat with a share of 74% is leading in total industrial heat demand. Currently, only 9% of industrial process heat demand is supplied from renewable energy sources (IEA, 2017a). Industrial processes must be well defined to qualify for effective solar heat applications.

2.1 Classification

The global industrial sectors can be classified according to their energy consumption shares as energy-intensive manufacturing, nonenergy-intensive manufacturing, and nonmanufacturing as shown in Table 2 (EIA, 2016). Nonenergy-intensive sectors, such as pharmaceuticals, paint, and adhesives are the most energy consuming ones (Ding et al., 2017; EIA, 2016). Bulk chemical is the highest energy consumer sector with a share of 28% of total energy consumption. Refining sector (18%) and mining sector (11%) follow bulk chemical sector (IEA, 2017b). According to Baniassadi et al (Baniassadi et al., 2015), approximately 30% of the energy consumed by the industry is used in food, chemical and petrochemical industries. The most energy intensive industrial processes are sterilization, washing, cleaning, drying, distillation, evaporation, hydrolysis, pasteurization and polymerisation (Kalogirou, 2003).

Table 2. World industrial sector: industry types, major industry groups and energy consumption (EIA, 2016).

Industry Types	Industry Grouping	Energy Share
Energy-Intensive Manufacturing	Food, pulp and paper, basic chemicals, refining, iron and steel, nonferrous metals, nonmetallic minerals	27%
Nonenergy-Intensive Manufacturing	Pharmaceuticals, paint and coatings, adhesives, detergents, electrical and electronic industry	39%
Non-manufacturing	Agriculture, forestry, fishing, mining, construction	34%

2.2 Process Temperatures

Industrial processes can be categorized in three groups according to process temperature range: low temperature (below 150 ºC), medium temperature (150 ºC - 400 ºC) and high temperature (above 400 ºC) (IEA, 2017a). Nearly half of industrial process heat demand is caused by energy intensive manufacturing sectors with high temperature industrial processes (Baniassadi et al., 2015; EIA, 2016; IEA 2017a, 2017b; Zanganeh, 2014).

Although high temperature processes are the most energy consuming ones, solar heat applications are not widely available at these temperature levels. For low temperature, solar heat applications may be more competitive compared to fossil fuels. Solar heat is generally preferred in industrial processes up to 100ºC with flat-plate collectors. In recent years, solar heat started to be used in processes up to 160 ºC with high-vacuum collector technologies. Linear concentrating or solar tower technologies that can exceed 400ºC are generally used in power sectors. Medium to high temperature industrial solar applications are still under development (IEA, 2017a).

Industrial processes in different sectors with operational temperature ranges shown in Table 3 are reported as the most suitable for solar heat applications (IRENA, 2015). The processes include preheating of raw materials, supply of hot water (Schmitt, 2016), bleaching, drying, dyeing, pressing, washing and boiling in textiles (EESI, 2011; IRENA, 2015; Lauterbach et al., 2012; Sharma et al., 2017a), bleaching, cleaning, cooking, evaporating, pasteurisation and sterilisation in food and beverages (IRENA, 2015; Lauterbach et al., 2012; Sharma et al., 2017b), drying, pressing, cooking, de-inking and bleaching in paper (EESI, 2011; Lauterbach et al., 2012; Mahadevan and Nallusamy, 2014), biochemical reactions, distillations, compressions, cooking and thickening in chemistry (Lauterbach et al., 2012), compression, drying and pickling in wood (Lauterbach et al., 2012) and various such applications in many more industries. Solar energy use in industrial sectors and processes at operating temperatures higher than 250°C shown in Table 3 are currently very limited except for CSP.

Table 3. Industrial processes suitable for solar heat applications and operational temperature ranges (ESTIF, 2006; IRENA, 2015; Lillo et al., 2017; Pezzutto, 2018)

Industrial Sector	**Processes**	**Temperature Range, °C**
Food & Beverages	Drying	30-90
	Washing	60-90
	Pasteurising	60-80
	Boiling	95-105
	Sterilising	60-120
	Heat Treatment	40-60
Paper Industry	Cooking and Drying	60-80
	Boiler feed water	60-90
	Bleaching	130-150
Non-metallic Mineral Industry	Brick curing	60-140
	Lime burning	>500
	Extruding	200-500
	Foundry	500-1000
	Clinker calcination	500-1000
Textile Industry	Bleaching	60-100
	Dyeing	70-90
	Drying, De-greasing	100-130
	Washing	40-80
	Fixing	160-180
	Pressing	80-100
Chemical Industry	Soaps	200-260
	Synthetic rubber	150-200
	Processing heat	120-180
	Pre-heating water	60-90
	Distilling	110-300
	Industrial Furnaces	500-1000
Plastic Industry	Preparation	120-140
	Distillation	140-150
	Separation	200-220
	Extension	140-160
	Drying	180-200
	Blending	120-140
	Moulding	100-500
Mining	Drying	100-400
	Concentrate smelting	100-400
	Heating solutions	100-400
	Melting	100-400
	Industrial furnaces	>1000
Thermal Treatment	Medium Tempering	350-450
Iron and Steel	Sinter	500-1000
	Direct Reduction	500-1000
	Furnace	>1000
	Smelting Reduction	>1000
All Industrial Sectors	Pre-heating of boiler feed water	30-100
	Industrial solar cooling	55-180
	Heating of factory buildigns	30-80

Lauterbach et al. (2012) identified processes below 200°C as suitable for the integration of solar heat. 90% of the process temperatures for food and beverage industry are between 100-200°C and the rest are between 200-300°C. Considering that food industries belong to the energy-intensive group given in Table 2, the energy saving potential of solar heat use can be significant (Compton et al., 2018). Sharma et al. (2017b) analyzed milk-processing plants in India. Results showed that 70% of total energy use is for process heating between 50-200°C in these plants.

2.3 Technology Requirements

Availability of technologies on the supply (solar energy) and demand (industrial users) sides are important for efficient use of solar heat in industry. Baniassadi et al. (2018) investigated optimum design parameters of solar systems for efficient industrial applications (Figure 1). With suitable collector and heat storage technology, increasing the collector area, heat storage size can have a significant effect on the performance of solar industrial applications.

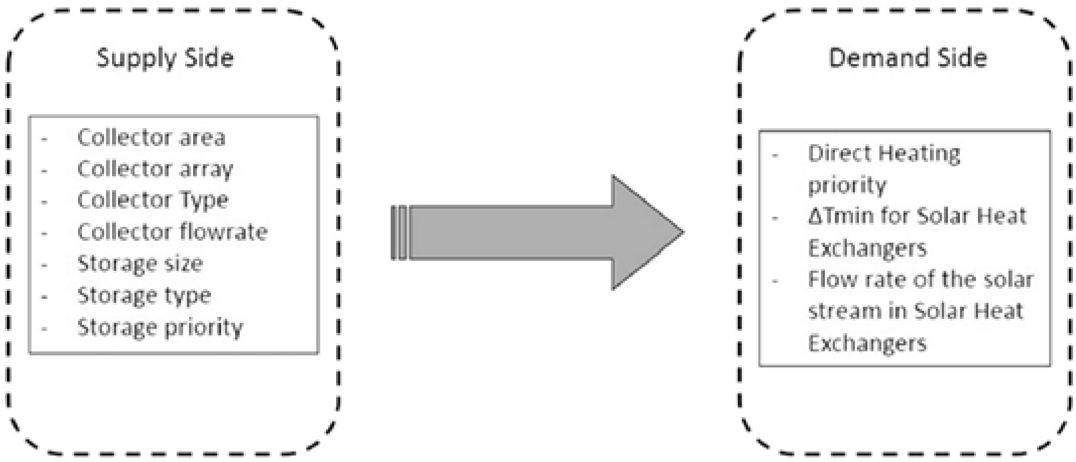


Figure 1. Requirement for industrial solar applications (Baniassadi et al., 2018)

Müller et al (Müller et al., 2014) determined solar-thermal requirements of brewery and dairy industries in Germany and concluded that availability of space for mounting solar collectors is crutial. This mainly depends on the roof design such as flat or saddleback. Selection of proper collector type according to the process temperature range is also an important parameter for industrial solar applications. Table 4 lists the solar collector types and their usable temperature ranges (Kalogirou, 2003). Flat plate collector (FPC) type is mainly used for low temperature industrial processes such as food, textile and dairy etc. On the other hand, parabolic trough collector (PTC) is mainly used for higher temperature industrial processes such as plastic, chemical etc. Stationary and single-axis tracking type collectors are the most prefarable collectors for industrial solar applications. (Kalogirou, 2003).

Table 4. Solar energy collectors (Kalogirou, 2003).

Motion	**Collector type**	**Absorber type**	**Concentration ratio***	**Indicative temperature range (°C)**
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50-200
	Compound parabolic collector (CPC)	Tubular	1–5	60-240
Single-axis tracking	Fresnel lens collector (FLC)	Tubular	10–40	60-250
	Parabolic trough collector (PTC)	Tubular	15–45	60-300
	Cylindrical trough collector (CTC)	Tubular	10–50	60-300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150-2000

* The receiver/absorber area of the collector

Process temperature range, collector types and size are the main factors to determine the cost. Figure 2 shows the relation between collector type, process temperature range, system capacity and installation cost (IEA, 2017a). As the process temperature range increases up to 400°C, installation cost increases because of needed concentrating solar technologies. But if collector size increases, installation cost decreases per unit kW energy.

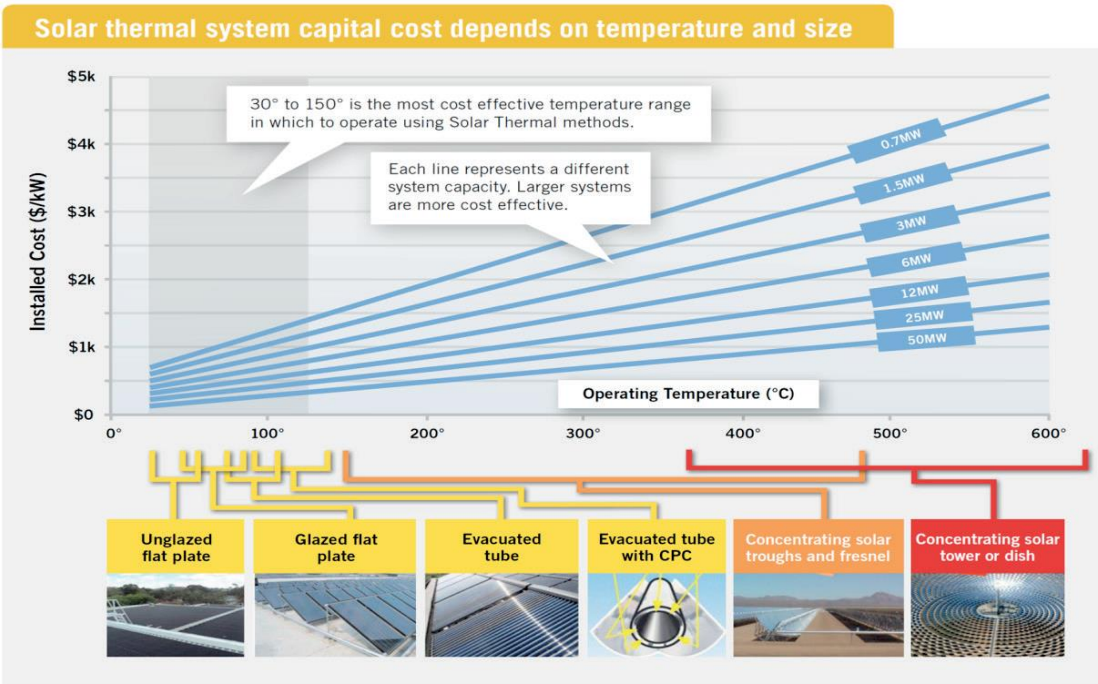


Figure 2. Relation between installation cost and process temperature range (IEA, 2017a).

3.Sensible Thermal Energy Storage

3.1. Theoretical Background

Sensible thermal energy storage is the simplest and maturest way to store heat (Becattini et al., 2017). Sensible energy is stored by changing temperature of sensible thermal energy storage materials (STESM) such as water, oil, rock beds, bricks, sand, or soil etc. Figure 3 shows the typical sensible heat storage diagram. There is no phase change during the temperature change of STESM (Alva et al., 2017). Stored sensible heat can be calculated using Eqn 1.

$$Q = m * C_p * \Delta T \qquad (1)$$

where m is the mass (kg) of STESM, C_p is the specific heat capacity ($kJ.kg^{-1}.K^{-1}$) of STESM, and ΔT (K) is temperature change in STESM.

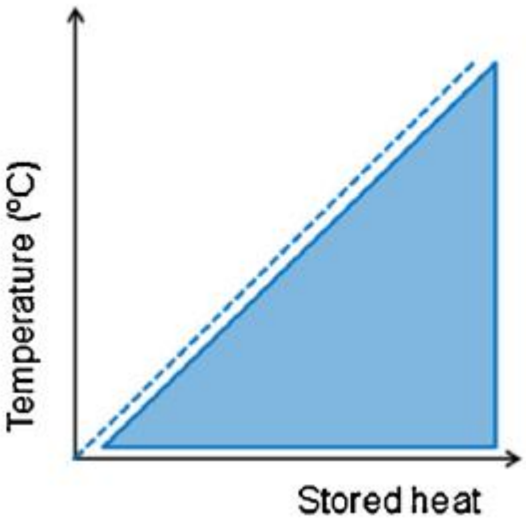


Figure 3. Temperature change of STESM during heat storage (Gracia and Cabeza, 2015)

The performance of a sensible heat storage system are evaluated according to González-Roubaud et al. (2017):

- Storage capacity [kWh or kJ]: energy stored in the system that depends on the storage process, the material and the size of the system;
- Power [kW]: energy stored per unit time that determines how fast the energy can be charged and discharged;
- Efficiency [%]: ratio of the energy delivered during discharge to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle;
- Charge and discharge time [h]: define how much time is needed to charge/discharge the system;
- Cost [$/kW or $/kWh]: refers to either capacity ($/kWh) or power ($/kW) of the storage system. The storage material, the heat exchanger for charging and discharging the system and the cost of the space and/or enclosure for the thermal energy storage are included.

3.2. Sensible Thermal Energy Storage Technologies

Sensible heat storage technologies can be classified as shown in Figure 4.

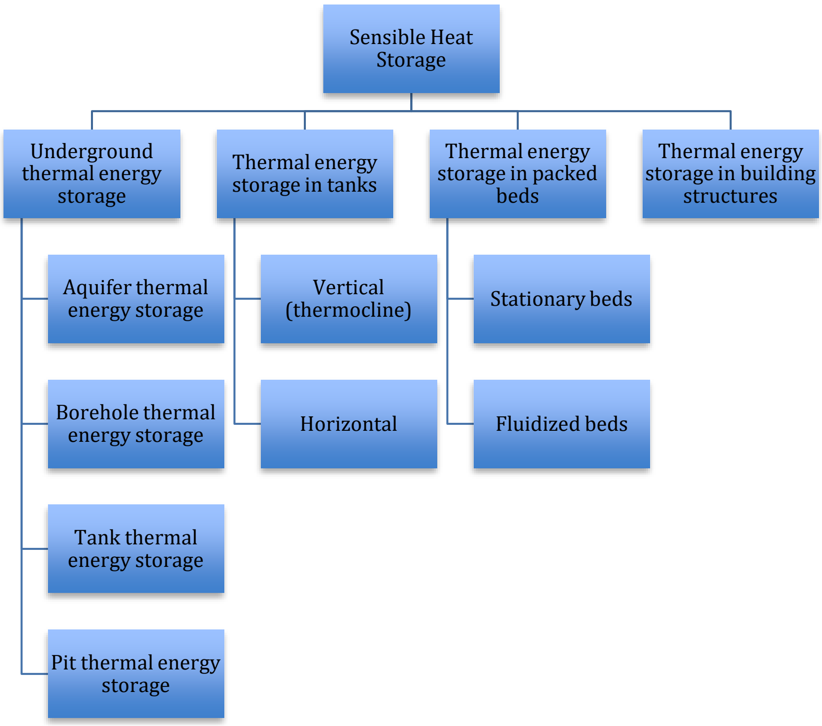


Figure 4. Classification of sensible heat storage technologies

There can be many feasible designs for a TES system and some are better than the others. Numerical modeling and experiments can be carried out to determine optimum parameters and the system performance of TES. Information on design and operation of STES Technologies can be found in the following sections.

3.2.1. Underground Thermal Energy Storage (UTES)

Underground soil and/or rock provide a large, invisible and isolated storage volume. The systems that make use of this environment are called "shallow geothermal". In deep geothermal higher temperatures available at greater depths due to natural geothermal heat originating from earth's magma is used. In contrast, shallow geothermal systems make use of the relatively low temperatures in the uppermost 100 m or more of the Earth´s crust. Near the surface, until about 10 m ground temperature is contolled by outside seasonal temperature changes, but below this depth it remains constant until around 100 m. This constant temperature is known as undisturbed temperature and this part of the ground is the so-called "neutral zone". The undisturbed ground temperature that varies between 2 - 20°C, depending on the climatic condition of the region is the basis of thermal energy storage in shallow geothermal systems (Sanner, 2005). Below the neutral zone, the temperature increase is governed by the geothermal heat flux values that typically vary between 40-120 mW m^{-2} (0.04-0.12 W/m^2) (Sanner, 2005).

UTES technologies use the heat capacity of the underground to store thermal energy from any natural or artificial source for seasonal or diurnal applications. Seasonal storage systems are very popular sensible TES systems due to high efficiency and low cost (IEA, 2018d). There are four main UTES systems shown in Figure 5 (Guo et al., 2017):

- Aquifer thermal energy storage (ATES)

- Borehole thermal energy storage (BTES)
- Pit thermal energy storage (PTES)
- Tank thermal energy storage (TTES)

UTES systems can store heat seasonally by using either water or water/gravel mixture. Although, they are generally preferred for low temperature applications (<40°C) (Zhang et al., 2016), they can be used applications above 40 °C (ECTP, 2019). Table 5 lists storage media and possible application temperature range for each UTES system.

Table 5. Underground thermal energy storage properties (ECTP, 2019).

UTES system	Storage Material	Possible Temperature Range
Aquifer thermal energy storage (ATES)	Aquifer formation	Up to well temperature
Borehole thermal energy storage (BTES)	Water-saturated formation or rock strata	Up to 80 °C
Pit thermal energy storage (PTES)	Water, water-Gravel mixture, water-soil mixture	Up to 85 °C
Tank thermal energy storage (TTES)	Water	Up to 95 °C

ATES systems employ large groundwater basins – aquifers – through wells that use groundwater as the medium of heat transfer between an external energy source such as solar energy and the aquifer. ATES has become an attractive seasonal technology due to the large saving of energy, with a small amount of driving energy producing a very large return. It can be used in heating and cooling applications for various buildings, business centers, shopping malls, hospitals, and industrial complexes etc. in a temperature range between 10-40°C (Gao et al., 2019; Lanahan and Tabares-Velasco, 2017). ATES can also be integrated in industrial plants such as plastics, paper, textiles, food and mining etc. (Dincer and Rosen, 2002). In a BTES system thermal energy is transferred to the underground by means of conductive flow from a number of closely spaced boreholes. Heat is stored underground by circulating heat transfer fluid such as water, glycol-water mixture in high-density polyethylene pipes used as ground heat exchangers, which can be vertical or horizontal (Kizilkan and Dincer, 2015). TTES and PTES systems use high volume underground pits or water tanks. In TTES, tank is buried completely in the underground. Different forms of underground cavities such as geological formations, abandoned mines, etc. can also be used in TTES. PTES use semi-buried man-made pits excavated in soil. In pit storage water is usually the storage material. There are also examples where gravel is used together with water to form a hybrid storage material. These systems are called gravel-pit storage. For TTES and PTES, heat is stored/discharged by pumping water to and from the storage tank. High investment cost of these systems is a drawback that limits the number of applications (Sarbu and Sebarchievici, 2018).

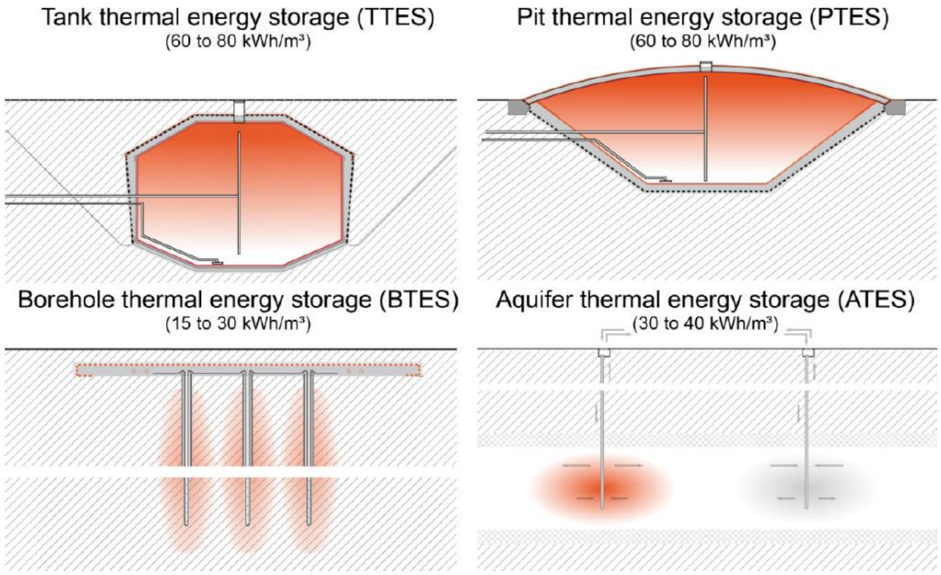


Figure 5. Seasonal thermal energy storage methods (IEA, 2015)

3.2.2. Water Tanks

Water tanks are the most well-known and widely used systems in sensible heat storage. Design of the tanks depends on the available heat/cold source and requirements of demand and availability of space. Tanks made of steel, stainless steel, concrete or plastic may be used. Different equipments such as heat exchangers, electric heaters, stratification enhancement structures can be installed in the tanks. Figure 6 shows different heat transport mechanisms used in water tanks, which are mostly used in solar applications for domestic hot water and/or space heating (Mangold and Deschaintre, 2016).

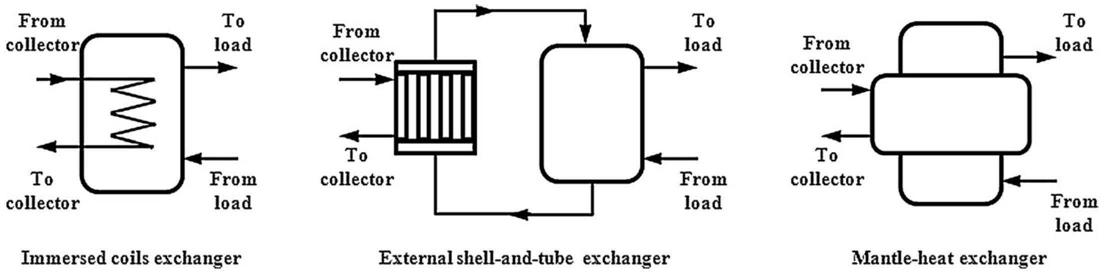


Figure 6. Common heat transport configurations for water tanks (Mangold and Deschaintre, 2016).

For the immersed coil heat exchangers, the best location is bottom of the tank where temperature difference between the fluid coming from the solar collector and the incoming water from the user is the greatest. With these designs, temperature tends to be uniform in the tank decreasing performance and cost- effectiveness of storage (Pinel et al., 2011). External heat exchangers can be more flexible for indirect systems and less expensive. In mantle heat exchangers, the heat transfer fluid from solar collectors or other sources circulates in the cavity between the two walls of the tank. The increased surface area enhances heat transfer rate. The special design of the tank increases cost (Haehnlein et al., 2010).

The tanks are insulated to retain thermal energy stored for long periods by minimizing heat losses. Better insulation will decrease the tank volume needed and minimize space requirement. However, care should be given to avoid thermal bridges that can enhance heat losses during installation of insulation.

Water density reduces with temperature, which causes hot water to rise upwards in a vertical tank and colder water will sink to the bottom. This effect known as stratification also as thermocline can be utilized for optimum performance of water tank thermal energy storage. Higher kinematic viscosity of water at higher temperatures enables water to move faster. Thermal conductivity also increases with temperature, which leads to faster stabilization of temperature differences in the tank.

Different stratification levels for vertical tanks are illustrated in Figure 7. Hollands and Lightstone (1989) reported that a perfectly stratified water tank could make a solar system produce 38% more heat than a fully mixed tank. The main reason is possibility to transfer heat to the cooler regions of an almost fully charged store. This enables higher quality energy to be usable from the warmer regions (Pinel et al., 2011). Additional benefit can be higher solar collector efficiency due to the lower temperature of the fluid returning to the collector by reducing heat losses to the ambient (Duffie and Beckman, 2006).

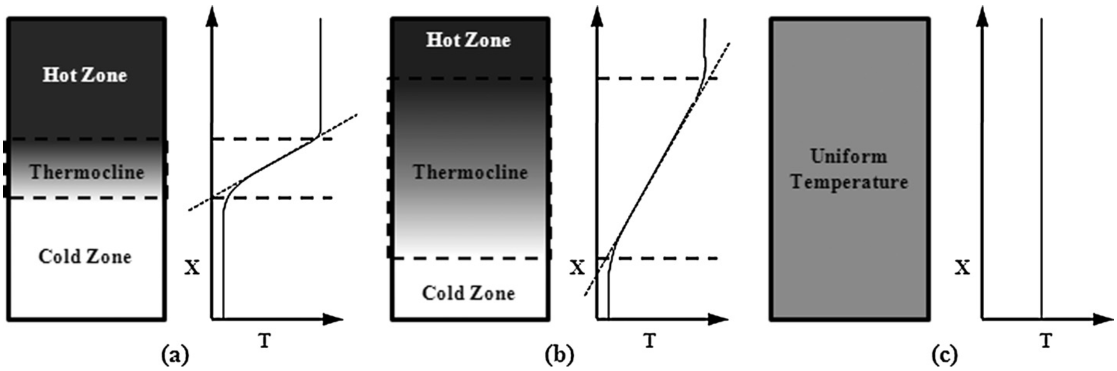


Figure 7. Different stratification levels within water tank and equivqlent storage capacities (Pinel et al., 2011).

Different methods or stratifier structures such as baffles (Altuntop et al., 2005), diffusers (Chung et al., 2008), fabrics and membranes (Andersen et al., 2007; Davidson and Adams, 1994) can be used to enhance stratification. Figure 8 shows baffles and membranes used as stratifiers in vertical tanks.

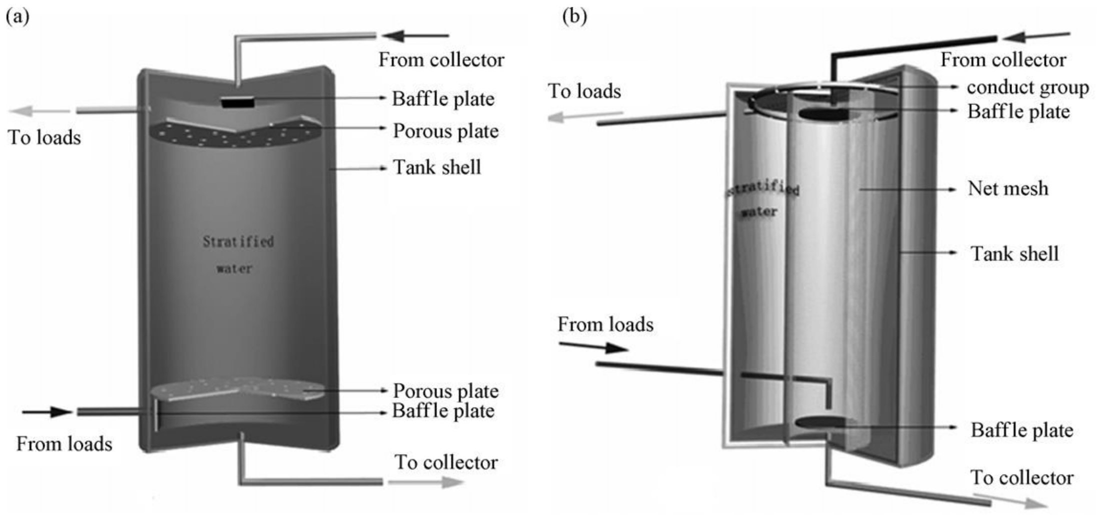


Figure 8. Structure and schematic design comparison between two types of tanks with thermal stratification: (a) baffle plate applied within the tank and (b) porous structure (Mangold and Deschaintre, 2006)

The geometrical factors that influence stratification are tank size, the aspect ratio of tank, inlet shape of diffuser system, and baffle size and its shape to control flow pattern (Lavan and Thompson, 1977; Sharp and Loehrke, 1979; Zurigat et al., 1990). Dincer and Rosen (2002) suggested increasing the depth of storage to favor stratification. The operating conditions (Berkel and Rindt, 2002; Knudsen and Furbo, 2004) like flow rate, inlet and initial tank water temperature, and cyclic periods of charging and discharging are also effective. Gautam and Saini (2020) reported that obtaining better stratification and thin layer of thermocline increases efficiency of storage system.

3.2.3. Packed Beds

Packed beds consist of a tank filled with packing material and a heat transfer fluid that is circulated through the bed to store or recover heat. Water and thermal oil are common heat transfer fluids (HTF). At elevated temperatures, thermal oils and steam are preferred. Solid materials such as rocks (Bruch et al. 2014a; Zanganeh et al., 2012), pebbles (Zavattoni et al., 2011), metals (Anderson et al., 2014; Cascetta et al., 2015; Khare et al., 2013), ceramics (Zunft et al., 2011) and recycled materials (Navarro et al., 2012) can be used as packing materials. Rock bed illustrated in Figure 9 is the cheapest packed bed. The pressure drop of the fluid through the packed bed is affected by the porosity of the bed. Predicting pressure drop in a rock bed is difficult due to irrregularity of rocks' shapes and sizes. Measured pressure drops can be higher than the predicted ones in a range of 10-30% (Zavattoni et al., 2011). It is possible to store the sensible heat between 500-750 °C in the packed bed depending on thermal properties of packing material (Khare et al., 2013).

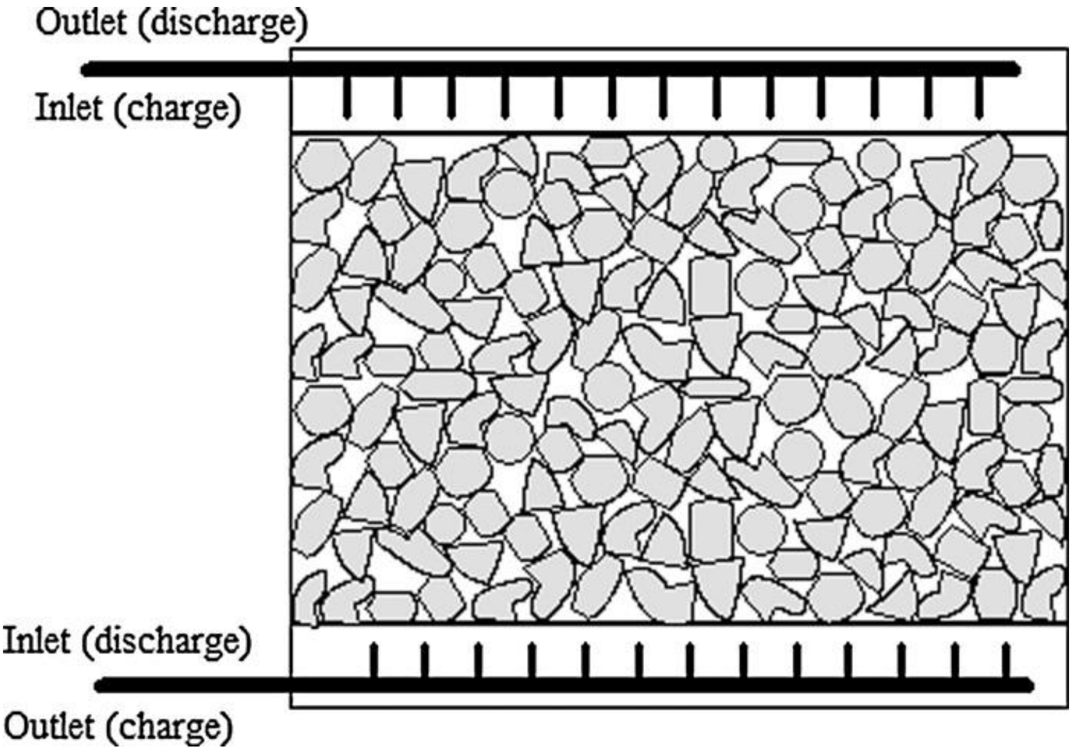


Figure 9. Rock bed storage system (Pinel et al., 2011)

Different configurations of tanks and packed beds can be used for various solar heat applications. In CSP plants, 2-tank system with molten salt as STESM is used (Figure 10 (a)). One of the tanks is referred to as cold and the other as hot. In (Prieto et al., 2016b), cold tank temperature is 286ºC and hot tank temperature 386ªC in operation of a molten salt pilot plant in Spain. Melting the molten salt takes several days.

In Figure 10 (b), single-tank packed-bed thermocline system is shown. Here storage tank is filled with storage material as packing. During storage, HTF heated by solar energy enters from top of the tank and storage materials absorb the heat from HTF. In the discharge, cold HTF enters the bottom of the tank and storage materials release the heat to HTF (Erregueragui et al., 2016; Stutz et al., 2017). Single tank thermocline systems provide 35% more advantage in investment cost compared to 2-tank storage systems (Yang and Garimella, 2010). Optimum velocity of HTF should be determined based on particle Reynolds number(Rep), which indicates type of flow regime in the storage tank. Flow regimes based on Rep are; fully laminar (Rep<10), nonlinear (10<Rep<150), unsteady laminar (150<Rep<300), fully turbulent (Rep>300) (He at al., 2018). Higher storage efficiency can be achieved in fully laminar regime by choosing operational and particle parameters to keep Rep below 10 (Koçak and Paksoy, 2019b).

In addition to Rep, Biot number should be considered to select optimum size of packing material. Biot number should be less than 0.1 to get homogeneous temperature distribution inside each packing material (Hoffmann et al., 2016).

The ratio of tank diameter to the packing diameter is also an important design parameter to have negligible wall effects. According to Bruch et al. (2014a), the ratio of tank diameter to packing diameter should be greater than 30 ($D_{tank}/D_s>30$).

Inlet charging HTF temperatures affects storage capacity and efficiency. As the charging temperature increases temperature difference between inlet and outlet increases that enhances storage capacity (Koçak and Paksoy, 2019b).

Three different storage tank geometries for STES based on their cross section are rectangular, truncated cone or cylindrical. Rectangular geometry provides the lowest

cost storage unit, but high-pressure drop due to corner effects causes inefficient operation (Gautam and Saini, 2020). Storage tank of truncated shape ensures low heat loss below 3.5% and overall efficiency of 95 % for multiple 8 h charging/ 16 h discharging cycles (Zanganeh et al., 2014).
Cylindrical tank with aspect ratio of greater than 1 (L/D>1) is the most common design that has been reported as highly efficient by previous studies (Bruch et al., 2014b; Klein et al., 2014; Cascetta et al., 2015).

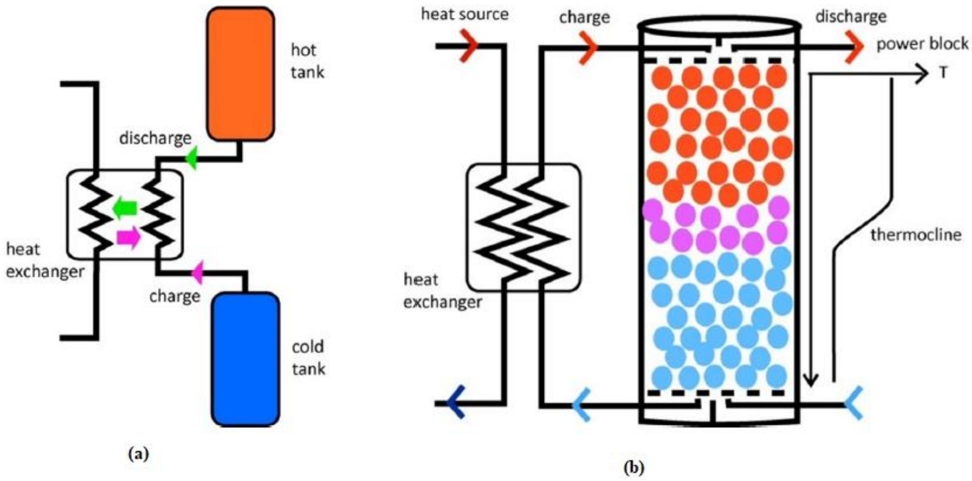


Figure 10. Sensible heat storage systems a)Two-tank storage system b)Single-tank thermocline storage system (Stutz et al., 2017)

3.3. Sensible Thermal Energy Storage Media

STESMs can be used in a wide range of temperatures. Their application areas and storage performance may be different depending on their physical, mechanical and chemical properties. Due to the different properties, each storage material has its own advantages and disadvantages. For example, water has higher heat capacity (4.2 $kJkg^{-1}K^{-1}$) compared with rock (0.82 2 $kJkg^{-1}K^{-1}$). On the other hand, water storage systems can be used in limited temperature range (up to 100 ºC), while rocks can be used up to 700 ºC. Besides thermal energy storage properties, mechanical resistance, cost, heat loss, and operation temperature range are important criteria for selection for sustainable STES system (Dincer and Rosen, 2002; Fernandez et al., 2015; Jemmal et al., 2016).

3.3.1. Properties

TES system performance mainly depends on physical and thermal properties of storage materials (Palacios et al., 2020, Alva et al., 2017). Table 6 lists groups of properties with desirable criteria for STESM. According to Klein et al. (2014) storage materials should have higher specific heat capacity and density, capability for operating at suitable temperature range, good thermal conductivity and low cost.

Table 6. Groups of properties and desirable criteria for STESM (Fernandez et al., 2015; Khare et al., 2012, 2013).

Properties	Criteria
Thermo-physical	High energy density (per unit mass or volume), high thermal conductivity, high heat capacity, high density, long term thermal cycling stability
Chemical	Long term chemical stability with no chemical decomposition, non-toxic, non-explosive, low corrosion potential or reactivity to HTFs, and compatible with materials of construction
Economic	Cheap and abundant materials with low cost of manufacturing into suitable shapes
Mechanical	Good mechanical stability, low coefficient of thermal expansion, high fracture toughness, high compressive strength
Environmental	Low manufacturing energy requirement and CO_2 footprint

Studies on sensible heat storage materials have been carried out since 1970s. Today more than 150.000 commercial materials in liquid or solid form are available for engineering purposes (Fernandez et al., 2010; Gracia and Cabeza, 2015). Liquid form STESMs have higher specific heat capacity and thermal conductivity compared with solid form STESMs like rock (Almendros-Ibáñez et al., 2018). Water, which is abundant, non-toxic and cheap, is the most common liquid sensible heat storage medium (Gracia and Cabeza, 2015). It can be used up to 90 °C operation conditions (Hasnain, 1998). Mineral oil, molten salts, liquid metals and alloys are also known as liquid STESMs (Alva et al., 2017).

Mohan et al. (2018) studied molten salt mixtures for high temperature thermal energy storage systems. They found that NaCl-KCl-$MgCl_2$ mixture was low-cost storage material and stable up to 700 °C.

Mineral oil is generally used as HTF up to 400 °C. Mineral oils do not freeze in the system during the cold weather or nights (Alva et al., 2017). But, due to the high cost of mineral oil, researchers focused on low cost thermal energy storage materials (Emerson, 2013). Molina et al. (2019) studied alternative cheap solid materials that can be used instead of thermal oil. Silica sand, natural rock, glass, steel, aluminia, quartzite and concrete were suggested as alternative storage materials up to 350 °C.

According to Fernandez et al. (2010) solid materials are divided into four categories such as metals and alloys, ceramics and glasses, polymers and elastomers and hybrids. Figure 11 shows density and specific heat capacity ranges of solid materials. For high energy density, higher specific heat capacity and higher density are must.

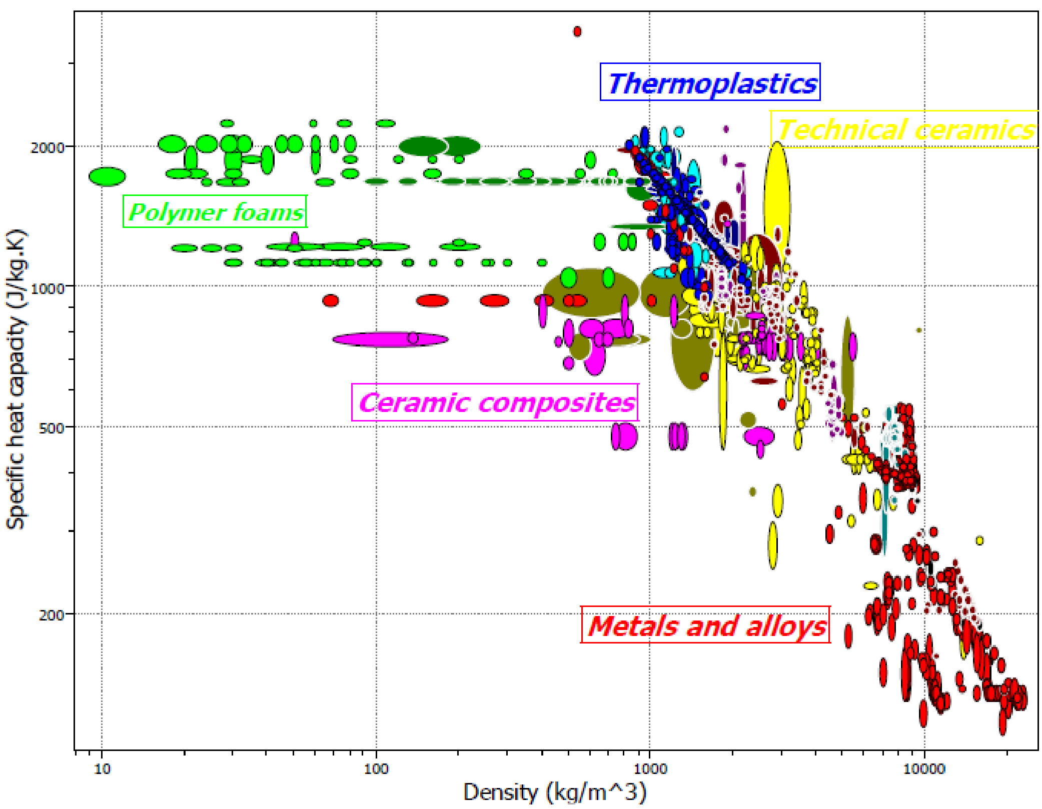


Figure 11. Benchmark chart for sensible heat storage materials (Fernández et al., 2010)

Comprehensive studies on storage materials have been carried out in the past. Table 7 shows the properties of STESMs. Sand rock, concrete, cast iron, cast steel, NaCl and brick are reported as the most common solid sensible thermal energy storage materials (Tian and Zhao, 2013). Rocks show good thermal performance up to 20 years. Concrete based materials are attractive options as STESM due to its low cost and high storage capacity (Alonso et al., 2016; Emerson et al., 2013). Concretes can be used in high temperture stotage systems up to 400 °C. Their thermal stabilities can be increased by using different mixture proportions. Emerson et al. (2013) studied economical concrete mixtures and developed a mortar from cement, fly ash and polypropylene fiber mixtures that could resist up to 600 °C.

According to Khare et al. (2013), it is possible to store sensible heat between 500-750 °C in the packed bed column with aluminum silicate composite materials. Bruch et al. (2014b) have extensively studied the use of silica rocks and silica sand mixture as thermal heat store material in packed bed to increase CSP power plant effectiveness. Schlipf et al. (2015) used silica sand, quartz and basalt gravel in different sizes as storage material to analyze performance of the packed bed storage system for use in the solar energy plant. Cascetta et al. (2015) investigated thermal energy storage performance of alumina beads. In another study, desert sand samples were analyzed to assess their heat storage material usage possibility (Diago et al., 2015). Lugolole et al. (2018) analyzed different size of granite samples in packed bed. Mertens et al. (2014) used quartzite-rock in a packed bed thermal energy storage system for a semi-industrial scale solar power plant (1.5 MWel).

Waste/inertized materials also create alternative storage materials at low cost. Inertized products such as by-products derived from mining and metallurgical industry (Navarro et al., 2012), asbestos-containing wastes (Faik et al., 2012), fly ashes from municipal solid waste (Faik et al., 2012), post-industrial ceramic (Motte et al., 2015), recycled nylon fiber from textile industry (Ozger et al., 2013) can be used as STESM for high temperature thermal storage in solar power plants. Miro et al. (2014) investigated a solid by-product from potash industry to test its usability as STESM. Its specific heat capacity was found as 0.738 kJ/kgK and it was durable up to 800 °C. Wang et al. (2018) investegited thermal properties of electric arc furnace (EAF) slag samples from steel making process. Samples were stable up to 1000 °C. Slag samples were suggested as good storage material candidates with high heat capacity of 3.6 kJ/m^{3}K.

Agalit et al. (2017) studied slags from an induction furnace in which ferrous metal scrap and fluxes were melted. It was found that induction furnace slags as waste materials can be used as cheap STESM with 1800 kJ/m^{3}K heat capacity up to 1000 °C TES applications.

Tisktine et al. (2017a) investigated properties of 52 rock types to be used in high temperature TES systems for industrial applications. Their thermal capacities were found between 2050-2550 kJ/m^{3}K. All rock samples were defined suitable for high temperature storage application for air-based solar systems. Beside this, storage performance of dolerite, granodiorite, hornfels, gabbro and quartzitic samples were better than others.

Kabeel et al. (2018) investigated thermal performance of graphite as STESM in single basin solar still. Single basin solar still with graphite showed 25-27% better performance than traditional single-basin still.

Table 7. Properties of sensible thermal energy storage materials

Material Name	Material Composition	Dimension	ρ, (kg/m^3)	C_p, (J/kg°C)	ρxC_p, (10^6J/m^{3}C)	Thermal conductivity k, (W/mC)	Thermal expansion coeff., K^{-1}	Operating temp., °C	Ref.
DW			2188	960-1457	3.19				(Koçak and Paksoy, 2019a)
Cofalit			3120	800-1034	2.49-3.22	2.1-1.4	8.8 x 10^{-6}		(Calvet et al., 2013)
Coal Fly Ash			2600	735-1300	1.91-3.38	1.3-2.1	4 x 10^{-6}		(Motte et al., 2015)
Electric Arc Furnaces Waste			3500	700	2.45	1.5-2.0	NA		(Motte et al., 2015)
WrutF			4154	980-1761	4.0-7.3	0.8	NA		(Navarro et al., 2012)
By-products of the potash production			2100	640-850	1.34-1.78	3-4	NA		(Navarro et al., 2012)
Waste Glass			2900	714-1122	2.1-3.2	1.16-1.59	8.7 x 10^{-6}		(Gutierrez et al., 2016)
By-products generated in steel industry			3972	910	3.6	NA	NA		(Grosu et al., 2018)
WDF (powder material produced during the steelmaking process in electric arc furnace)			3967	510 @100C	2.02	0.7	NA		(Navarro et al., 2012)
Alumina balls	Al_2O_3≥89.5 wt %)	7-9 mm	3350	902	3.02	30		Up to 550	(Cascetta et al., 2015)
Silica	Silica gravel/Silica sand (%80:%20 wt)	30mm:3mm	2500	900	2.25	0.1		Up to 250	(Bruch et al., 2014a)
Desert Sand				926.1				Up to 1100	(Diago et al., 2015)
Brick			3200	800	2.56	0.1			(Kuravi et al., 2012)
Gneiss Rock			2740	820	2.26	3.0			(Jemmal et al., 2016)
Basalt			2644	770	2.04	2.08			(Tiskatine et al., 2017b)
Concrete			2200	850-920	1.87	1.5-2.3			(Ozrahat and Ünalan, 2017; Prasad and Muthukumar, 2013)
Cast steel			7800	600	4.60	40			(Prasad and Muthukumar, 2013)
Cast iron			7200	560	4.03	37			(Prasad and Muthukumar 2013)
NaCl			2160	1150	2.5	5.0		Up to 500C	(Tian and Zhao, 2013)

3.3.2. Comparison of STESM with Other TES Materials

Comparison of TES materials is given in Table 8. Research and development studies on thermal energy storage materials are hot topic among the research community. Studies on sensible heat storage materials are the most mature compared to latent or thermo chemical heat storage materials (Becattini et al., 2017). But, storage capacities of STESMs are lower than the others (Li, 2016; Liao et al., 2018).

Application temperature under system integration conditions is an important factor in material selection. For PCMs, melting temperature is the key property to decide which PCM is suitable for application (Boda et al., 2017). STESMs should be thermally stable below application temperature.

Latent heat storage materials have higher material cost compared with STESMs. By 2030, the latent TES investment cost in Europe is aimed to be decreased below 50 €/kWh (EERA, 2018).

Table 8. Comparison of different type of TES materials (Abedin et al., 2011)

Performance Parameters	Thermal Energy Storage Materials		
	Sensible	**Latent TES**	**Chemical**
Temperature range	Up to: 110 °C (water tanks) 50 °C (aquifers and ground storage) 400 °C (concrete)	20-40 °C (paraffins) 30-80 °C (salt hydrates)	20-200 °C
Storage density	Low (with high temperature interval): 0.2 GJ/m3 (for typical water tanks)	Moderate (with low temperature interval): 0.3-0.5 GJ/m3	Normally high: 0.5-3 GJ/m3
Lifetime	Long	Often limited due to storage material cycling	Depends on reactant degradation and side reactions
Technology status	Available commercially	Available commercially for some temperatures and materials	Generally, not available, but undergoing research and pilot project tests
Advantages	Low cost reliable simple application with available materials	Medium storage density Small volumes Short distance transport possibility	High storage density Low heat losses (storage at ambient temperatures) Long storage period Long distance transport possibility Highly compact energy storage
Disadvantages	Significant heat loss over time (depending on level of insulation) Large volume needed	Low heat conductivity Corrosivity of materials Significant heat losses (depending on level of insulation)	High capital cost Technically complex

3.3.2.1. Storage capacity

Energy density of storage materials can be defined as energy release per unit volume. Higher energy can be stored in materials with higher energy densities (Lefebvre and Tezel, 2017). Figure 12 compares storage capacities of different TES materials. Thermo-chemical storage materials can store much more energy in a smaller volume, however, thermo-chemical storage technology has still a low TRL in industrial applications. STESM requires the highest volume to store desired heat (Cabeza et al., 2011) and heat losses from the system will also increase as storage volume increases.

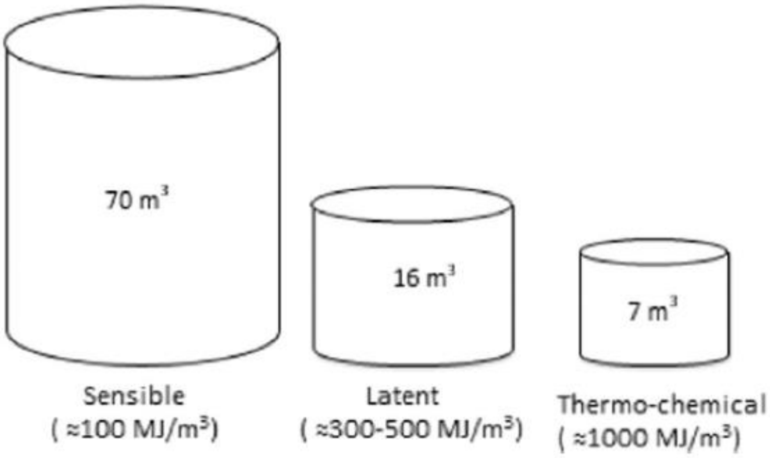


Figure 12. Comparison of volume of TES methods (Tatsidjodoung et al., 2013)

TES capacities of phase change materials are higher than sensible heat storage materials (see Figure 13), but the price of PCMs that can operate above 150 °C is very high (Mawire and McPherson, 2009). Due to the technical difficulties and high price of PCMs, latent heat storage is costly for industrial applications (Zanganeh, 2014). According to Konuklu et al. (2015), latent heat storage is mostly used in heating and cooling applications in buildings.

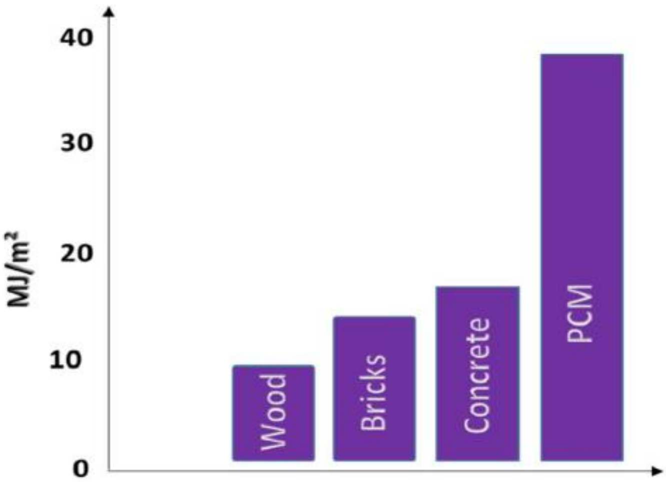


Figure 13. Comparison of energy storage densities (heating from 20 to 26 °C) (Madad et al., 2018)

Romani et al. (2019) compared storage capacity of TES materials. As seen in Figure 14, water as sensible thermal energy storage material has lower storage capacitiy compared with PCM and TCM materials.

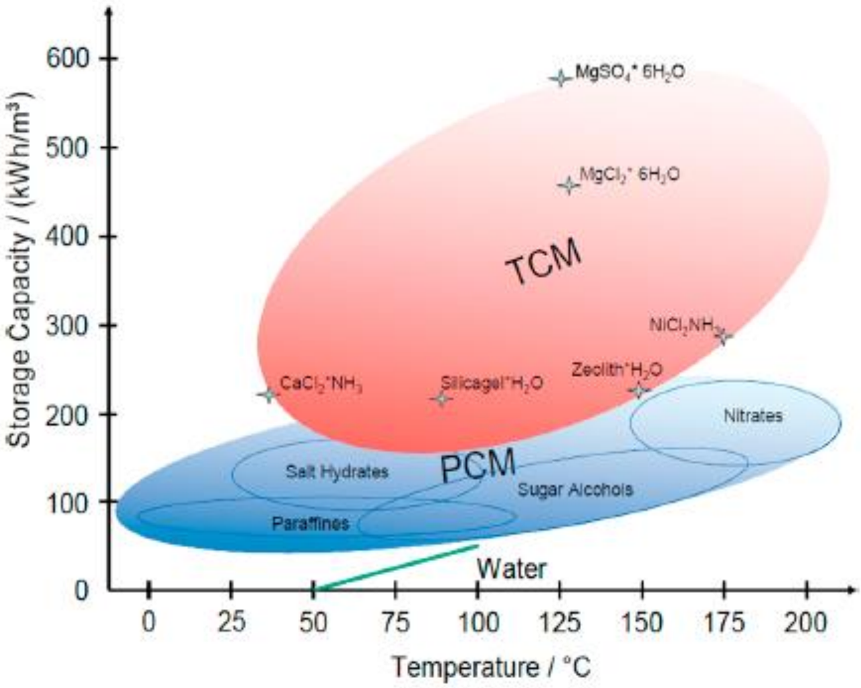


Figure 14. Comparison of storage capacity of storage materials based on storage technologies (Romani et al., 2019)

Xu et al. (2017) compared thermal properties of coarse sand and oil-saturated coarse sand in a shell-and-tube thermal energy storage system, shown in Figure 15. Coarse sand has 0.6-1.7 mm grain size and 0.38 porosity. Air was used as heat transfer fluid and entered the tubes of the shell-and-tube storage tank at 55 °C with 3.8 m/s velocity. When the coarse sand was saturated with Xceltherm 600 heat transfer oil, its specific heat capacity increased from 705 J/kgK to 942 J/kgK and efficiency of storage system increased from 46.5 % to 51.5 %.

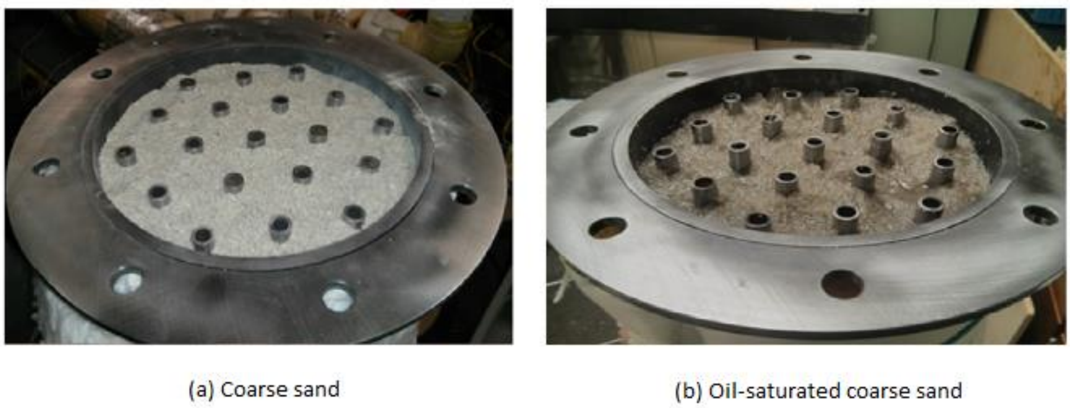


Figure 15. Shell-and-tube TES tank, (a) filled with coarse sand and (b) oil-saturated coarse sand (Xu et al., 2017)

3.3.2.2. Stability

Selecting an appropriate STESM is important for the performance of the storage system. However, high storage capacity is not the only criterion for selecting the appropriate STES. Stability also plays an important role in the selection of storage material (Baba et al., 2019). STESMs have stable chemical and low corrosion properties (Li, 2016). Rocks as storage material are most suitable for high temerature applications due to their good thermal and chemical stabilities (Allen et al., 2014; Baba et al., 2019; Barton, 2013; Hänchen et al., 2011). Py et al. (2017) tested stability of basalt and flint stone and no chemical and thermal instability was observed up to 1000 ˚C.

3.3.2.3. Heat transfer properties

Although PCMs have higher energy density than STESMs, their thermal conductivities are lower (Rao et al., 2018). Low thermal conductivity of PCMs leads to poor thermal performance of storage system. There are some studies in literature to enhance heat transfer properties of PCMs. Inserting metal foam in PCMs increase the heat transfer between PCM and HTF and as a result, the melting time decreases (Atal et al., 2016; Fleming et al., 2015; Liu et al., 2013; Yu et al., 2018).

Storage capacity and heat transfer properties of sand-basalt mixture was numericaly studied by Kiwan and Soud (2019). Sand has higher heat capacity and density, but its thermal conductivity is lower than basalt. As basalt ratio increased in the mixture, bulk heat capacity decreased. However, adding basalt to the mixture improved the temperature distribution and increased bulk temperature for the same amount of stored energy.

Thermal properties of water and solid STESMs were compared in Figure 16 (Li, 2016).

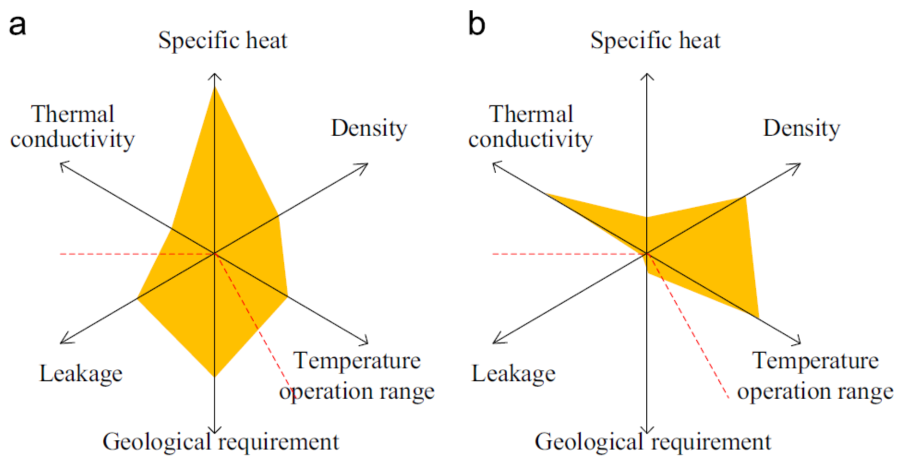


Figure 16. Comparison of thermal properties of water (a) and solid STESMs (b) (Li, 2016).

Tiskatine et al. (2017a) showed thermal properties of some rock types suitable for high temperature applications in Figure 17. Rocks with higher content of quartz have higher thermal conductivity and thermal capacity.

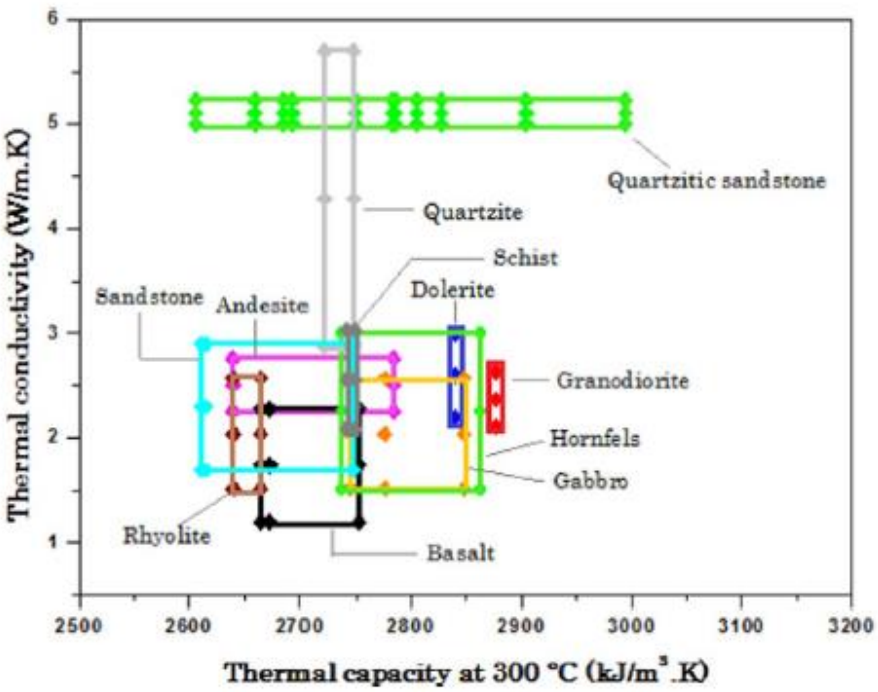


Figure 17. Thermal properties of some rock types (Tiskatine et al., 2017a)

3.3.2.4. Cost

The cost of energy storage systems is one of main factors that determine whether storage systems can be used in industrial applications or not (Chen et al., 2019). Rock-bed storage systems are defined as a cheap way to store thermal energy (Allen et al., 2014; Barton, 2013; Becattini et al., 2017; Hänchen and Brückner, 2011; Heller and Gauche, 2013; Jemmal et al., 2016; Mertens et al., 2014; Tiskatine et al., 2017a). According to Gasia et al. (2017) waste and industrial by-products offer alternative low cost STESMs.

Rao et al. (2018) analyzed compressive strength/cost ratio of 5 different concrete grades from M20 to M40 according to IS 10262:1982 standart. M30 had the highest strength per cost and it was selected as sensible storage material to used in shell-and-tube storage column. Compressive strength/cost analysis is given in Table 9.

Table 9. Compressive strength/cost ratio of concrete samples (Rao et al., 2018)

Mix Design	σ (kN)	Cost, $	σ/cost, (kN/$]
M20	530	0.202	2623.7
M25	640	0.243	2633.7
M30	900	0.285	3157.8
M35	1000	0.327	3058.1
M40	1040	0.361	2880.8

Combined latent-sensible storage systems provide an alternative way to increase storage performance and to decrease cost. Geissbuhler et al. (2016) made simulation studies for a 1000 MWhth industrial scale combined sensible/latent heat storage system. Encapsulated $AlSi_{12}$ materials were placed on top of rock packed bed column to reduce storage material cost. Costs of $AlSi_{12}$ and rock were 25.744 $\$/m^3$ and 66 $\$/ m^3$, respectively. Simulation results showed that exergy efficiency was greater than 95% and material cost was below 15 $/ kWhth. Ahmed et al. (2019a) also studied combined sensible-latent heat storage system. Cost of the sensible-latent heat storage system prepared from brick manganese rod structures and encapsulated PCM capsules decreased to 37 $/kWh, while cost of storage system filled with encapsulated PCM capsules was 42 $/kWh.

Tehrani et al. (2017) compared the cost of 4 different thermal energy storage systems such as 2-tank molten salt (2-tank), single-medium termocline (SMT), dual media termocline (DMT) and shell-and-tube (ST). Low cost concrete was used in ST and DMT systems. Compared with 2-tank, DMT, SMT and ST systems had 60%, 23% and 17% lower cost, respectively (Tehrani et al., 2017).

According to Al-Azawii et al. (2018), alumina is an expensive STESM. However, its high stability, high heat capacity and high thermal conductivity properties make it preferable in industrial applications.

3.3.3.Preparation methods

3.3.3.1.Physical methods

The characteristics of storage materials, especially if they are natural or waste and by-products can be significantly different and heterogeneous. Their humidity, dimensions, shapes, densities or composition may vary for each sample. Dimensions and homo-structure of STESM is one of the effective criteria on storage performance (Elouali et al., 2019). To meet these criteria, STESM developed from waste materials have to be prepared and processes such as crushing, sieving, drying, pressing, melting, molding, mixing, compressing can be used in preparation.

Koçak and Paksoy (2019a) applied crushing and sieving processes on demolition wastes to prepare homogenous dusts. In this study, to obtain uniform shape with the same dimensions, demolition waste dust was mixed with cement and water at fixed proportions and then poured into moulds before it was dried to the required humidity level.

Py et al. (2011) used Cofalit as STESM by applying melting, molding and cooling processes to by-product of ceramic industry. According to Gutierrez at al. (2016) glasses from municipality wastes can be used as STESM after obtaining uniform shapes by applying melting, molding and cooling processes.

Girardi et al. (2017) prepared different concrete mortar formulations by adding polyamide fiber waste from textile industry, metallic powders, recycled metallic shavings and steel fibers in concrete to improve its thermal properties. As a result, thermal conductivity of concrete increased from 0.74 W/mK up to 2.74 W/mK by adding recycled metallic shavings.

3.3.3.2. Chemical methods

Samala et al. (2019) synthesized cobalt (II) sulfate heptahydrate ($CoSO_4.7H_2O$) and phosphoric acid (H_3PO_4) mixture in 1:1 ratio to produce non-calcined $Co_3(PO_4)_2$ $4(H_2O)$ Na_2HPO_4 $0.1Na_2SO_4$ mixture and calcined $Co_3(PO_4)_2$ $3.5(H_2O)$ Na_2HPO_4 $0.1Na_2SO_4$ mixture. Both samples showing endothermic behavior during heating process can be used as STESM. But calcined sample was a better option for high temperature ranges up to 300 °C. Lao et al. (2019) synthesized cordierite-SiCw composite ceramics with a-Al_2O_3 to improve its heat capacity from 1.28 $Jg^{-1}K^{-1}$ to 1.4 $Jg^{-1}K^{-1}$.

4.TES for Solar Heat Industrial Applications

4.1. Current Solar Heat Industrial Applications

Industrial solar applications are seen in a few countries and generally as small scale projects. According to database produced by International Energy Agency Solar Heating and Cooling Technology Collaboration Programme, only 741 solar heat industrial plants (SHIP) with an overall collector area of 662,648 m² (567 MW_{th}) were installed worldwide by the end of 2018 (IEA, 2019). 333 of these SHIP plants are large scale and 300 of those have TES units (http://ship-plants.info/).

According to European Commission 2018 report, energy constitutes 1-10 % of total costs in most of the industrial sectors such as paper, food, and textiles. It exceeds 10% for some special sectors such as lime, cement. Table 10 shows energy cost shares of industrial sectors (Rademaekers et al., 2018). The shares show the importance of cutting energy use in the industry. Reduction of energy consumption and cost and using high quality energy are accepted as key performance indicators in industries (Owodunni, 2017). Recently, with increased competition, energy efficiency has become an important issue for the industry and research has begun on the integration of solar energy in different industrial processes. In industry, solar energy is usually used for hot water production and space heating. Currently, major solar heat industrial plants are located in Chile, China, Germany, Spain, Austria and Italy. In order to determine thermal energy requirement in industries, it is necessary to define proses type, proses temperature, heat demand and rate of heat transfer fluid (Suresh and Rao, 2017).

Table 10. Energy cost shares of industrial sectors (Rademaekers et al., 2018).

Industrial Sectors	Average	Min Level	Max Level
Pharmaceutical products	1.5%	1.1%	2.8%
Beverage	2.6%	2.4%	2.7%
Fruit and vegetables	3.0%	2.5%	3.6%
Textile	3.3%	2.1%	6.4%
Pulp and paper	3.7%	3.1%	4.1%
Basic chemicals	6.7%	5.7%	7.7%
Mining and quarrying	2.9%	3.4%	2.7%
Iron and steel	8.8%	7.3%	11.9%
Electricity, gas and steam	14.6%	11.4%	17.0%
Cement, lime and plaster	21.4%	16.3%	23.5%

More than half of solar industrial applications are in food and beverage sector (see Figure 18) according to a study by Farjana et al. (2018b). Mining and quarrying industries' share in solar thermal applications is 6%. The largest industrial solar plant was built by Chile-Codelco Gabriela Mistral in Mining & Quarrying industry with 39300m^2 collector area, 4000 m^3 of thermal energy storage and 27510 kWth thermal power. It supplies 85% of the process heat needed to refine copper (IEA, 2017a). This solar plant is shown in Figure 19.

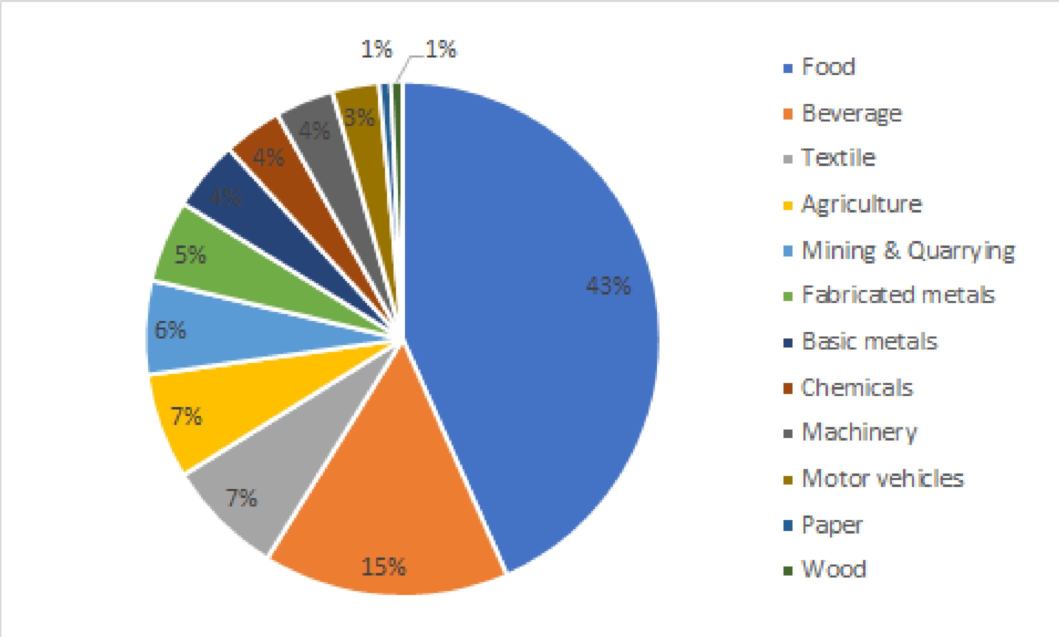


Figure 18. Solar application ratio according to industrial sectors (Farjana et al., 2018b).

Figure 19. Industrial solar application in a copper mine industry in Chile (Sunmark, 2014).

IRENA Technology Brief E21 (2015) reported in 2014 that 140 solar thermal plants are used in industry worldwide with a total capacity of over 93 MWth (>136 000 m^2). Only 18 of them have large-scale with more than 1000 m^2 collector area; the others are small-scale pilot projects, mostly in food, beverage and textile industries.

In the comprehensive review by Lauterbach et al. (2012), the potential of solar energy use in German industry is analyzed. Solar energy is extensively used in processes below

200˚C in food, beverage and chemistry industries in Germany. This provided energy saving of 16 TWh per year in Germany.
Meyers et al. (2016) studied energy efficiency and CO_2 emission reduction in the food and beverage industry in 6 different European countries. It has been determined that up to 40% of energy efficiency can be achieved in processes which solar energy and heat pump were integrated together.
An example of 1000 m^2 evacuated tube solar collector field was installed in a New Zealand milk powder plant and integrated in the milk spray dryer process (Atkins et al., 2010).
Industrial solar applications were also integrated to a textile industry in China (9 MWth). As seen in Figure 20, textiles industry in China provides 55 ˚C pre-heated water from 13000 m^2 flat plate collectors. The pre-heated water is sent to a boiler and then heated to around 100 ˚C to use in the dyeing processes (UNEP, 2015).

Figure 20. Industrial solar application in a textile industry in Hangzhou China (UNEP, 2015)

In India, more than 60% of solar energy plants are used for industrial processes. For example, a dairy industry in India supplies 13% of the process heat from solar energy plant (IRENA, 2015). Figure 21 shows a SHIP application in India. In this system parabolic mirror collectors with 16000m^2 collector area were integrated to an industrial cooking system to achieve heat higher than 100 ˚C.

Figure 21. Scheffler dishes associated in pairs in a cooking system at Hyderabad (India) (CSH, 2018)

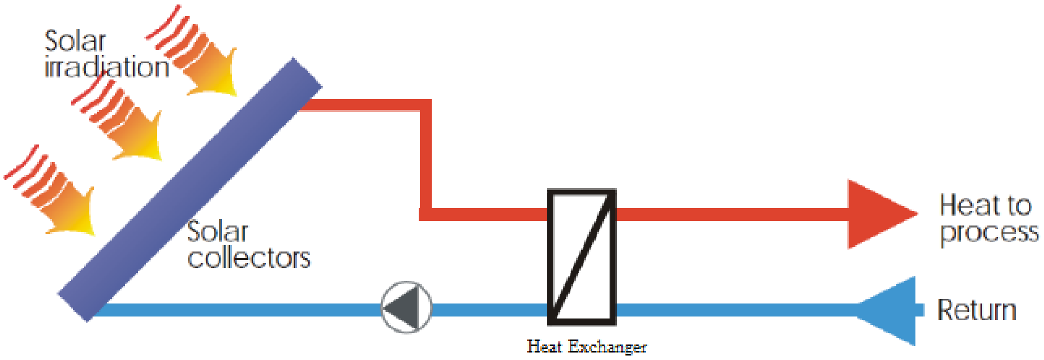
A flat plate collector field with 7804 m^2 collector area was installed in Prestage Foods industry in USA. Solar field with approximately 5 MWth thermal power is used to feed 71-82 °C heat water/glycol fluid to cleaning process. 946 m^3 storage tank is integrated to the processes as both supply and process level (http://ship-plants.info/).
Figure 22 shows solar system with 1067m² large flat plate collectors by BERGER GmbH, which produces cooked ham and sausage in Austria. Solar system includes 60 m^3 water tank to store the solar heat over the weekends. The system provides heat for cleaning and drying processes at 60°C (Pietruschka et al., 2016).

Figure 22. Solar (a) and storage (b) systems at BERGER company (Pietruschka et al., 2016).

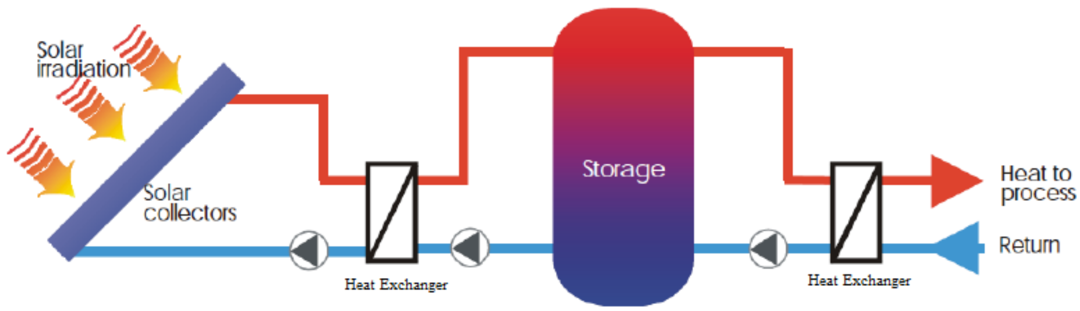
Haagen et al. (2015) studied solar energy integration in pharmaceutical industry in Sahab, Jordan. F-11 Industrial Solar Fresnel collectors with 396 m² was installed and steam at 166 °C and 6 bar generated to heat pharmaceutical processes such as chemical synthesis, fermentation, extraction etc. Solar heat system reduced the diesel consumption of the pharmaceutical industry approximately 30000 L/year (Haagen et al., 2015).

4.2. TES Integration Alternatives in Solar Heat Industrial Applications

Integration of TES in industrial solar energy systems reduces energy demand and fossil fuel use. Figure 23 shows integration of solar energy in industrial processes without (a) and with (b) storage (UNEP, 2010).



(a)



(b)

Figure 23 Solar heat industrial process, (a) without storage, (b) with storage (UNEP, 2010)

TES systems have been used in industrial processes since 19^{th} century (IEA, 2018d). TES store the solar energy for continuous and effective use of solar energy in industrial applications. This ensures the balance between supply and demand (Bruch et al., 2014a; IRENA, 2013). Solar energy systems can be integrated to processes in industries in various ways. The most preferred levels of integration are supply and process sides.
Steam boilers are commonly used by industries to provide process heat demand. Natural gas, fuel oil or coal are generally used in the boiler house. The steam or hot water obtained from the steam boilers used in the central heating system is distributed to the processes. Solar energy can be used in the boiler house (integration on supply level) or can be integrated directly to a specific process (integration on process level). According to Vajen et al. (2012), both levels have different advantages and disadvantages.
In integration of solar heating system on supply level, as seen in Figure 24, solar energy is feeding directly to the steam boiler. In this case, the temperature of hot water or steam coming from solar energy system can be increased and it can be distributed to processes at all temperature ranges (Vajen et al., 2012).

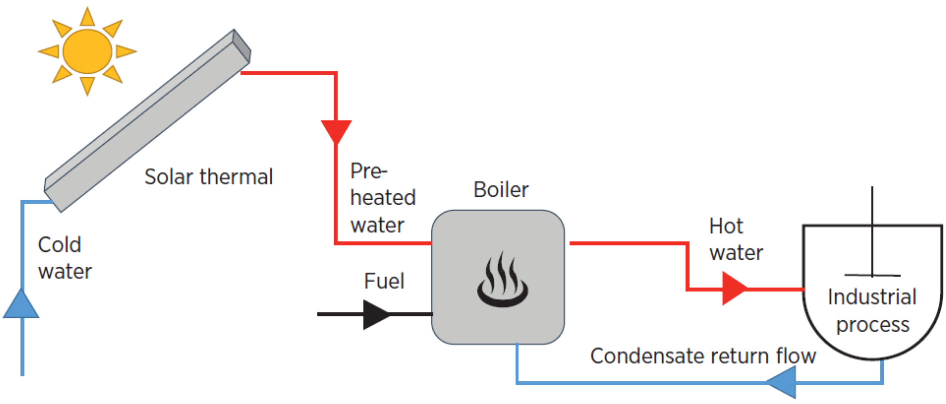


Figure 24. Principles for pre-heating of solar energy (IRENA, 2015)

In the integration of solar heating systems on process level, as seen in Figure 25, solar energy can be integrated to the processes with additional heat source. Accordging to Schmitt (2016) the integration on process level is more complex compared to supply level.

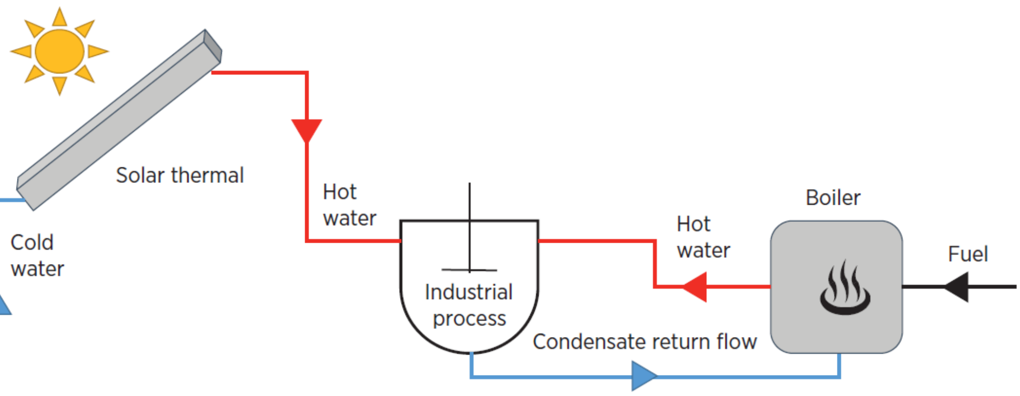


Figure 25. Principles for direct integration of solar energy (IRENA, 2015)

On process level integration, solar energy can be integrated in industrial processes in different ways. As shown in Figure 26, solar energy can be directly integrated to low temperature industrial processes without additional energy source. In this case, storage will be an important component to ensure that heat is available throughout the day.

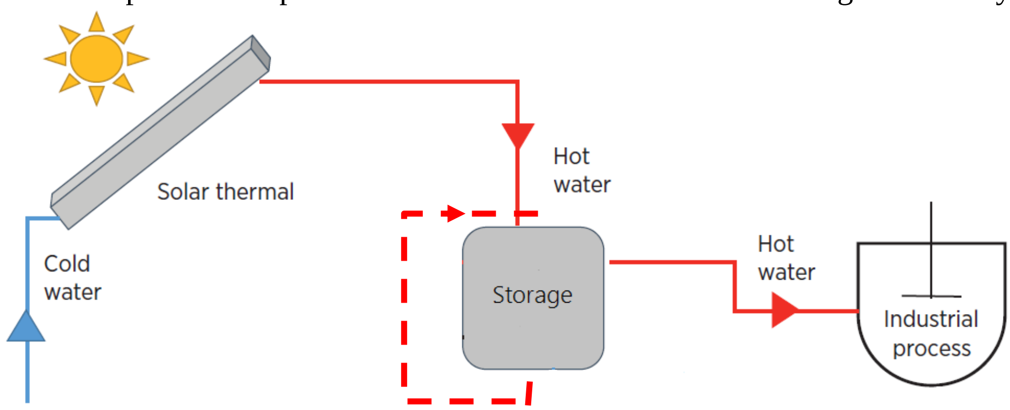


Figure 26. Principles for storage of solar energy (IRENA, 2015)

4.3. Case studies

Buscemi et al. (2018) studied the potential of STES integrated with linear Fresnel collectors (LFC) in a pasta industry in Sicily, Italy. In this system, concrete was used as STESM with 920 J/kgK specific heat and 2340 kg/m^3 density. System can be integrated to medium temperature (80-250°C) processes. Figure 28 shows integration models of TES system to pasta processes. When the pasta factory is not in operation (Fig 27a), LFC heats the concrete blocks in TES system. When the factory is in operation (Fig. 27b), during sunny hours the LFC heats both TES system and pasta processes. If heat from LFC is not enough, both LFC and TES system can be activated together (Fig 27c) During night hours LFC is not active and heat is provided directly from TES unit (Fig 27d)

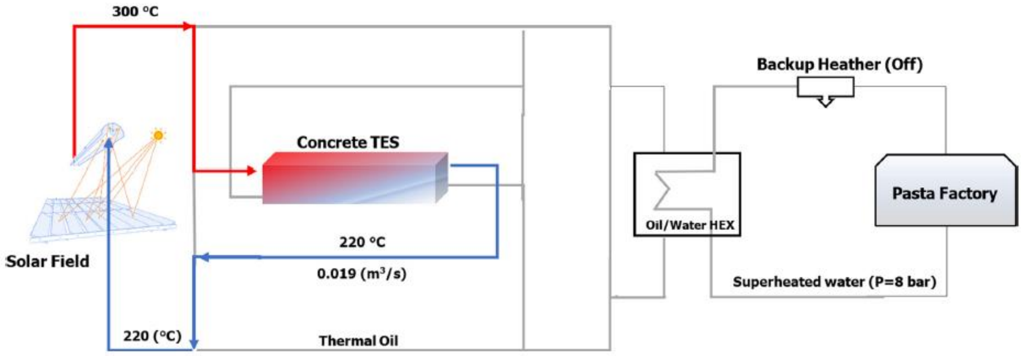


Figure 27 (a). Charging of the CTES (Weekend days - daylight hours) (Buscemi et al., 2018)

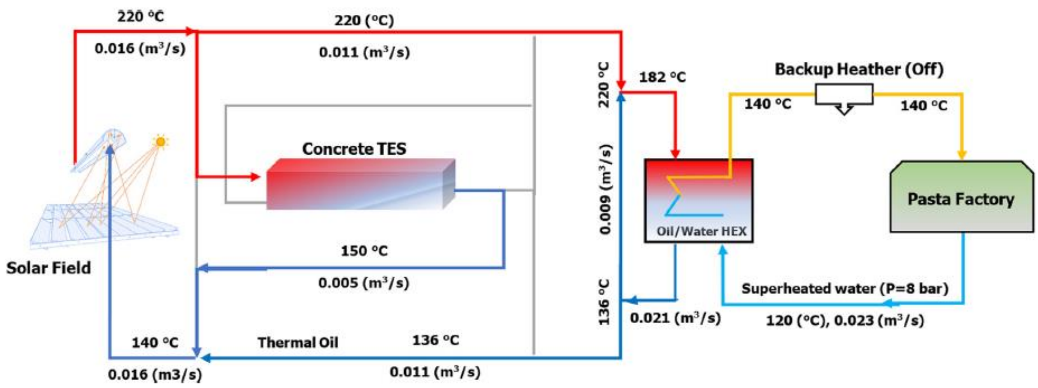


Figure 27 (b). Direct use and charging of the CTES (Weekdays – daylight hours) (Buscemi et al., 2018)

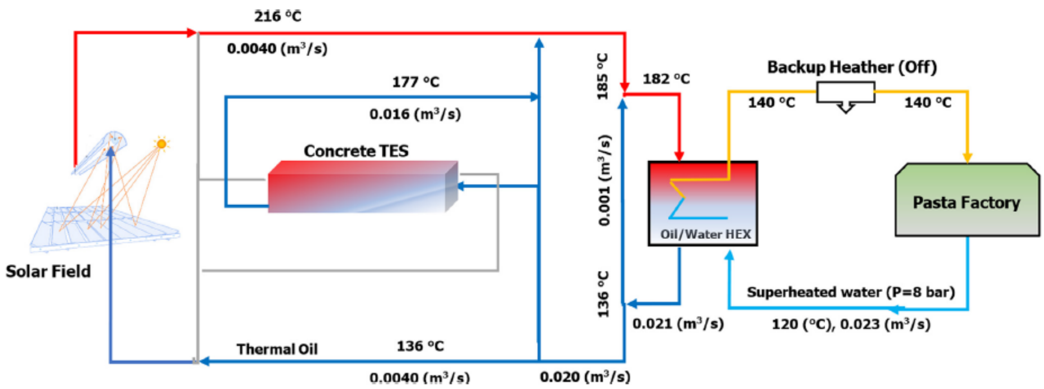


Figure 27 (c). Direct use and integration from the CTES (weekdays – daylight hours) (Buscemi et al., 2018)

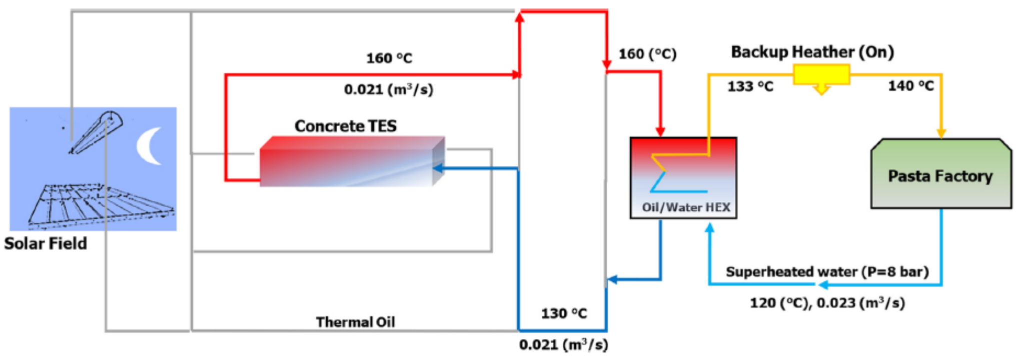


Figure 27 (d) Integration from the CTES (Weekdays -nighthours) (Buscemi et al., 2018)

Figure 28 shows integration of solar energy to mashing process in a brewery industry (Brewery Goess, Austria). In this system the solar thermal system with 1500 m^2 gross collector area directly connected to a 200 m^3 pressurized solar energy storage tank to store steam. Mashing process starts at 58°C and finalizes at around 78°C. When the temperature of storage system is enough for mashing process, heat is taken out from storage unit. If the temperature of storage unit is less than the process temperature, storage unit is by-passed, and heat is taken out from biomass CHP plant and excess heat from mashing process is fed to storage unit again. By this integration, 30% of the energy demand of mashing process was supplied from solar energy. Also, 1570 MWh/year natural gas and 38000 tons/year of CO_2 emissions were saved.

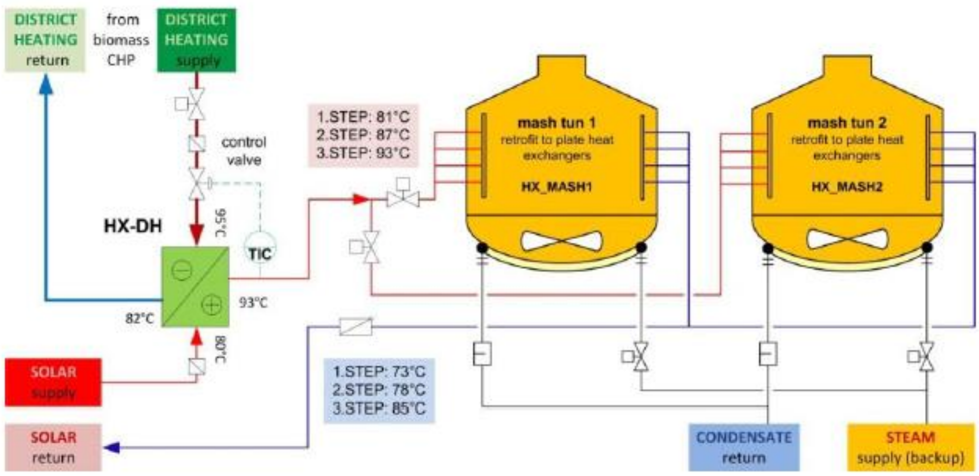


Figure 28 Schmatic diagram of integration of solar energy in Brewery Goess, Austria (Mauthner et al., 2014)

As shown in Figure 29, 1620 m^2 flat plate collectors were integrated to pasteurization process in brewery in Valencia, Spain. In this system, before the feeding to the process, solar energy was stored in atmospheric storage tank with a 350 m^3 water volume. 45% of energy demand of the pasteurization process was achieved from solar energy integration. As a result, 1100MWh/year natural gas and 26750 tons CO_2/year were saved.

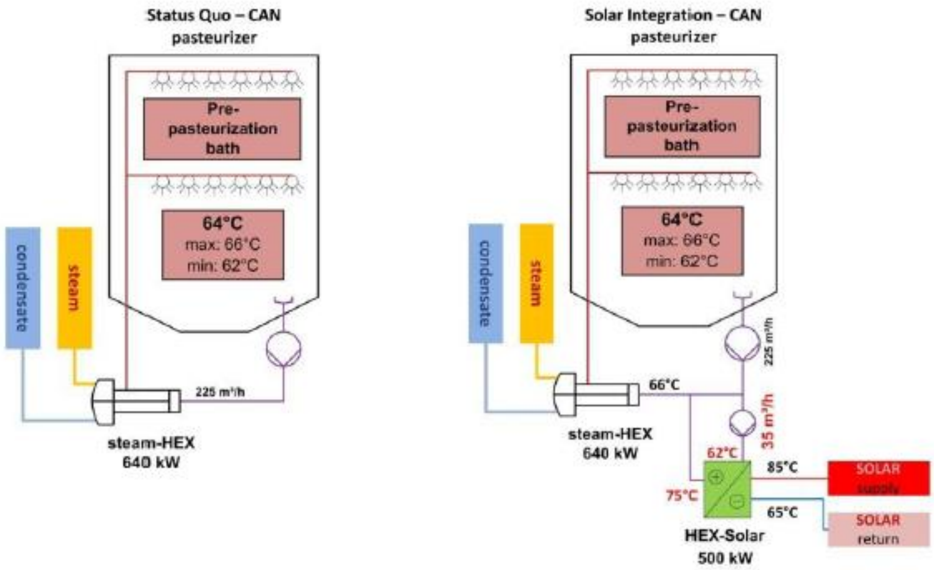


Figure 29. Schematic diagram of integration of solar energy in brewery in Valencia, Spain (Mauthner et al., 2014)

Figure 30 shows the schematic diagram of integration of flat plate collectors with 4725 m^2 collector area in Vialonga, Portugal for drying of green malt. In this project, solar energy was stored by 400m^3 atmospheric storage tank and 3760MWh/year natural gas and 89000 tons CO_2/year were saved.

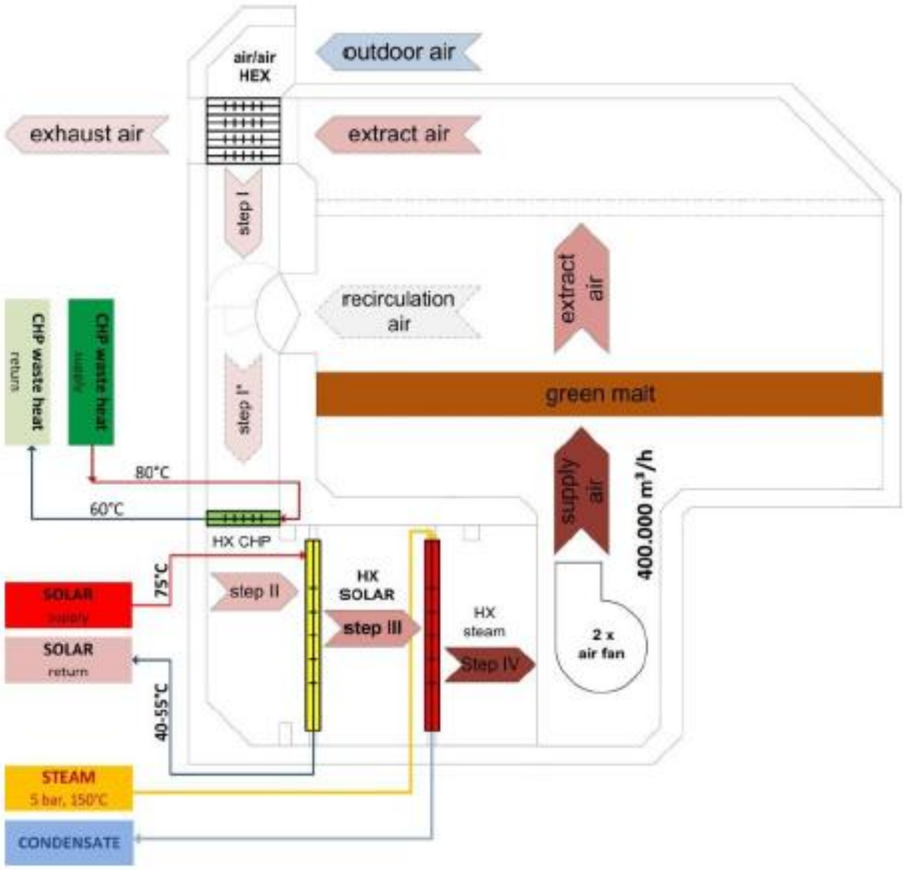


Figure 30 Schematic diagram of integration of solar energy in Vialonga, Portugal (Mauthner et al., 2014)

Haagen et al. (2015) studied solar energy integration in pharmaceutical industry in Sahab, Jordan to provide steam at 166 °C and 6 bar. Atalay et al. (2017) integrated packed bed thermal thermal energy storage system to solar dryer to dry apple slices between 45-55 °C with %76.8 less energy. Figure 31 shows each element of solar assisted drying with packed bed storage system. The system consists of two air collectors (2), a drying cabin (4), fans (6,9, 13, 17), a rectangular packed bed cabin (10) with 2m height, 1m length and 1 m thickness. The storage cabin is filled with two tonnes of pebbles (11). Air is used as heat transfer fluid and it comes from solar collector and enters directly storage cabin. During the charging period, hot air increases storage cabin temperature up to 60 °C.

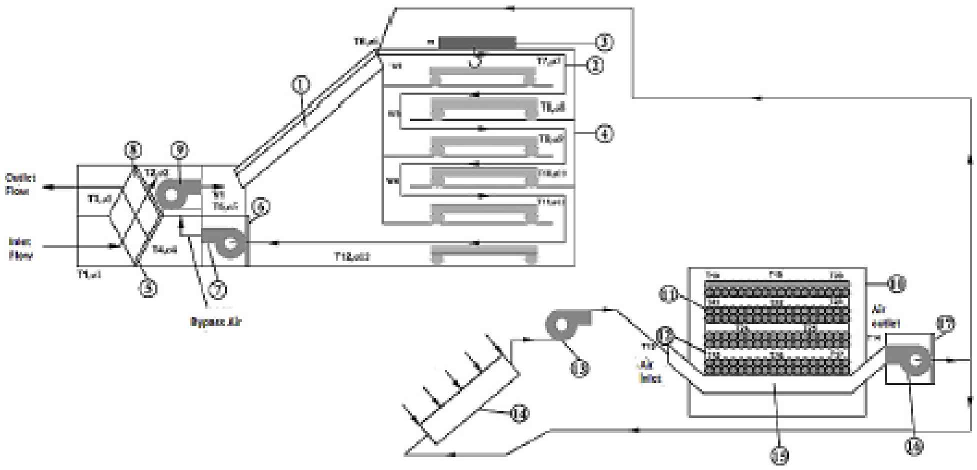


Figure 31. Schematic diagram of packed bed storage system integrated to solar dryer (Atalay et al., 2017)

In some cases, solar energy, heat pump and TES can be used together to increase temperature level to meet process requirements and optimize system performance. Ismaeel and Yumrutaş (2020) investigated the performance of underground thermal energy storage tank with solar assisted heat pump in wheat drying process. Total energy input to the drying system supplied by solar energy was determined as 76.6 % with TES tank volume of 200 m^3 and coefficient of performance (COP) for the heat pump was 4.43. Qiu(2016) integrated water storage tank and solar assisted heat pump in a food drying process. Energy saving up to 58.17 % was provided with thermal storage solar assisted-heat pump system. Kim et al. (2018) recommended integration of hot water storage tank in solar assisted heat pump for hot water supply to extent the annual operation hours with lower capital cost.

Tables 11-14 list the currently operated and under construction industrial solar energy applications with thermal energy storage in mining, food, beverage and textiles industries. The majority of these use short term water storage at process temperatures below 100 °C.

Table 11. SHIP with TES for Mining and Quarrying industry (http://ship-plants.info/)

Project/Site	Country	Total Capacity, kWth	Technology Type	Collector Area, m^2	HTF in Solar Field	Processes	Process Temperature, ˚C	TES	Storage Capacity	Storage Material
Codelco Gabriela Mistral	Chile	27510	FPC	39300	Water	Electro winning process	50	Short term-water storage	4300m3	Water
Anglo Plat – Brakfontein	South Africa	378.0	FPC	540		cleaning		Short term-water storage	42m3	
Anglo Plat – Middelpunt	South Africa	126.0	FPC	180	water/glycol	cleaning		Short term-water storage	14.2m3	Water
Minera El Rob Penoles	Mexica	231.0	FPC	297	water/glycol	Preheat of water	60-80	Short term-water storage	15m3	Water
Northam Platinum's Booysendal Mine	South Africa	134.4	FPC	192	water/glycol	cleaning	60	Short term-water storage	30m3	Water
Penoles Totolapan I	Mexico	42.0	FPC	54	Water	general process heating	60-70	Short term-water storage	3m3	Water
Penoles Totolapan II	Mexico	112.0	FPC	144	Water	general process heating	65-75	Short term-water storage	8m3	Water
Penoles Totolapan III	Mexico	31.5	FPC	40	water	general process heating	65-85	Short term-water storage	3m3	Water
Xstrata Elands Mine	South Africa	352.8	ETC	504	water/glycol	cleaning	60	Short term-water storage	60m3	
Hellenic Copper Mines	Cyprus	532.0	FPC	760	Water	extraction	-	-	100.0	

flat plate collector: FPC
evacuated tube collector: ETC
parabolic trough collector:PTC
Lineer fresnel collector: LFC

Table 12. SHIP with TES for Food industry (http://ship-plants.info/)

Project/Site	Country	Total Capacity	Technology Type	Collector Area, m^2	HTF in Solar Field	Processes	Process Temp., ˚C	TES	Storage Capacity	Storage Material
1 Of Tov Hatching Farm	Israel	212	FPC	270.6	water/glycol	cleaning	65	Short term-water storage	20	Water
Agrana Fruit	Mexico	112	PTC	742.5	water	process heating	25-100	Short term-water storage	9	water
Agropecuaria Tarasca S. de P.R. de R.L.	Mexico	126	PTC	540.0	water	Pelletized of Birds	25/95	Short term-water storage	12.15	water
Alimentos y Productos para Ganado Lechero	Mexico	179	PTC	1031.25	water	Water Heating	20-60	Short term-water storage	24.4	water
Alpino S.A	Greece	518	FPC	740.0	water/glycol	preheating water	20-70 °C	Short term-water storage	25	water
Barcel	Mexico	120	FPC	172	water	Preheating	60-70	Short term-water storage	12	water
Bonaprime Slaughterhouse	Mexico	45.5	FPC	65	water	preheating water	65-75	Short term-water storage	3	water
Battenkill Valley Creamery	USA	37	FPC	53	NA	preheating water	NA	Short term-water storage	NA	water
Bonilait Dairy	France	1050	FPC	1500	water/glycol	cleaning processes	80	Short term-water storage	30	water
Carnes La Laguna Slaughterhouse	Mexico	69	ETC	99	water	Cleaning	65-80	Short term-water storage	6	water
Carnes Muma	Mexico	50	ETC	72	water	cleaning	60-80	Short term-water storage	5	water
Carnes Selectas De Mexico Sa De Cv	Mexico	122	FPC	175	water/glycol	cleaning	55-85	Short term-water storage	5	water
Comfosa, S.A de C.V.	Mexico	202	PTC	1155.0	water	process heating	20/94	Short term-water storage	15.2	water
Canels S.A. de C.V.	Mexico	118	PTC	577.13	water	cooling processes	25/80	Short term-water storage	2	water
Carnes Selectas de Sonora S.A. de C.V.	Mexico	22	PTC	89.48	water	cleaning	20/70	Short term-water storage	3	water
Carnes Selectas de Sonora S.A. de C.V.	Mexico	22	PTC	89	water	cleaning	20/70	Short term-water storage	3	water
Centro Lechero Cooperativo de los Altos SCL	Mexico	94	PTC	422	water	cleaning	19/92	Short term-water storage	9.5	water
Conservas del Norte S.A de C.V.	Mexico	104	PTC	660	water	cooking	25/95	Short term-water storage	9	water
Dausa Milk	India	77	FPC	110	Na	cleaning	75-85	Short term-water storage	5	water
Durango Dairy Company (Productos Lácteos COVBARS)	Mexico	46	PTC	265	water	pasteurization	20/95	Short term-water storage	7	water
Edmund Merl - Gourmet Foods	Germany	397	FPC	568	na	cleaning	60	Short term-water storage	30.0	water
Eisvogel Hubert Bernegger	Austria	30	FPC	44	water/glycol	cleaning	Na	Short term-water storage	2.5	water
Emmi Dairy Saignelégier	Switzerland	360	PTC	627	water/glycol	general process heating	NA	Short term-water storage	15	water
Enfriadora Jaliciense S.A. de C.V.	Mexico	62	PTC	250	water	process heating	19/92	Short term-water storage	10	water
Futtermittel Fixkraft	Austria	226	FPC	324	water/glycol	process heating	na	Short term-water storage	6	water
GAMESA-QUAKER PEPSICO MEXICO	Mexico	45	FPC	64	water	process heating	60-70	Short term-water storage	4	water

GRUPO BIMBO	Mexico	162	FPC	232	water	process heating	60-80	Short term-water storage	15	water
Golan Winery	Israel	246	FPC	244	water/glycol	Cleaning	85	Short term-water storage	30	water
Grupo Mirasol de Occidente SA de CV	Mexico	64	PTC	396	water	Cooking	21/95	Short term-water storage	5	water
Grupo Mosa la Luz SA de CV	Mexico	92	PTC	693	water	Cooking	55/110	Short term-water storage	9.6	water
HP Dairy State	India	84	FPC	120	na	Pasteurization	na	Short term-water storage	6	water
IMATEC TORTILLA DOUGH FACTORY	Mexico	87	FPC	125	water	Cooking	65-85	Short term-water storage	5	water
INDUSTRIAS CRICOTL	Mexico	50	FPC	72	water	Cooking	55-85	Short term-water storage	3	water
Jebel Ali - Chocolate Factory	United Arab Emirates	357	FPC	510	na	process heating	na	Short term-water storage	5	water
Krispl Fruit Juice	Austria	78	FPC	112	na	Pasteurization	80	Short term-water storage	20	water
Kwality Walls Ice Cream	India	84	FPC	120	na	Extraction	na	Short term-water storage	11	water
Lacto Productos El Indio	Mexico	74	PTC	401	water	process heating	20-95	Short term-water storage	5	water
Lácteos Mojica	Mexico	59	PTC	132	water	Pasteurization	20-95	Short term-water storage	4.5	water
MARINELA CDMX	Mexico	114	FPC	164	water	process heating	60-70	Short term-water storage	9	water
Mandrekas S.A.	Greece	119	FPC	170	water	yoghurt maturing	40-45	Short term-water storage	2	water
Matatlan Dairy	Mexico	46	PTC	66	water	process heating	na	Short term-water storage	2.5	Water
Mevgal S.A.	Greece	NA	Na	NA	water/glycol	Cleaning	NA	Short term-water storage	NA	Water
Milma Dairy	India	1008	FPC	1440	Na	Pasteurization	Na	Short term-water storage	60	Water
Moguntia Spice Making	Austria	154	FPC	220	NA	Cleaning	Na	Short term-water storage	20	Water
Montesano - Jerez de los Caballero	Spain	17	FPC	252	na	Cleaning	40-45	Short term-water storage	30	Water
Nestle Chiapas	Mexico	455	FPC	650	water	process heating	90	Short term-water storage	25	Water
Nestle Dairy Plant Chapa De Corzo	Mexico	126	PTC	460	Water	Pasteurization	90	Short term-water storage	5	Water
Nestle Dairy Plant Lagos De Moreno	Mexico	137	PTC	245	Water	Pasteurization	90	Short term-water storage	5	Water
Nutrición Marina	Mexico	97	PTC	310	Water	Cooking	Na	Short term-water storage	7.5	Water

Procarne Slaughterhouse "A"	Mexico	77	FPC	110	Water	Cleaning	65-75	Short term-water storage	6	Water
Procarne Slaughterhouse "B"	Mexico	67	ETC	96	Water	Cleaning	65-80	Short term-water storage	5	Water
Panchmahal Dairy	India	330	FPC	472	NA	process heating	Na	Short term-water storage	20	Water
Parle Products Ltd. Neemrana	India	67	ETC	97	Na	process heating	70-75	Short term-water storage	7	water
Perfetti van Melle	Netherlands	1860	FPC	2400	Na	process heating	Na	Short term-water storage	95	Na
Poultry Processing Malaysia PPNJ	Malaysia	163	ETC	181	water	Blanching	70-75	Short term-water storage	8	Water
Prestage Foods	United States	5462	FPC	7804	water/glycol	cleaning	Min 60	Short term-water storage	946	Water
Procesadora de Alimentos Integrales - PAISA	Mexico	116	PTC	577	water	Cooking	95	Short term-water storage	3	Water
Quesera Lacteos Ticoy, S.A. de C.V	Mexico	42	PTC	250	water	pasteurization	20-95	Short term-water storage	6	Water
Quesos La Doñita	Mexico	22	PTC	66	Water	pasteurization	NA	Short term-water storage	1.5	Water
Quesos la Ordeña	Mexico	35	PTC	165	Water	process heating	20-80	Short term-water storage	3	Water
Rastro Garibay	Mexico	43	PTC	250	Water	process heating	18/95	Short term-water storage	3.1	Water
Sana International	Mexico	168	FPC	240	Water	process heating	55-75	Short term-water storage	7.5	Water
Santa Anita Dairy	Mexico	47	ETC	68	Water	Cleaning	60-70	Short term-water storage	3.5	Water
Sukarne Slaughterhouse	Mexico	136	ETC	195	Water	cleaning	70-80	Short term-water storage	10	Water
Sukarne Slaughterhouse- Mexicalı	Mexico	70	FPC	100	Water	cleaning	NA	Short term-water storage	5	Water
Solar Pasteurization	Mexico	240	PTC	1641	Water	pasteurization	85	Short term-water storage	50	Water
Stapleton-Spence Fruit Packing Co.	United States	1845	Unglazed collector	2637	NA	process heating	NA	Short term-water storage	50	Water
Tyras S.A.	Greece	728	FPC	1040	water/glycol	cleaning	20-80	Short term-water storage	50	Water
La Trinidad	Mexico	60	PTC	226	water	process heating	90	Short term-water storage	4.8	Steam
Barcel S.A DE C.V.	Mexico	78	PTC	529	thermo-oil	cooking	35-164	-	0.15	-
Nestle Toluca	Mexico	2590		3700	water	process heating	37	-	500	-

Table 13. SHIP with TES for Beverage industry (http://ship-plants.info/)

Project/Site	Country	Total Capacity	Technology Type	Collector Area, m^2	HTF in Solar Field	Processes	Process Temperature, ˚C	TES	Storage Capacity	Storage Material
Achaia Clauss S.A.	Greece	215	FPC	308	Water	Cleaning	40-60	Short term-water storage	15	Water
Bevco, S. De R.L. De C.V.	Mexico	15	PTC	34	Water	pasteurization	20/90	Short term-water storage	2.5	Water
Barrington Brewery & Restaurant	United States	57	FPC	82	-	Process heating	-	Short term-water storage	5.7	water
Bourdouil	France	52	FPC	105	water/glycol	cleaning	15-70	Short term-water storage	6	water
Brauerei Hald (brewery for beverages)	Germany	19	FPC	25	water/glycol	cleaning	60	Short term-water storage	3	water
Brewery Radoy	Ukraine	151	FPC	216	water/glycol	Process heating	-	Short term-water storage	15	water
Brown's Brewing Co	United States	37	FPC	51	-	cleaning	-	Short term-water storage	4	Water
CBC Brewery	South Africa	84	FPC	120	-	Process heating	-	Short term-water storage	10	Water
Casa Armando Guillermo Prieto S.A de C.V.	Mexico	136	PTC	816	Water	Process heating	-	Short term-water storage	9.9	Water
Cider house Hostetin	Czech Republic	25	FPC	36	water/glycol	pasteurization	-	Short term-water storage	9	Water
Destilería 501 S.A de C.V	Mexico	94	PTC	610	Water	evaporation and distillation	19/99	Short term-water storage	8	Water
Gatorade Mexico	Mexico	39	FPC	56	Water	process heating	60-70	Short term-water storage	3	Water
GICB Wine Cellars	France	130	ETC	216	Water	cooling processes	70-95	Short term-water storage	1	Water
Gatorade	United States	2954	FPC	4221	water/glycol	process heating	35	Short term-water storage	114	Water
Goess Brewery	Austria	1064	FPC	1520	water/glycol	process heating	80-90	Short term-water storage	200	Water
Milwaukee Brewing Co.	United States	72	FPC	104	-	process heating	-	Short term-water storage	4	Water
Nestle Waters	Saudi Arabia	360	FPC	515	-	Cleaning	-	Short term-water storage	15	Water
Winery Grombalia	Tunisia	49	LFC	132	Water	cooling processes	-10/7	short-term water storage	1	Water

Table 14. SHIP with TES for Textile industry (http://ship-plants.info/)

Project/Site	Country	Total Capacity	Technology Type	Collector Area, m^2	HTF in Solar Field	Processes	Process Temperature, ˚C	TES	Storage Capacity	Storage Material
Acme McCrary	United States	520	FPC	743	water/glycol	drying	-	Short term-water storage	1	water
Allegro S.A. Children's Cloathing Manufacturer	Greece	49	FPC	70	water/glycol	Cleaning	33-66	Short term-water storage	3.5	water
Guetermann Polygal	Mexico	315	FPC	450	water	Process Heating	55-85	Short term-water storage	20	Water
Harlequin	Spain	33	FPC	47	-	painting	-	Short term-water storage	5	Water
Ruyi Textile	China	6932	ETC	9903	Water	Process Heating	60	Short term-water storage	-	Water
Sharman Shawls	India	252	FPC	360	Water	Bleaching	100	Short term-water storage	8	Water

5. Sustainability Aspects

There are some important aspects in integration of TES in solar heat applications that has to be considered in sustainable transition to low carbon technologies in industry. For optimum solar process applications, analysis of both the energy efficiency and exergy recovery of TES system are necessary (Riahi et al., 2019). For a holistic approach, the environmental impact of TES is analyzed with Life Cycle Assessment (LCA) and carbon footprint evaluation (Lopez-Sabiron and Royo, 2014; Nienborg et al., 2018). For a comprehensive sustainability analysis, embodied energy of the materials used need to be considered. Finally, opportunities using TES as part of distributed energy management solutions and smart grids that will give added value and additional benefits should be analyzed (Rostampour et al., 2019).

According to Institute for Sustainable Future report (2017), TES systems have lower environmental and social impact than Li-ion batteries, lead acid batteries, compressed air energy storage (CAES) and hydrogen energy storage (ITS, 2017). Recently, Boer et al. (2020) proposed an initial framework to evaluate and improve the sustainability of technologies integrating TES for a circular economy. In this case study, different scenarios considered different options for recycling.

Oro et al. (2012) compared three different storage systems (high temperature concrete sensible TES system, molten salt sensible TES system and latent TES system from eutectic salt mixture) by using life cycle assessment methodology. Altough energy storage capacity of high temperature concrete TES system is very low; its global impact per kWh stored is lower than molten salt STES and latent TES systems. Heath et al. (2009) compared thermocline storage system filled with silica sand with 2-tank storage system with molten salt. Greenhouse gas (GHG) emissions were found to be nearly half for thermocline designed storage systems. Lalau et al. (2016) compared economical and environmental impact of conventional 2-tank molten salt TES system with storage unit using recycled ceramics. Using recycled ceramics from industrial wastes decreased 60% in water consumption, 30% in primary energy demand and payback time was found below 3 years with 25-30 years of lifetime. Table 15 shows sustainability studies related to STES systems in literature.

Table 15. Sustainability aspects of STESM Studies

STES system	Storage Material	TES Capacity	Location	Max operation temp, °C	Sustainability issues	Findings	Ref.
A tubular heat exchanger integrated into STESM	High Temperature Concrete	390 kWh	Plataforma Solar de Almeria (Spain)	390 °C	Concrete TES, molten salts sensible TES and molten salt mixture latent TES Systems are compared by LCA. Life Cycle Assessment (LCA) is developed based on the Eco-Indicator 99 (EI99) impact assessment method	Even though the energy storage capacity of the solid media is lower than the salt and PCM systems, the global impact (0.15 Impact/kWh) is low	(Oro et al., 2012)
2-tank storage system	Molten Salt mix (60 wt.% $NaNO_3$ and 40 wt.% KNO_3)	600 MWh	Andasol, Granada, Spain	550 °C	Concrete TES, molten salts sensible TES and molten salt mixture latent TES Systems are compared by LCA. Life Cycle Assessment (LCA) is developed based on the Eco- Indicator 99 (EI99) impact assessment method	Compared with PCM and solid media, the molten salts system presents higher global impact (5.67 Impact/kWh) during the operational phase, due to the use of two salts pumps, a water pump in the refrigerator system on the bottom, and electric heaters.	(Oro et al., 2012)
2-tank storage system	Mined nitrate salt	1990 MWhth	Daggetta, California, US	NA	Environmental impact of the two-tank and thermocline TES systems were compared by using hybrid LCA method (SimaPro v7.122 LCA modeling software)	Switching from two-tank to thermocline TES configuration reduces LC GHG emissions.	(Burkhardt et al., 2011)
Thermocline	Synthetic nitrate salt	1990 MWhth	Daggetta, California, US	NA	Environmental impact of the two-tank and thermocline TES systems were compared by using hybrid LCA method (SimaPro v7.122 LCA modeling software)	Synthetic nitrate salts may increase LC GHG emissions by 52% compared to mined salts.	(Burkhardt et al., 2011)
Thermocline	Silica Sand	NA	United States	NA	LC method is applied for 50 MWe CSP plant with six hours of two tank (molten salt) and thermocline tank (silica sand) thermal storage configurations	Embodied emissions for the 50 MWe thermocline system is 7890 $MTCO_2e$ used in 6-hour. This is less than half of two-tank molten salt storage system	(Heath et al., 2009)

2-tank	Molten Salt (40% Potasium Nitrate 60% Sodium Nitrate)	NA	United States	NA	LC method is applied for 50 MWe CSP plant with six hours of two tank (molten salt) and thermocline tank (silica sand) thermal storage configurations	Embodied emissions of GHGs from the materials used in the 6-hour, 50 MWe two-tank system are estimated to be 17,100 $MTCO_2e$.	(Heath et al., 2009)
Seasonal Storage & Tank storage	water-glycol mixture (0.67:0.33 weight)	208 kW	Zaragoza, Spain	60 °C	LCA assessment methods are applied to Central Solar Heating Plants with Seasonal Storage system. GHG emissions is evaluated by implementing IPCC 2017, IMPACT 2002+ and CED methods in SimaPro 7.3.3 program	Storage systems present significantly lower contribution in CO2 emissions. Storage systems' CO2 equivalent emissions per unit of total thermal energy demand is 22.58 kg CO2 eq/MWh. It is about 18% of total system emissions.	(Raluy et al., 2014)
Indirect 2-tank	Molten salt	1900 MWh_{th}	Daggett, United States	380 °C	Environmental implications such as GHG emissions, water consumption and land use of molten salt TES system in CSP plant was compared with CSP plant with a natural gas-fired heat transfer fluid heater	GHG emissions of CSP plant with molten salt TES is 80% less than plant with a natural gas-fired heat transfer fluid heater	(Klein and Rubin, 2013)
Thermocline	Cofalit	NA	Andasol Power Plant, Spain	1000 °C	Economical and environmental impact of storage unit using recycled ceramics was compared with conventional 2-tank molten salt TES system by LCA method.	Using termocline storage system filled with cofalit instead of molten salt 2-tank storage system allows reduction on GWP (40%), CED (30%) and water (60%).	(Lalau et al., 2016)
Thermocline	Basalt	NA	Andasol Power Plant, Spain	1000 °C	The embodied energy, GHG emissions and water consumption ratios were investigated by LCA method according to ISO 14040.	Using termocline storage system filled with basalt instead of molten salt 2-tank storage system reduced primary energy demand (65%), potential climate change (60%) and water consumption (80%) with 2 months payback time.	(Nahhas et al., 2018)

5.1. Sustainability Design Aspects

Using and storing of renewable energy in industry reduces production costs and increases the competitiveness of industry. Moreover, carbon emissions are reduced, and environmental degradation is prevented. Table 16 lists design criteria of a solar TES system.

Table 16. Design criteria of a solar thermal energy storage system (Tian and Zhao, 2013)

Criteria	Influencing factors
Technical criteria	• High thermal energy storage capacity • Efficient heat transfer rate between HTF and storage material • Good mechanical and chemical stability of storagematerial • Compatibility between HTF, heat exchanger and/ or storage material • Complete reversibility of a large number of charging and discharging cycles • Low thermal losses and ease of control
Cost-effectiveness criteria	• The cost of thermal energy storage materials • The cost of the heat exchanger • The cost of the space and/or enclosure for the thermal energy storage
Environmental criteria	• Operation strategy • Maximum load • Nominal temperature and specific enthalpy drop in load • Integration to the power plant

For industrial solar applications, some key points to be taken into consideration are as follows (Schmitt, 2016):
- Pre-Feasibility Assessment
- Analysis of Company
- Identification of Relevant Heat Sinks
- Evaluation of Integration Points

To ensure effective integration of TES in industrial processes, interrelated requirements between TES and processes must be ensured. As shown in Figure 32, industrial process requirements should be met by TES system parameters such as storage capacity, temperature range, cycle frequency etc.

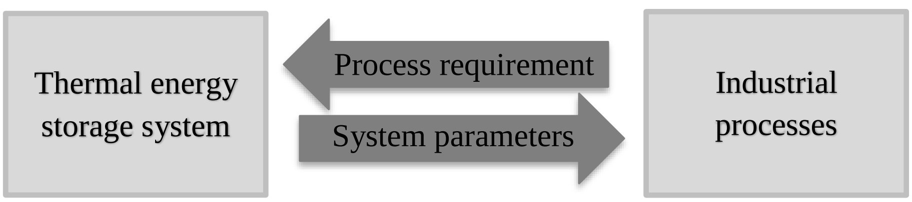


Figure 32. Requirements between thermal energy storage and industrial processes (Gibb et al., 2018)

Marti et al. (2018) defined the optimal storage system to be low cost and high efficient. Operational, geometrical, thermopyhsical and performance parameters affecting the optimal storage systems are given in Table 17.

Table 17. Parameters for optimal storage systems (Marti et al., 2018)

Operational Parameters	Thermopyhsical Parameters
HTF flow	Thermal conductivity
Charging/Discharging times	Density
Inlet Temperature	Heat Capacity
System Pressure	Viscosity

Geometrical Parameters	Performance Parameters
Storage tank dimension	Outlet temperature
Insulation thickness	Charged Capacity
Partical Diameter and shape	Net discharged energy
Porosity	Supplied energy
	Efficiency
	Cost

The optimum choice of parameters given in Table 17 is crutial for successful sustainable design and operation of STES systems. The previous sections 3.2 and 3.3 were dedicated on the design and operation of sensible TES systems and selection of materials based on their properties.

Kalogirou (2003) examined optimum design parameters for the maximum life cycle savings (LCS). As a result, system performance is mainly depending on collector area and storage tank volume. If collector area increases, more solar energy is collected but investment cost increases. On the other hand, if storage tank volume increases, more heat is stored but heat losses from the storage tank to the environment is increased. Optimum collector area and storage tank volume depend on process temperature range and collector type as given in Figures 33 and 34.

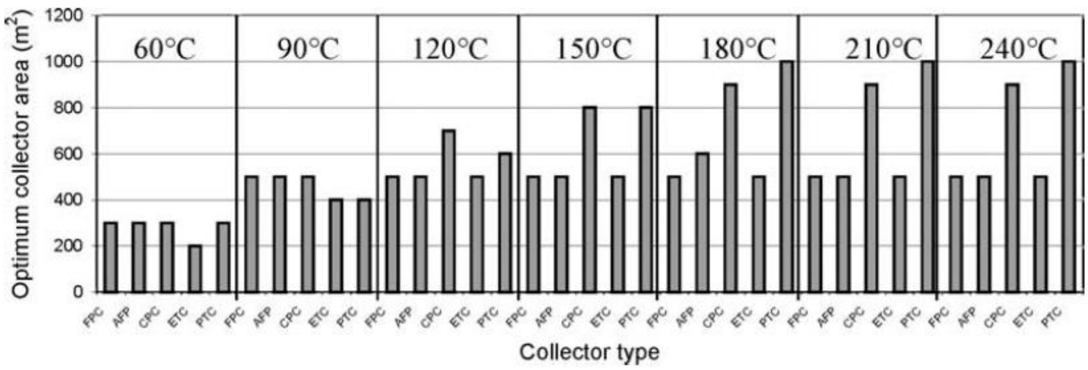


Figure 33. Optimum collector area for collector types and process temperatures (Kalogirou, 2003)

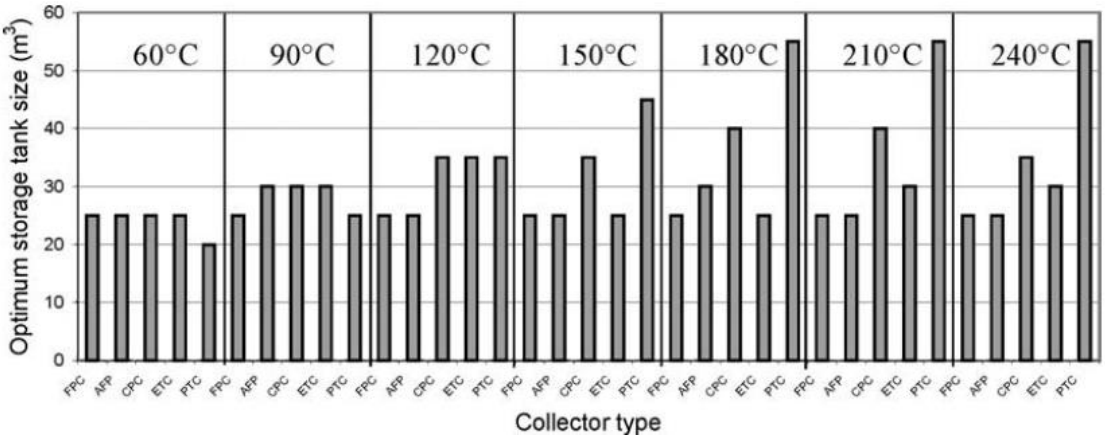


Figure 34. Optimum storage tank volume for collector types and process temperatures (Kalogirou, 2003)

In literature, researchers mainly focus on physical, chemical and thermal performance of storage materials in TES. However, technological, economical and environmental factors are basic system requirements that should also be considered.

5.2. Life cycle assessment and CO_2 footprint

Life cycle assessment (LCA) is the main tool to understand potential environmental impacts of systems and to reduce carbon footprint according the ISO 14040/14044 standards (Nienborg et al., 2018; Piemonte et al., 2011). Carbon footprint is an element of LCA methodology. Carbon footprint is defined as total amount of CO_2 that enters atmosphere caused by a process, in general expressed as grams of CO_2 equivalent per kilowatthour of generation (g CO_2 eq/kWh).

According to Global Energy Statistical Yearbook data (2019), CO_2 emissions from fuel combustion were 32.9 Gt CO_2 in 2018. Main carbon emission producers from fuel combustion are coal (44%), oil (33%) and natural gas (23%). Figure 35 indicated that developed countries have decreased or stayed constant level of CO_2 emissions from fuel combustion, in recent years.

Renewable energy sources provide environmental benefits with low CO_2 footprint (100g CO_2 eq/kWh) compaired to fossil fuels (above 1000 gCO_2 eq/kWh) (Aman et al., 2015). Especially, solar energy as a renewable energy source is inexhaustible source and it does not release harmfull emissions such as CO_2, SO_2 and NOx. Solar energy can be used in industrial plants, power plants, buildings and transportation. This is why many countries all over the World as an alternative green energy source prefer solar energy and researchers focus on environmental benefits of solar energy (Hernandez et al., 2014; Kabir et al., 2018; Kannan and Vakeesan, 2016; Shahsavari and Akbari, 2018). For example, Indian government wants to increase solar energy capacity from 20 GW to 100 GW untill 2022 to reduce harmfull gas emission from fossil fuels (Kar et al., 2016).

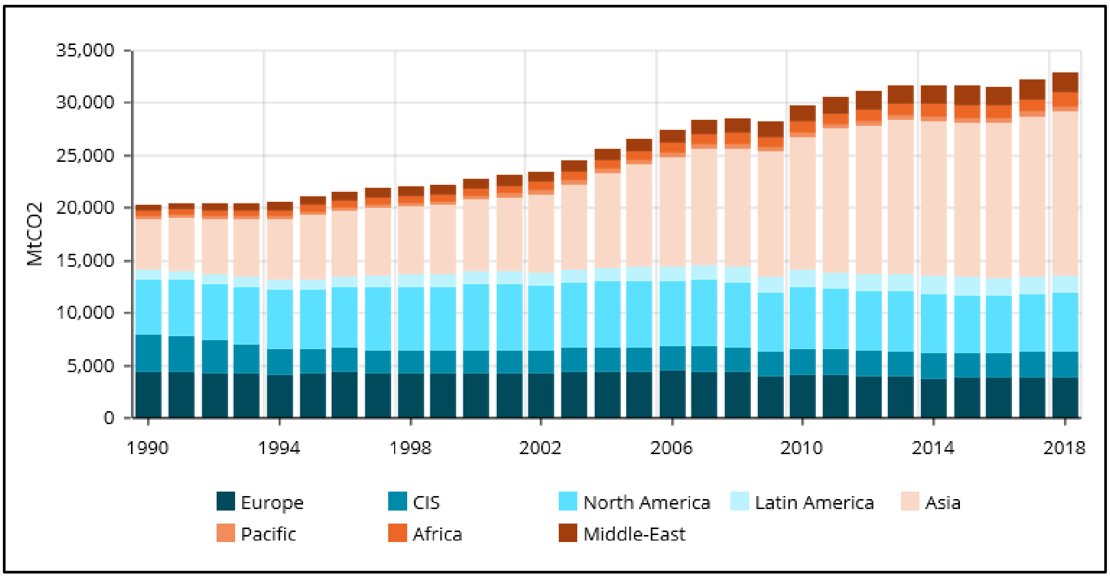


Figure 35. CO_2 emissions from fuel combustion in the World during 1990-2018 (Yearbook Energy Data, 2019).

According to Gasia et al. (2017) CO_2 footprint and the life cycle LCA are the main environmental factors. Kylili et al. (2018) examined life cycle assessment (LCA) for industrial solar applications. For large scale industrial solar thermal energy storage applications, it is found out that energy and carbon savings are approximately 35 - 75 GJ and 2-5 tonnes of CO_2 per kWth.

Oro et al. (2012) compared environmental impacts of solid (concrete) STES, liquid (molten salt) STES and LTES systems (molten salt) for solar power plants. LCA studies showed that concrete STES system has lowest environmental impact per kWh stored.

By using embodied energy and CAPEX methodologies, Jacob et al. (2016) quantified the environmental and economic impact of two (2) PCM-based and a liquid metal-based TES system, to identify if any or all of the proposed systems can reduce the environmental and economic impacts of the current two-tank molten salt system.

Piemonte et al. (2011) demonstrated that CSP plant with 2-tank molten salt storage systems is most preferable with respect to other conventional oil and gas power plants by LCA method.

TES systems provide opportunities for both efficient use of solar energy and reduction of CO_2 emissions. Ahmed et al. (2019b) performed review study on lower carbon footprint in desaliation process by using solar energy and thermal energy storage.

Life cycle costing (LCC) that covers all sustainability aspects – economic, environment and social -is the basis for LCA. For a thorough assessment, LCC tools can be used to determine the best solution with TES (Naves et al., 2019).

5.3. Distributed Energy Storage

In coming decades, it is expected that renewable energy sources will replace fossil fuels when considering the damages caused by fossil fuels to the environment and the fact that renewable energy is unlimited and cheap. Although renewable energy sources are more environmental and sustainable than fossil fuels, their added value should be improved by using them in distributed energy storage (DES) systems. DES systems provide more effective method to ensure balance between supply and demand in renewable power generation (Sue et al., 2014). DES can also be used for increasing renewable energy resource availability from power to different users such as buildings, industry and transportation. However, DES systems need to be further developed due to their high capital cost and limited life cycles (Sun et al., 2019). Performance of DES systems in solar power plants can be enhanced by optimal placement, sizing and operation (Das et al., 2019; Sameti and Haghighat, 2018). Das et al investigated optimal placement of DES systems to improve medium voltage IEEE-33 bus distribution system by reducing voltage deviations and power losses (Das et al., 2018a). In this study, performance factors such as placement, sizing and operation conditions of energy storage systems in distributed network to increase power quality were investigated.

5.4. Smart Grids

Smart grid is another alternative way to achieve maximum benefit from energy storage in renewable energy systems (Tao and Gao, 2020; Zame et al., 2018). Smart grids ensure communication between supplier and consumer to manage demand, reduce losses in the energy transmission lines, protect the distribution network and reduce costs. Energy storage is an essential component of smart grids to maintain energy balance between supply and demand. Integration of energy storage systems to smart grids is important for energy sustainability (Bayindir et al., 2016). Developments in smart grid and storage technologies are promising for future investments (Guney and Tepe, 2017; Lucas and Chondrogiannis, 2016).

5.5. Sector Coupling

Renewable energy sources and surplus energy produced in one sector can be used as supply in another sector. Energy storage closes the gap between these sectors in terms of distance and time. Surplus energy from one sector can also be transformed into other energy forms before it is used in another sector.

- Power ←→Buildings ←→ Industry
- Power ←→Buildings ←→ Transportation
- Power ←→Buildings ←→ Agriculture
- Agriculture ←→ Industry

Figure 36 shows different sector coupling alternatives (Nuffel, 2018). Some of these flexible concepts are so-called:

- Power-to-Heat
- Power-to-X (Chemicals)
- Vehicle-to Grid

With such models, more sustainable exploitation of renewables ensured by connecting different end-users to different renewable energy sources. Energy storage systems are major technologies that regulate fluctuations of energy supply (Boblenz et al., 2019). This method can provide more efficient and flexible energy systems. Also, the cost of decarbonisation can be reduced (Boblenz et al., 2019; Nuffel, 2018).

Sensible TES systems are 50 – 100 times cheaper than electrical storage systems. This makes them most preferable storage system in distribution network (Hennessy et al., 2019). In sector coupling, both large and small scale sensible TES systems can be used. Large scale and long term thermal energy storage systems can be preferred as central-TES scenario. But, thermal losses should be minimized with an insulation system (Brown et al., 2018). For such large scale applications STES is the most cost-effective. Industry as one of the important end users can benefit as a provider of surplus heat and also receive renewables for sustainable production. Especially Power-to Heat and Power-to-X options can be considered for industrial applications.

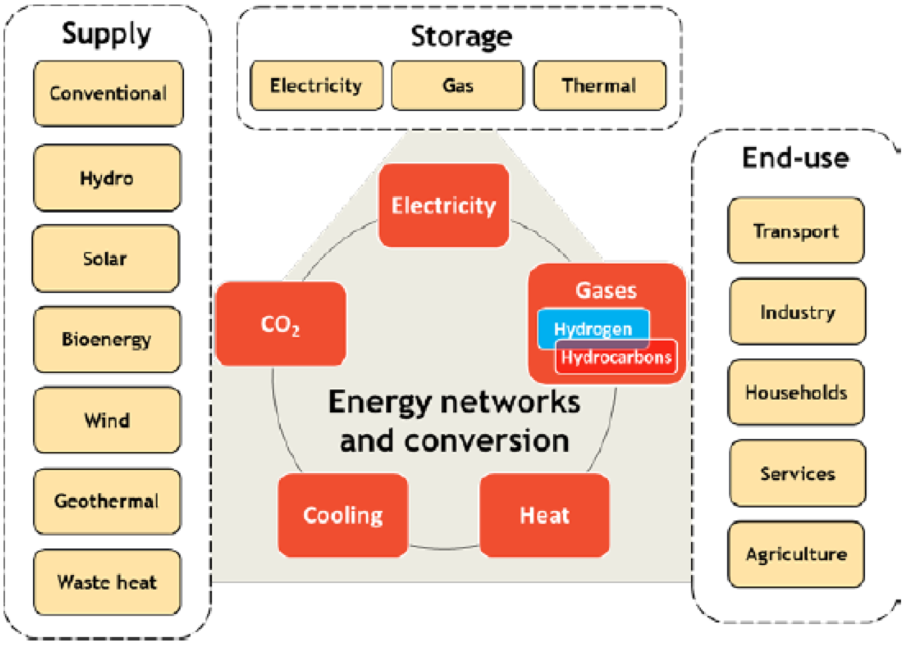


Figure 36. Sector coupling of energy systems (Nuffel, 2018).

6. Summary and Analysis

Extensive review of literature shows that STES can be a key technology in cost effective solar heat industrial applications. Although the awareness about the importance of using solar energy in industrial applications is increasesing, there are still opporunities to be discovered and aspects to be developed in this field. Table 18 summarises the findings of this review.

Table 18. Summary of findings for review on STES in solar industrial applications

	Existing Situation	Challenges	Opportunities
TES Materials	Natural materials such as rock, pebble, and water used as STESMs, long and reliable lifetime, no corrosive effect, higher thermal conductivity of most solid TES materials compared to PCMs	Depletion of natural sources, low storage capacity	Using low-cost waste based materials as STESMs with better storage properties
Design of TES	Water tank storage used commonly in SHIP, packed bed design is well known but not used commonly in current industrial solar applications	Water tank application temperature limited up to 100 °C, larger volume needed causes higher heat loss	Using packed-bed TES system with low cost and sustainable STESMs for higher temperature applications, heat pump integration together with STES, new design alternatives combining latent and sensible TES
Applications	Existing number of industrial SHIP plants in the World is 741, 300 of 333 large scale SHIP systems have a TES unit, Integration of TES in mainly low temperature industrial applications (<100 °C)	Higher investment cost (more than double) of collector systems for medium-high temperature applications, expensive HTF for high temperature applications needed	Decreasing pay-back times by integrating effective and low cost TES system, using alternative HTFs such as CO2
Sustainability	Lower global impact per kWh stored energy, reduction of greenhouse gas and embodied emissions	Difficult to compete with low fossil fuel prices, high cost of solar collectors and HTF for higher temperature applications, high pay back times (min. 7 years with TES)	Obligations to meet climate change targets, new applications models such as sector coupling, integrating STES using waste-based materials in circular economy

7. Conclusions and Future Outlook

This study presents an overview of existing research on sensible thermal energy storage systems and applications in solar heat industrial processes. Main conclusions are summarized below:

- There is an urgent need to switch from fossil fuel based energy systems to renewables in industry. Solar energy is the most abundant and promising renewable source, but it is still not widely used in industrial applications.
- Solar heat industrial processes are classified in 3 groups according to temperature range: low temperature (below 150 ºC), medium temperature (150 ºC - 400 ºC) and high temperature (above 400 ºC). Current solar industrial applications are generally for low temperature processes due to availability of inexpensive solutions by flat plate collectors.

- More than half of the existing solar heat industrial process projects are operated in food and beverage industries to supply hot water up to 95 °C for pasteurisation, cleaning and pre-heating processes. Water STES systems are used for such low temperature applications with significant reduction in fuel cost and CO_2 emissions.
- Latent heat storage and thermochemical heat storage systems have higher energy densities than sensible thermal energy storage systems, but cost-effective solutions for especially medium-high temperature industrial applications can be achieved by only STES systems.
- STESMs such as, rock, sand, or soil are well-known and abundant natural materials used for medium-high temperature range. Need for thousands of tonnes of STESMs in industrial applications may not be a sustainable solution due to extensive depletion of natural sources.
- Waste-based materials as STESMs are promising for high temperature TES applications up to 1000 °C. Such STESMs increase sustainabilty of solar heat applications in industry by decreasing greenhouse gas and embodied emissions and reducing the cost. They have good thermal properties with high thermal stability, heat capacity and thermal conductivity.
- Packed bed thermocline technology is well known and can be used as STES for sustainable and low cost applications in all temperature ranges of industrial processes.

In the future, integrating STES systems to achieve climate change targets in a sustainable way can increase industrial solar heat applications around the world. Some recommendations are:

- Industrial scale production of waste material as STESM can widen their applications.
- STES that uses waste-based materials can be a significant technology in closing the loop in circular economy that is part of the European Green Deal.
- Policy measures to encourage use of solar heat in industrial processes are needed.
- Further opportunities of new application modes such as cross-sectorial coupling in industrial solar heat applications should be investigated.

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