Thermal energy storage for solar power plant applications

Tonderai Linah Ruwa*, Humphrey Hugh Adun, Serkan Abbasoğlu
Department of Energy Systems Engineering
Cyprus International University
Haaspolat-Lefkosa, North Cyprus
*tomwenje@gmail.com

***Abstract*— As awareness of global warming and its adverse effects as caused by human activities increases in the world, renewable energy is fast gaining popularity as a way of combating the "energy trilemma" i.e. meeting requirements for environmental sustainability, energy security and energy equity. (WEC, 2015) The sun is the primary source of renewable energy with the exception of geothermal energy. Solar energy utilization is however limited due to intermittency of the resource. Solar thermal power plants employ solar radiation as the heat source to produce steam to drive turbines and produce electricity. Solar Thermal Energy (STE), unlike other solar energy conversion technologies, offers potential for storage of excess energy produced, for later use. This is a sure way of increasing operation hours and thus capacity to produce power. The paper reviews thermal energy storage systems and shows that the storage material is the main driving force in system design considerations.**

Keywords—solar thermal energy, storage systems, system components, capacity factor, efficiency

I. INTRODUCTION

As awareness of global warming and its adverse effects as caused by human activities increases in the world, renewable energy is fast gaining popularity as a way of combating the "energy trilemma" i.e. meeting requirements for environmental sustainability, energy security and energy equity [1]. The sun is the primary source of renewable energy with the exception of geothermal energy. It supplies the earth with 174 PW of radiant power before attenuation [2]. 51% of this reaches the earth's surface and is available for utilization.

Solar energy utilization involves the use of radiation from the sun in many ways, the most developed falling under two major categories; conversion of light energy directly to electrical energy – photovoltaics, and direct use of heat energy - solar thermal. Both concepts have been applied widely in modular as well as large scale installations.

Solar photovoltaic panels are used from a few watts in electronic devices like watches and calculators to utility scale installations like the Solar Star Power Station in California, USA, which is the largest plant with 579MW installed capacity. (DOE, 2015) Solar thermal power includes the flat plate collectors mostly used in domestic and commercial applications for water and space heating as well as the concentrating collectors used in utility scale applications. The world's largest concentrated solar power plant is Ivanpah Solar Electric Generating System in California, USA with an installed capacity of 392MW. [3]

The capacity factor of any energy system is ratio of the actual energy produced to the energy that would be produced if the system was working at installed capacity all the time. Renewable energy systems rank very low in capacity factor because of intermittence of resources [4]. If there is no wind, a wind turbine will simply not turn or if there is insufficient water in the rivers to fill the reservoirs, a hydro power plant cannot generate electricity. Solar has a greater limitation in that at night there is no energy received from the sun at all. This 'idle' time correspond to a sizeable chunk of the hours available in a year. Consequently, capacity factors of renewable energy systems are lower than the non-renewable with hydro being the highest at 40%, then wind at 25% and solar lowest in a range of 10-25%.

II. SOLAR THERMAL POWER PRODUCTIONS

In solar thermal applications, the collectors and the energy storage components are the essential parts determining performance. [5] The collectors are designed and fabricated to have good optical performance to capture as much of the received solar radiation and direct it to the receiver. The storage components are essential in that solar energy, and most renewable sources, are intermittent. When nighttime and weather variations are considered, the actual availability of solar radiation is low. It is this variability of the solar resource that makes storage critical.

Figure 2 shows a schematic of the components making up a solar thermal power plant with storage. The solar field has the mirrors, receivers, support structures, collector systems, heat transfer fluid (HTF), heat exchanger, HTF pumps, tracking and piping components. The thermal storage units comprises of the storage media, it's encapsulation, methodology, HTF, storage tank, heat exchanger and tank insulation.

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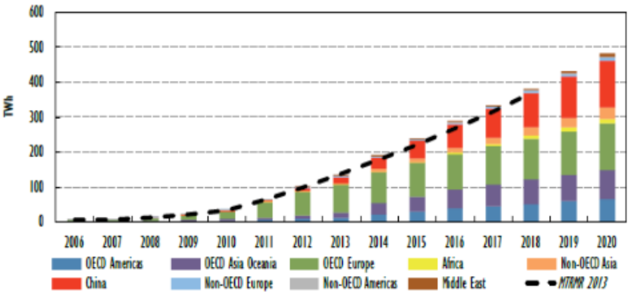

Fig. 1. Solar energy consumption and projection.

The power block is basically the same as in all other thermal power plants with the turbine, generator, heat exchangers, cooling tower and balance of the system [6] The figure also shows of solar energy collected during the day and how storage levels out the electricity production

III. SOLAR THERMAL ENERGY STORAGE

The collected solar energy in a solar thermal power plant is either used directly in the steam cycle or it is stored for later use. The efficiency of the storage system impacts on the overall efficiency of the power plant. For storage systems to have high performance they have to be durable with a very good heat transfer rate and high thermal storage density and low cost [7]. Thermal energy storage (TES) systems are integrated and function by buffering the system during the cloudy times, protracting delivery hours and improving yearly capacity factor

This paper reviews the different energy storage technologies.

A. Storage system design

In designing storage systems, consideration of the following has to be made; environmental sustainability, economic feasibility and technical feasibility. Starting from the plant level, considerations have to be made to determine the duration of storage, charge/discharge rates and integration of the storage system with the solar field and power block. Following which, there should be design at the component level to select the storage type, storage material, encapsulation material, compatibility between storage materials and HTF, cyclability and environmental impact. Overall, system level design will consider containment, heat exchangers, pumps, piping, compatibility with HFT on solar side and working fluid on power block side, assembly of sub-components, controls, efficiency and costs. Storage systems increase the investment cost of solar thermal power plants significantly and hence the design from the outset should be cost effective.

B. Storage materials

Materials are chosen based on the following properties;

- An excellent thermal storage capacity
- Compactness of the storage system

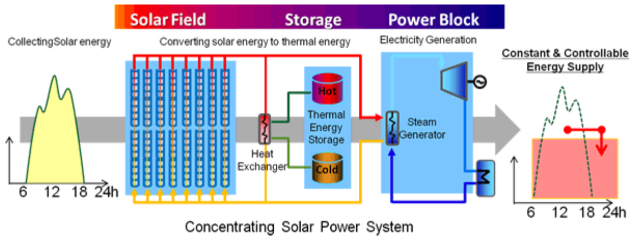

Fig. 2. Concentrating Solar Power System with storage

- High rate of transfer of the heat, from transfer fluid to storage material and throughout the material itself
- Mechanical and chemical stability
- Durability
- Cost

Density, specific heat capacity, thermal conductivity, coefficient of thermal expansion and cycling stability are the thermophysical properties of the materials considered in selection

IV. TYPES OF STORAGE MATERIALS

There are three main types of storage materials with differing storage mechanisms. In order of increasing storage capacity, these are; sensible heat storage, latent heat storage and chemical heat storage.

A. Sensible heat storage

These materials store heat by raising the temperature of the storage medium without changing its phase. The materials may be solid state or liquid state, storing energy during an increase or decrease in temperature of the storage media. The properties of some popular solid state sensible heat storage materials are given in TABLE 1 and TABLE 2. These materials have very good properties i.e. working temperature, thermal conductivity and low cost. However, the specific heat is relatively low and would imply that the storage units would be cumbersome.

Molten salts are the most popular when it comes to liquid state sensible heat storage. This is because they are very stable, non-toxic, non-flammable with high thermal conductivity and low vapor pressure and viscosity. Low melting is a crucial property for good performance of molten salts in sensible heat storage as this makes it easier to unfreeze the materials and keep them liquid. Safety issues arise in the use of oils because they have a high vapor pressure and require an airtight system. Though it has the highest thermal conductivity, liquid sodium may not be widely applied due to its chemical instability which poses safety risks and ultimately, high costs in trying to mitigate those risks. TABLE 3 shows the properties of some molten salts and high temperature oils.

With many cheap materials, sensible heat storage is widely applied and developed but has the lowest storage capacity. This results in larger, less compact systems. Though with higher storage capacity, latent heat storage has its shortcoming of low heat transfer, thus requiring augmentation. The greatest heat storage capacity is achieved with chemical storage. However, the following limitations affect these systems; complex reactor and reaction systems, poor durability and low stability.

B. Latent heat storage materials

Latent heat is the energy that is absorbed or released by a substance during a phase change process. It is termed latent as there is no observed temperature change. Latent heat storage materials may also be called phase change materials. They store and release energy during the phase change processes of melting / fusion or evaporation/condensation. Such materials should therefore have high enthalpies of phase transition. These enthalpies are much higher than sensible heat making these PCMs better storage media. TABLE 4 shows some phase change materials and their properties.

TABLE 1 SOLID-STATE SENSIBLE HEAT STORAGE MATERIALS (TIAN)

Material	**Material properties**		
	Working temperature(°C)	***Density (kg/m^3)***	***Thermal conductivity (W/mk)***
Sand Rock Minerals	200-300	1700	1.0
Reinforced concrete	200-400	2200	1.5
Cast Iron	200-400	7200	37.0
NaCl	200-500	2160	7.0
Cast steel	200-700	7800	40.0
Silica fire bricks	200-700	1820	1.5
Magnesia fire bricks	200-1200	3000	5.0

TABLE 2 SOLID-STATE SENSIBLE HEAT STORAGE MATERIALS (TIAN)

Material	**Material properties**		
	Specific heat (kJ/kg°C)	***Specific heat ($kW\ h_t/m^3°C$)***	***Cost per kg (US$/kg)***
Sand Rock Minerals	1.30	0.61	0.15
Reinforced concrete	0.85	0.52	0.05
Cast Iron	0.56	1.12	1.00
NaCl	0.85	0.51	0.15
Cast steel	0.60	1.30	5.00
Silica fire bricks	1.00	0.51	1.00
Magnesia fire bricks	1.15	0.96	2.00

TABLE 3 LIQUID-STATE SENSIBLE HEAT STORAGE MATERIALS (TIAN)

Material	**Material properties**						
	Working temperature (°C)	***Density (kg/m^3)***	***Thermal conductivity (W/m K)***	***Specific heat (kJ/kg°C)***	***Specific heat ($kW\ h_t/m^3°C$)***	***Cost per kg (US$/kg)***	***Cost per $kW\ h_t$ (US$/$kW\ h_t$)***
solar salt	220-600	1899	-	1.5	0.79	0.93	10.7
solar salt	120-500	1992	0.52	1.4	0.77	1.19	13.1
Mineral oil	200-300	770	0.12	2.6	0.56	0.30	4.2
Synthetic oil	250-350	900	0.11	2.3	0.58	3.00	43.0
Silicone oil	300-400	900	0.10	2.1	0.53	5.00	80.0
Nitrite salts	250-450	1825	0.57	1.5	0.76	1.00	12.0
Liquid sodium	270-530	850	71.0	1.3	0.31	2.00	21.0
Nitrate salts	265-565	1870	0.52	1.6	0.83	0.50	3.7
Carbonate salts	450-850	2100	2.0	1.8	1.05	2.40	11.0

TABLE 4 PHASE CHANGE MATERIALS AND PROPERTIES (TIAN)

Material	Material properties				
	Phase change temperature (°C)	***Density (kg/m³)***	***Thermal conductivity (W/mK)***	***Latent heat (kJ/kg)***	***Latent heat (MJ/m³)***
RT 100 (PARAFFIN)	100	880	0.20	124	-
E117 (INORGANIC)	117	1450	0.70	169	245
A164 (ORGANIC)	164	1500	-	306	459
$NaNO_3$	307	2260	0.5	172	389
$MgCL_2$	714	2140	-	452	967
LiF	850	-	-	-	1800
48%$CaCO_3$-45%KNO_3-7%$NaNO_3$	130	-	-	-	-
$MgCl_2$.KCl-NaCl	380	2044	0.5	149.7	306

C. *Chemical heat storage materials*

Endothermic reactions are those chemical reactions which absorb heat energy whilst exothermal reactions release energy. This is usually due to the breaking or forming of chemical bonds. Chemical heat storage is based on these reactions. A good chemical storage system should have excellent chemical reversibility, large chemical enthalpy change and simple reaction conditions. Table 5gives properties of some materials used in chemical heat storage.

Improving heat transfer

Some PCMs have very low thermal conductivities though they have high heat storage capacity. In aid of this shortcoming, some thermal conductivity enhancers such as metal fins, metal beads and metal powders may be employed to achieve an improvement of 60-150%. Other materials that may be used in enhancement are carbon fibers, carbon cloths and carbon brushes. One example is Paraffin/CENG (Compressed Expanded Natural Graphite) which is a composite material made up of paraffin whose thermal conductivity is enhanced by incorporated 5% graphite. Figure 3 and 4 show these enhancers.

TABLE 5 CHEMICAL HEAT STORAGE MATERIALS

Material	Material properties	
	Temperature range (°C)	***Enthalpy of reaction***
Iron carbonate	180	2.6 GJ/m³
Methanolation demethanolation	200-250	-
Metal hydrides	200-300	4 GJ/m³
Ammonia	400-500	67 kJ/m³
Hydroxides	500	3 GJ/m³
Methane/water	500-1000	-
Calcium carbonate	800-900	4.4 GJ/m³
Metal oxides (Zn and Fe)	2000-2500	-
Aluminum ore alumina	2100-2300	-

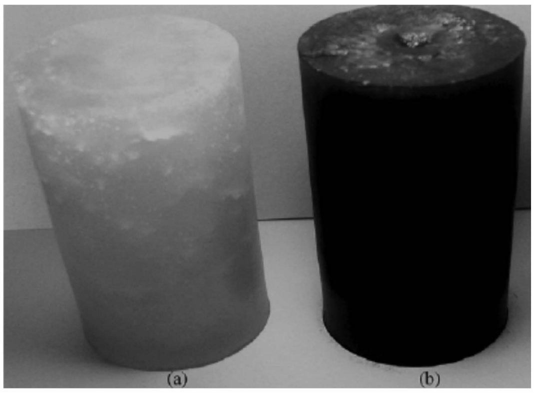

Fig.3. (a) pure paraffin as PCM and (b) Paraffin/graphite composite

V. OTHER SYSTEM COMPONENTS

The storage system incorporates other components which are selected once the storage material has been decided on as it determines the operating temperatures such as HTF, containment materials, tank stands, piping and pumps. Examples of containment materials are carbon steel and high nickel alloys. Fig. 5 shows a storage tank foundation of a 2-tank thermal storage system consisting of a concrete foundation, foam glass insulation, fire bricks and a steel slip plate. Heat transfer materials compatible with the system containment materials and operating temperatures are also chosen. Some materials are stable at very high temperature but solidify at lower temperatures making them unsuitable for a low temperature system.

VI. APPLICATION OF THERMAL STORAGE

Spain and USA have the highest installed capacity of solar thermal power. 71% of these power plants use parabolic troughs in the solar field [8]. Many of these have thermal storage systems with storage duration ranging from half an hour to eight hours. Andasol Solar Power Station in Granada Spain has a 150MW capacity and a 7.5 hour, 2-tank storage system using molten salts. Solana Generating Station in Arizona, USA has a 6 hour storage system and 280MW capacity. A 6 hour storage system incorporated into a 50MW solar thermal power plant would increase capacity factor from about 28 up to 43% and consequently increase LCOE by 10%.

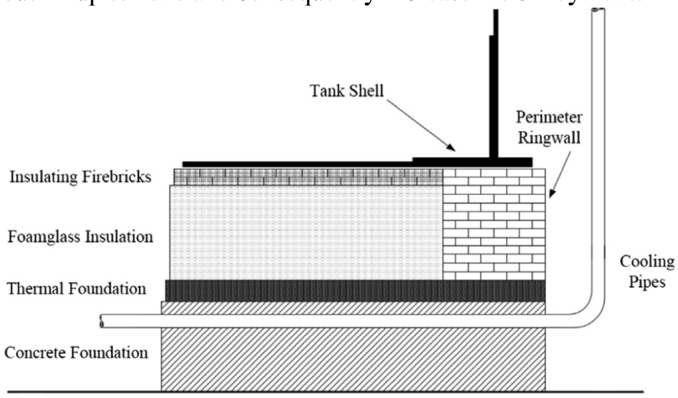

Fig. 5 Storage tank foundation

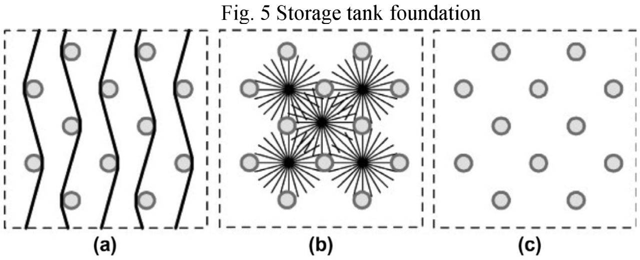

Fig.4. Carbon enhancers (a) fiber cloth (b) fiber brush (c) no carbon fiber

VII. CONCLUSION

Thermal energy storage undoubtedly improves performance in solar thermal power plants by increasing the number of plant operation hours, decreasing the number of turbine start-ups and ultimately increasing capacity factor. There are many available options for thermal storage. The review shows evidently that the determining component of the storage system is the storage material. In terms of cost it takes up almost 50%. Much research is going into storage material improvements.

Acknowledgment

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