Assessment of Solar Thermal Energy Storage Systems: Methods, Components and Integration

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Abstract - To address both the effects of climate change and our insatiable want for energy, an energy paradigm shift is required. The adoption of cutting-edge energy technology is required for this change to occur. Thermal energy storage is essential for balancing energy demand and supply, as well as guaranteeing system stability and maximizing the potential of intermittent renewable energy sources. It may not only maximize the usage of renewable energy and lower the price of electricity at night, but it may also provide flexibility and auxiliary services for solving future power supply/demand challenges. There is still a need for a clear and complete source of knowledge to provide related concepts as well as applications even if there are numerous good review materials in the literature covering different heat storage technologies independently. In order to study their performance, various TES types such as sensible, latent, and sorption have been briefly detailed in this work.

Keywords - Thermal Energy Storage, Balancing Energy Demand, Renewable Energy Sources, Power Supply, Heat Storage Technologies.

I. INTRODUCTION

Sustainability has become an everyday aspect of our lives, since climate change has been a crucial problem all across the globe. Most of the world's energy usage including greenhouse gas emissions is mainly attributed to the use of the non-renewable sources of energy such as fossil fuels and the built environment. All parts of human labor which result in alterations to the physical environment in order to deliver humans with sufficient surrounds for working, living as well as leisure activities are referred to as the "built environment". It doesn't only apply to the places we call home; it also includes public areas like parks, roadways, bridges, as well as other infrastructure. Nearly 36 percent of the world's total consumption of energy and 39 percent of its greenhouse gas emissions are attributed to the construction industry alone. Population growth as well as rapid urbanization are predicted to increase the built environment by 60 percent by 2050 [1]. As a consequence, carbon emissions need to be cut 40percent below 1990 levels by 2030 in Europe, for instance [2]. Another element which contributes to therise in the energy consumption is the urban heat island effect. This phenomenon occurs when the built environment absorbs and produces heat from human activity, causing cities to rise in temperature. Although cooling demand is predicted to rise by up to 750 percent in the residential sector as well as up to 275 percent in the non-residential sector by year 2050, this influence is not insignificant[3]. When it comes to heating as well as cooling, more than 3-quarters of our energy needs are now met by fossil fuels[4]. Since gas emissions and environmental health are linked, it is essential to minimize energy consumption while generating energy in an efficient as well as sustainable manner.

Approximately 90% of the world's total energy budget is accounted for by the processes (conversion, transport, as well as storage) associated with heat, which serves as a connection between primary as well as secondary energy sources [5]. In order to close the heat demand-supply gap, thermal energy storage (TES) technologies may help to improve not only the production but also the consumption of thermal energy. By reducing waste recovery, heat losses, and energy-saving measures, TES may also take control of the whole energy nexus, which includes all of the system's mechanical, electrical, fuel, as well as lighting components.

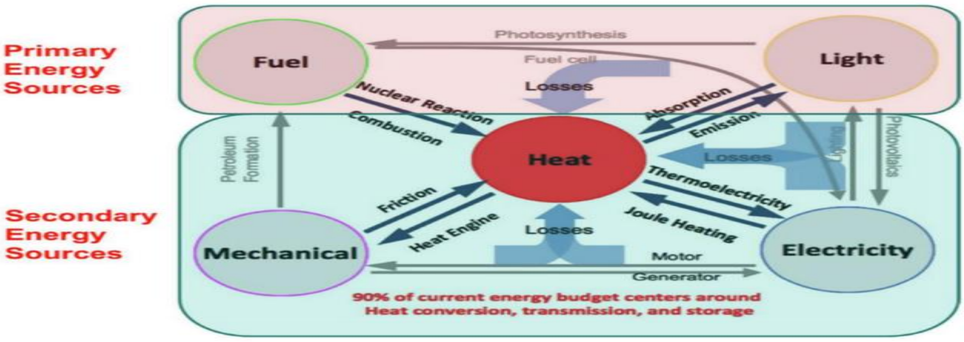

Fig 1. The Position Of Heat At The Core Of Energy Nexus Creating Connections Between Mechanical, Electrical, Light, As Well As Fuel Energy Sources [5].

As demonstrated in **Fig 2**, the "round-trip efficiency" of the thermal systems rises from less than 50 percent to roughly 70 to 100 percent as a result of the heat loss amount constituted by the system by means of TES methods. AsTES materials may absorb the surplus heat while charging, lowering heat losses and enhancing the overall efficiency of TES systems[6]. In order to reduce convective heat losses in the double storage tanks, it is important to use low-thermal conductivity materials like elastomeric materials (0.14 W/mK) as well as inert gases like argon (0.0160 W/mK) or apply vacuum to reduce the heat losses from the thermal storage tank's convection**. Fig 1** shows the position of heat at the core of energy nexus creating connections between mechanical, electrical, light, as well as fuel energy sources [5].

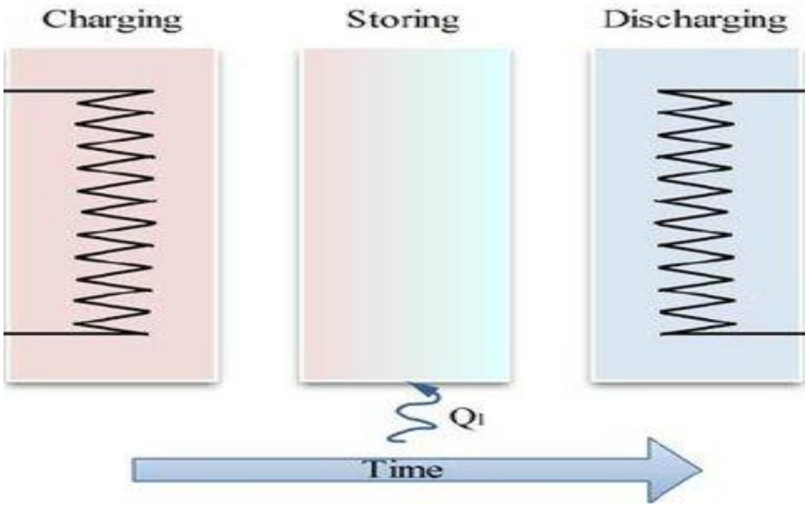

Fig 2. Principle of Thermal Energy Storage[7].

Research over this topic may benefit from this comprehensive examination of the TES approaches, which includes detailed explanations of relevant ideas as well as provides researchers with the necessary information to further their understanding[8]. Along with a comprehensive review and introduction to numerous materials that are currently being used in TES research with information on their thermo-physical characteristics, a focus on the practical applications as well as how they can be integrated with the other renewable energy systems has also been included in the work[9]. **Fig 2** shows Principle of Thermal Energy Storage[7].

II. THERMAL ENERGY STORAGE SYSTEMS

Multiple criteria may be used to classify thermal energy storage devices. Classification based on the TES technology is among the most often used. This includes "sensible heat storage"and the"latent heat storage", sorption, plus chemical processes.

Sensible Heat Storage

Gautam&Saini (2020),[10]&[11],in their review reasserted that the thermal energy stored by a material in the form of "sensible heat" is used to change its temperature and increase the heat capacity. Other variables include the material's thermal conductivity; the flow velocity of the "heat transfer fluid", as well as the thermal diffusivity may affect charging as well as discharging power. Both liquid and solid forms of a sensible heat storing substance are possible. Water is the most often used liquid because of its high specific heat capacity, cheap cost, plus ease of availability. As a storage medium for both space heating as well as cooling, water is the most typical choice including the household demands of hot water. Aquifers as well as solar ponds, both of which employ water as the storage medium, have also been thoroughly examined byKoçak et al.[2] in their work. Thermal oils as well as molten salts are other typical “sensible heat storage materials” in the liquid form, although their heat capacity is lower than water but their cost is greater. Earth resources like rocks, gravel, sands, wood, ceramics, as well as concrete are suitable “heat storage materials” in solid form. Solid metals may also be used in high-temperature operations. Due to their lower “specific heat capacity” as well as greater operating and maintenance costs, solid materials have lower “energy density” than liquids.

Latent Heat Storage

When a material experiences a phase transition, it stores thermal energy in the form of the latent heat as opposed to the “sensible heat storage”. There are four kinds of phase shifts that are taken into account by latent thermal energy storage processes: “solid–liquid, solid–solid, liquid–gas, as well as solid–gas”. PCM with solid-to-liquid transitions is the well-researched and widely used. Solid–solid has a lower latent heat than this transition. There might be a 10% or less expansion of the initial volume of the substance during the phase shift. Solid–solid transitions, as opposed to solid–liquid transitions, release less latent heat when the material transitions between polymorphic phases. Thermal energy is stored as well as released most efficiently during the solid-to-liquid and liquid-to-gas transitions, which need storage containers or open-air systems. Air, nitrogen as well as carbon dioxide are the three gases that may be discharged into the environment safely in this circumstance. An in-depth examination of the latent heat storage mechanism as well as its multiple applications in multiple sectors, as well as current technical as well as material breakthroughs, is provided bySadeghi, (2022) [5].

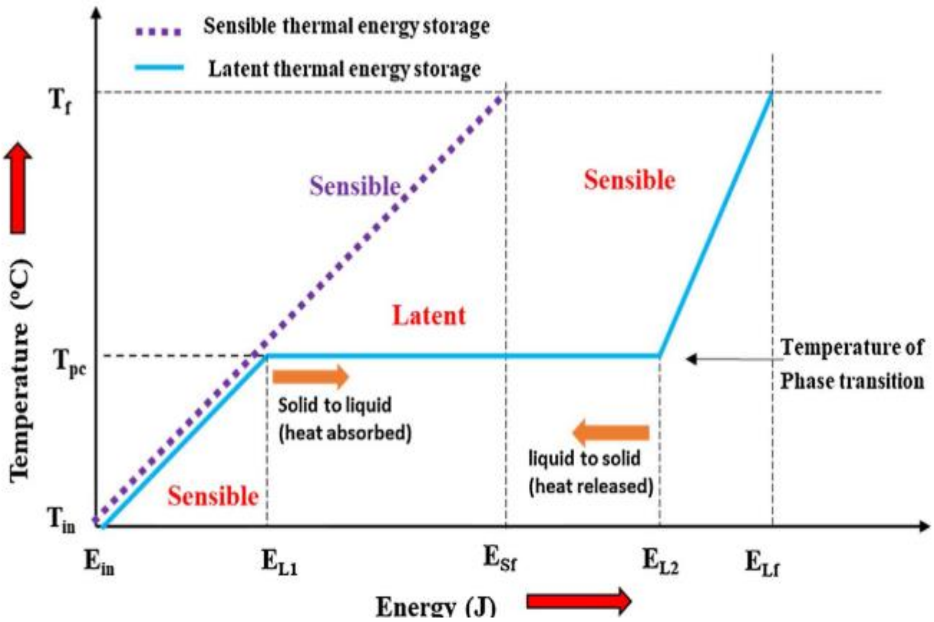

Fig 3 . Temperature curve of PCM undergoing the process of heat storage [12].

The benefits of latent TES, as described by Reddy et al.[12]area high “specific heat of fusion” and the capacity to store a large amount of energy with a little temperature shift, making it very efficient. When compared to the sensible heat materials, PCM has multiple times the storage capacity as well as an efficiency between 75 to 90 percent. Illustrated in **Fig 3** is the PCM phase transition profile. Chemical characteristics of PCMs (organic, inorganic, as well as eutectic PCMs) determine which PCMs are accessible at a given temperature range. Non-pure PCM undergoes its phase shift transition throughout a series of temperatures rather than at a consistent temperature [12].

Thermochemical Energy Storage (Sorption or Chemical Reactions)

A “chemical reaction or a sorption mechanism” is used to store heat energy in this technique. The endothermic as well as exothermic reactions that take place in a chemical reaction are responsible for storing and releasing energy.

When a gas (sorbate) comes in contact with a liquid or solid (sorbent), the gas settles down and is characterized as a surface phenomenon. Absorption as well as adsorption can be applied for the sorption of the sorbate by sorbent. This gas is called sorbate, as well as the liquid or solid substance is called sorbent. Mehari et al. [13]explain absorption as the process of sorbate penetration into a liquid sorbent, whereas adsorption is the phenomena of sorbate uptake and retention on the solid

sorbent surface see **Fig 4** a and b. Physisorption as well as chemisorption are two distinct types of sorption processes. In the absence of any kind of change in molecular structure of the TCM possessing divariant equilibrium at T_h, physisorption is explained by van der Waals forces as well as hydrogen bonds in the physical interaction between sorbate with the sorbent. The principles of physisorption heat storage are presented by Kuznik et al., (2018) [14]in their review work. We then look at research done at three different scales: reactor, material, and system to see what has been discovered.
The process of chemisorption occurs due the valence forces as well as the change in the TCM's structural configuration having mono variant equilibrium because of the chemical reactions in the TCM at T_r.

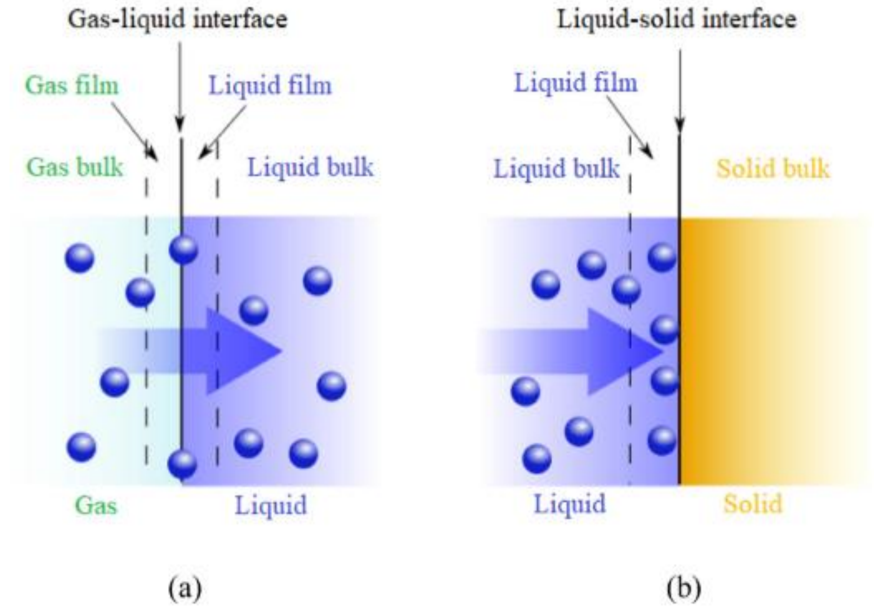

Fig 4 a) A liquid substance absorbing a gas through Absorption, b) A solid absorbing a liquid through Adsorption [5].

Closed and open thermochemical sorption storage systems are the most common types. In a closed system, there is no exchange of mass with the surrounding environment and may thus function in vacuum. Thus, allowing the use of "low-grade heat sources" for the evaporationof the working fluid more effectively. Based on 31 European sites, Bott et al., (2019) [15], reported on the current technology and forecast future developments based on approximately 800,000 m^3 of stored energy, which equates to the capacity of 56,600 megawatt hours (MWh) in the scenario of optimal storage utilization. Since the vapor is discharged into the environment when using an open system, the most common working fluid is water. Energy may be stored in thermochemical batteries with nearly little energy loss, making them an attractive option for a long-term or seasonal energy storage [17-19]. Nevertheless, its principal drawbacks are connected to its high complexity, high cost (particularly in the closed systems), and low heat transmission (for chemical reactions), as well as low stability, which decreases the storage efficiency over a certain time.

III. MATERIALS FOR SOLAR THERMAL ENERGY STORAGE SYSTEMS

An important first stage in the development of a TES system is to decide on the storage material[16], that has a significant impact on final system design. TES materials should meet the following standards, which are generally agreed upon:

i. A temperature range that is acceptable for the intended use.
ii. Energy density is quite high
iii. An excellent ability to transfer heat
iv. Densely populated
v. Sub cooling is quite low in this case (or supercoiling)
vi. Corrosion-proofing properties
vii. The capacity to withstand changes in temperature and pressure
viii. Non-toxic, non-flammable, and non-explosive
ix. small changes in vapor pressure or volume
x. Cost-effective and accessible in big numbers are the main advantages of this product

As there is no one TES material which can fulfill all of the criteria, every material has its own set of advantages and disadvantages. There are three types of TES materials: those that store heat as latent heat, those that store heat as a chemical energy, as well as those who store both. **Table 1** shows Physiothermal Prosperities of certain SHS materials.

Table 1. Physiothermal Properities of Certain SHS Materials[16]

Sensible Heat Storage material	Heat-capacity (J/kgK)	Density (kg/m^3)	Thermal-conductivity (W/mK)	Energy-density (kJ/m^3)
Graphite	609	2260	155	13,339.8
Aluminum	945	2700	238.4	2551.5
Copper	419	8300	372	3477.7
Molten salt (Nitrate based)	1542.3	2240	0.5	1.28×10^6
Granite	892	2750	2.9	2453
Iron	465	7850	59.3	3650
Sand	710	1631	1.8	1562
Concrete	879	2400	1.28	1933.8
Water	4163	998.3	0.609	4175
Engine oil.	1880	888	0.152	36×10^6

IV. CONCLUSIONS

Thermal energy storage plays an important role, as it may assist us control the demand and production of energy which are now out of phase. Although TES storage systems are limited in length, their integration may enable the use of the renewable energy, decrease energy consumption, as well as offer flexibility as well as auxiliary services in the event of supply/demand issues. Even though there are a number of important review articles in the literature covering multiple heat storage technologies, there is still a need for a clear and complete source of knowledge to highlight relevant concepts along with its applications. The main goal of this review paper is to analyze key research contributions concentrating on and connecting both the practical applications as well as the scientific parts of the issue after presenting thermal energy storage materials and operating technique.

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