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Thermal Energy Storage for Solar Plant Applications- A Review

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ABSTRACT: *This paper presents a reviewonthermalenergy storage systems and shown that the storage material is the main driving force in system design considerations. In solar thermal applications, the collectors and the energy storage components are the essential parts determining performance. The collectors are designed and fabricated to have good optical performance to capture as well as received solar radiation and direct it to the receiver. As awareness of global warming and it's 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. The market and research activities related to thermal energy storage systems have increased in recent years. 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. The 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.*

Key words~ *Thermal, Solar, Energy, plants, Collectors.*

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I. INTRODUCTION

Global warming is a major issue in the global community and this environmental menace is as a result of the greenhouse gases in the atmosphere. The major emitter of these gases is fossil fuels. Due to growing energy demands in the world as a result of growing world population, there has been more production of energy through hydrocarbon energy sources [1]. In a bid to curb future disastrous effects of fossil fuels effects, the use of renewable energy resources for energy production has steadily increased over the last decade. One of the major areas that have been commercially utilized as it relates to renewable energy production is solar energy.Solar energy is a renewable energy whose source is from the sun. The solar resource is enormous compared to our energy needs. In total, the sun offers a considerable amount of power: about 885 million terawatt hours (TWh) reach the earth's surface in a year, that is 6,200 times the commercial primary energy consumed by humankind in 2008 – and 4,200 times the energy that mankind would consume in 2035 following the IEA's Current Policies Scenario. It can be captured and transformed into heat or electricity. It varies in quantity and quality in places but also in time, in ways that are not entirely predictable. Its main components are direct and diffuse irradiance. The solar irradiance, i.e. amount of power that the sun deposits per unit area that is directly exposed to sunlight and perpendicular to it, is 1,368 watts per square meter (W/m^2) at that distance. Ultimately, of course, all energy supplies on Earth derive from the sun and solar energy provides a continuous stream of energy [2].

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 falls under two major categories; conversion of lightenergydirectly 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 [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%.

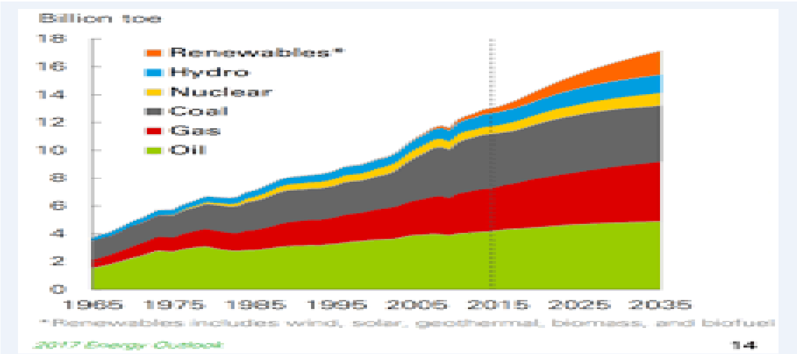

Fig. 1 Solar energy consumption and projection.

1.1 Aim and Objectives

The studyaimedatreviewing the thermal energy storage systems and shows that the storage material is the main driving force in system design considerations.

1.2Objective

The main objectives of the study were:

i. The paper highlighted the potential for existing and emerging solar-thermal storage materials in meeting growing global demand for renewable and sustainable thermal energy (heat).
ii. It showedthe efficiency of the thermal storage system impacts on the overall efficiency of the power plant.
iii. It showed how market and research activities related to thermal energy storage systems have increased in recent years;
iv. The review had shown how thermal solar energy can be exploited in various ways to generate heat.
v. To provide clean energy with zero emission recording to environmental analysis;

II. SOLAR THERMAL POWER PRODUCTION

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. 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 2 also shows how solar energy collected during the day and how storage levels out the electricity production.

2.1Solar Heat Market

The current market for solar-thermal technologies is relativelysmall but growing quickly. Considerable potential withimportant drivers exists for this strong growth to continue.

2.1.1 Current Market

Renewable energy sources provided 13.8% of the world'stotal energy supply in 2015 [17]. Although solar energy remains asmall fraction of this total (below 2%), it has a fast growth ratecompared to other renewable sources (solar-thermal: 11.7%per year, PV: 46.2% per year, both on average since 1990).

This growth has been made possible by the implementationof national policies that have supported renewable projects inEurope, and by the Chinese policy of high subsidies for PV [17, 18].The solar heat market represents a notable share of the globalheating market, mainly in providing space heating and domestic hot water (DHW)[16].The cumulative capacity of installed solar water heatershas reached 435 GWth and saved 116.4 million tons of CO_2equivalents[16]. This capacity increased by more than 6% in 2015despite a market slowdown in China (which accounts for 77%of all new installations) and Europe [19].Whilst the market for PV is well established in Europe,the annually-installed solar-thermal area in the EU lags that ofPV. For example, 16.5 million m^2 of solar-thermal collectors wereinstalled in Germany by 2012, compared to 230 million m^2ofPV [20]. Although solar-thermal technology is mature and readyfor mass deployment, significant market development is stillneeded in most EU countries.Potential market for solar-thermal technologies can play a leading role in meetingthedecarbonisation targets set in Europe and beyond. The IEAEnergy Technology Perspectives 2012 [21] shows solar heatinghas the potential to cover more than 16% of the low-temperatureheat use in an energy mix scenario that ensures a globaltemperature rise below 2 °C by 2050. In Europe,this share translates into 45% growth of the installed solarthermalcapacity by 2020, setting a challenging target of 1 $m^2$of collector area installed per European citizen by 2020 and of1.3 m^2 by 20505, [19, 21]. A large effort is needed to reach these goals because of the current fragmentation of the solar-thermalmarket[16]. The cases of Cyprus (where theinstalled capacity has reached 480 Wth per capita) Austria andGreece are particularly promising when contrasted with theopposite extremes of the UK, France, Italy, Spain and Portugal(below 10 Wth per capita). It is evident that a significantpotential for solar-thermal exists in some countries that receivesimilar solar energy to Greece and Cyprus and more thanAustria, and where the installed capacity per person is 10 timesbelow the target.Important factors that influence the solar heat market are thecost of local alternatives (oil, gas, coal, biomass, electricity,etc.), the characteristics of the local energy infrastructure andthe economy of key industrial sectors, such as construction.Denmark, for instance, has had a strong solar-thermal marketsegment. Despite having one of the lowest irradiance levelsin Europe, it has seen a growth of solar installations due tofact that most installations are connected to local districtheatnetworks.

2.2 Solar Energy-To-Heat Conversion

Sunlight is converted directly into thermal energyinsolarthermalcollectors. The sunlight is absorbed by a material, converted to heat and transferred to a fluid stream. The heated fluid (generally air, water, or antifreeze liquid) can be used for several purposes such as space heating, hot-water heating, process heating, and even cooling[9,10,11].Several designs of solar collectors are available, including with or without single or multiple glass covers, or with a vacuum for reducing the heat losses in so-called unglazed, glazed or evacuated collector designs. High-performance collectors feature thermal absorbers with special selective coatings that maximise the sunlight absorption and further reduce heat losses [10]. Black chrome over a nickel base is often used on copper plates, or alternatively, a titanium-nitrideoxide layer [12]. By reducing heat losses, the presence of a glass layer or vacuum allows operation with higher efficiencies at higher temperatures over an extended temperature range. A particularly interesting design is the evacuated-tube collector with heat pipes, in which the fluid evaporates and condenses in tubes as it transfers heat, in a relatively efficient and affordable design [11].

2.3Benefits of Solar Technologies

Solar energy is available worldwide and can play a key role in facilitating energy independence and resilience at the regional, national, local and household level. Low- and medium-temperature solar-thermal technologies can generate heat for many diverse residential, commercial and process heating applications, which can form natural distributed energy provision systems with high reliability. The renewable energy sector employs 9.5 million people worldwide, of which 3.7 million are in the solar sector (including photovoltaics -PV-, solar heating and cooling) [15]. Small-scale thermal and stand-alone applications create opportunities for local economic development in a much localised value chain covering design, manufacture, installation and maintenance. In addition, solar systems are insulated from the instabilities of oil price fluctuations, conflicts and financial uncertainty [14].

III. METHOD

This paper reviews the different energy storage technologies. A number of different sources were used to collect the information presented in this paper. The paper is based on a review of relevant scientific publications and projects, as well as communication with solar thermal energy storage system manufacturers and installers. The list of projects and producers that was gathered in IEA SHC Task 42 – Compact solar Storage has been used as a starting point [4].

Other sources of information are publications in peer-reviewed journals and conference proceedings, as well as company information, case studies and personal communication. A thorough evaluation of thermal solar Storage's performance is beyond the scope of this publication, but the performance of thermal. The assessment was made using some indicators. That is the evaluation is based on findings from the literature review, and information from producers and installers.

IV. RESULTS

4.1Solar 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.

The thermal conversion process of solar energy is based on well-known phenomena of heat transfer. In all thermal conversion processes, solar radiation is absorbed at the surface of a receiver, which contains or is in contact with flow passages through which a working fluid passes. As the receiver heats up, heat is transferred to the working fluid which may be air, water, oil, or a molten salt. The upper temperature that can be achieved in solar thermal conversion depends on the insolation, the degree to which the sunlight is concentrated, the specific heat of the working fluid, and the measures taken to reduce heat losses from the working fluid. Since the temperature level of the working fluid also can be controlled by the velocity at which it is circulated, it is possible to match solar energy to the load requirements, not only according to the amount but also according to the temperature level, i.e., the quality of the energy required. In this manner, it is possible to design conversion systems that are optimized according to both the first and the second laws of thermodynamics.

According to the Energy Information Administration (EIA), water heating accounted for 6.7% of commercial building energy use, and solar energy supplied approximately 2% (0.05 Quads/year) in 2010 [6]. EIA also estimated that 3% of buildings have solar thermal systems and, for the facilities that have solar thermal, approximately one third of the DHW load is supplied by the on-site solar thermal system [14].Domestic hot water (DHW) systems are primarily served by electric and natural gas heating systems, with the majority of the heating coming from natural gas [14]. Facilities switching to solar thermal that currently use electric hot water heating will have better economics than facilities with natural gas heating systems, due to the increased cost of electricity on a $/MMBtu basis [5]

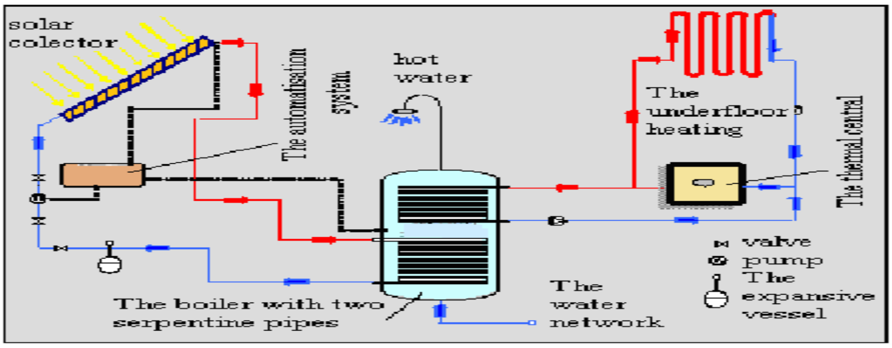

Figure 2: Domestic hot water fuel sources

4.1.1 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 [14].

4.1.2Storage Materials

Materials are chosen based on their properties favoring the following:

i. An excellent thermal storage capacity;
ii. Compactness of the storage system;
iii. High rate of transfer of the heat, from transfer fluid to storage material and throughout the material itself;
iv. Mechanical and chemical stability;
v. Durability;
vi. Cost.

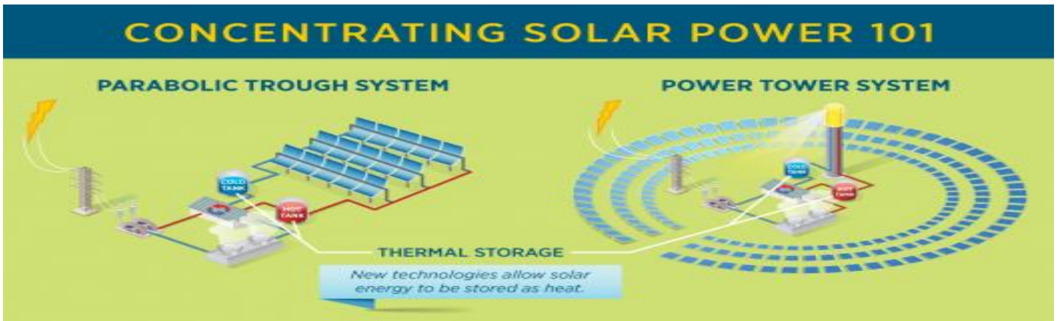

Figure 3: Concentrating Solar Power System with Storage [12].

Density, specific heat capacity, thermal conductivity, coefficient of thermal expansion and cycling stability are the thermophysical properties of the materials considered in selection. There are three main types of storage materials with differing storage mechanisms [5]. In order of increasing storage capacity, these are; sensible heat storage, latent heat storage and chemical heat storage. Store heat by raising the temperature of the storage medium without changing itphase. 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 [12].

4.1.3Sensible Heat Storage Materials

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. 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 [6].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 vapour 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 2 shows the properties of some molten salts and high temperature oils [7].

4.1.4 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 [7]. These enthalpies are much higher than sensible heat making these PCMs better storage media. Table 3 shows some phase change materials and their properties.

Table 1: Solid-state sensible heat storage materials [7]

Material	Working temperature (°C)	Density (kg/m^3)	Thermal conductivity (W/mK)	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$)
Sand-rock minerals	200-300	1700	1.0	1.30	0.61	0.15	4.2
Reinforced concrete	200-400	2200	1.5	0.85	0.52	0.05	1.0
Cast Iron	200-400	7200	37.0	0.56	1.12	1.00	32.0
NaCl	200-500	2160	7.0	0.85	0.51	0.15	1.5
Cast steel	200-700	7800	40.0	0.60	1.30	5.00	60.0
Silica fire bricks	200-700	1820	1.5	1.00	0.51	1.00	7.0
Magnesia fire bricks	200-1200	3000	5.0	1.15	0.96	2.00	6.0

Table 2: Liquid-state sensible heat storage materials [7]

Material	Working temperature (°C)	Density (kg/m^3)	Thermal conductivity (W/mK)	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$)
Hitec solar salt	220-600	1899	-	1.5	0.79	0.93	10.7
HitecXL 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 3: Phase change materials and properties [7]

Material	Phase change temperature (°C)	Density (kg/m^3)	Thermal conductivity (W/mK)	Latent heat (kJ/kg)	Latent heat (MJ/m^3)
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

4.1.5 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 [6]. A good chemical storage system should have excellent chemical reversibility, large chemical enthalpy change and simple reaction conditions. Table 4 gives properties of some materials used in chemical heat storage [7].

4.2Improving 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% [6]. 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 4: Chemical heat storage materials [7]

Material	Temperature range (°C)	Enthalpy of reaction	Cost per kg (US$/kg)
Iron carbonate	180	2.6 GJ/m^3	**2.5**
Methanolationdemethanolation	200-250	-	**0.95**
Metal hydrides	200-300	4 GJ/m^3	**0.78**
Ammonia	400-500	67 kJ/m^3	**3.3** **1.15**
Hydroxides	500	3 GJ/m^3	**2.0**
Methane/water	500-1000	-	**2.3**

Calcium carbonate	800-900	4.4 GJ/m^3	**0.78**
Metal oxides (Zn and Fe)	2000-2500	-	**1.0**
Aluminium ore alumina	2100-2300	-	**3.00**

Figure4: Photograph of (a) pure paraffin as PCM and (b) Paraffin/graphite composite

4.2 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. Figure 6 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

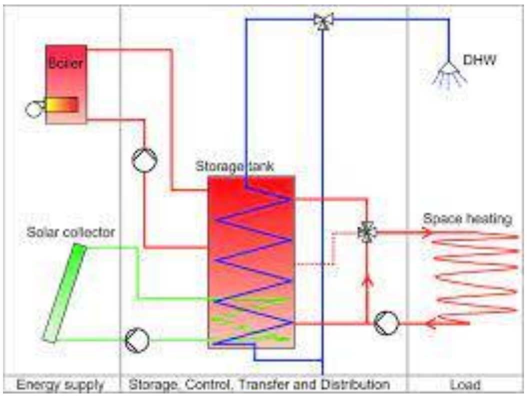

Figure 6: Storage tank foundation

4.3 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%.

V. DISCUSSION

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.

The Thermal energy storage technology market is still very small and it shows in different countries a strong dependence on individualcompanies. The choice of thermal energy storagetechnologyseems to bedriven by other factors. The economic benefit of thermal energy storage today depends to a large degree on the availability ofsubsidies, or funding of pilot projects.

VI. CONCLUSION

In the past decade, thermal energy storagehas gone from largely project-specific developments to relativelystandardized systems. The market is still very small compared to the solar components markets, but a number ofcommercial products are now available. Different types of systems have gained ground in different countries basedon the composition of the earlier markets for PV and solar thermal, but also depending on the success of individualcompanies. The available economic subsidy schemes may also have contributed to shape the markets in the differentcountries.

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