R15.1 Report on the Methodology to Characterize Various Types of Thermal Storage Systems

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Project SFERA

Deliverable 15.1

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July 2010

Solar Facilities for the European Research Area

ABSTRACT

Nowadays many scientific and technological efforts are being devoted to R&D on thermal energy storage for solar power plants. The objective of Task-1 (WP-15) is to provide a systematic approach to classifying, characterizing, and comparing various types of thermal storage concepts in order to lay out a basis for a scientifically sound methodology of developing, designing and validating cost-effective thermal energy storage systems for large-scale CSP plants. This report examines the-state-of-the-art solar thermal storage technologies for electric power generation, with a special focus on such characteristics categories as thermodynamics, storage medium properties, heat transfer capability and thermal efficiency, chemical stability and compatibility of materials, design and operational issues. It also underlines the role and importance of such basic parameters of solar power plants as a solar fraction and solar multiple for assessing thermal storage systems. The results of this report are supposed to assist the other Tasks of WP-15 in developing the methodologies for standardized testing, evaluation and assessment of different energy storage materials and systems.

Keywords: Solar power plants; Thermal storage; CSP systems; Storage capacity; Storage materials; Heat transfer fluid; System analysis and characterization.

Nomenclature

CSP	Concentrating solar power
DNI	Direct normal irradiance
E	Thermal energy (kW h m^{-2})
GS	Granada, Spain
HSM	Heat storage material (medium)
HTF	Heat transfer fluid
LV	Las Vegas, USA
MR	Mitspe Ramon, Israel
PCM	Phase change material
Q	Thermal power (W m^{-2})
STES	Solar thermal energy storage
t	Time (h)
yr	Annual operational cycle (8760 h)

Greek letters

α	Solar fraction of hybrid power plants
β	Solar collector factor (solar multiple)
φ	Nominal storage capacity (kW h m^{-2}; h; day)

Subscripts

A	Annual total quantity of energy
F	Fossil fuel power in the hybrid mode
L	Thermal power equivalent to electric load
R	Direct normal radiation
S	Storage
0, 1, 2, 3	Thermal power variables shown in Fig. 1

Contents

1. Introduction

This report is devoted primarily to energy storage for solar thermal electric power plants using solar thermal energy to generate electricity. In the last two decades, Concentrating Solar Power (CSP) technology has successfully demonstrated its capability of converting solar radiation into high-temperature heat. The produced power is the cleanest and most efficient form of renewable energy. Today, a growing number of commercial CSP-based electric power plants have been either already in operation or under construction in various sun rich regions around the globe, where annual direct normal irradiation is close or above 2 MWh/m^2 (EPRI 2009), (SolarPACES 2009), (Staley, et al. 2009), (Trieb, et al. 2009), (Fernandez-Garcia, et al. 2010). The most advanced CSP systems, the parabolic trough concentrators, compact linear Fresnel reflectors and power towers, are capable to power the conventional steam/gas turbine cycles for electricity generation (Mills 2004), (Müller-Steinhagen and Trieb 2004). In addition, solar dish/engine systems are being designed to convert the concentrated radiation from the sun into electricity typically by means of a kinematic Stirling engine, although a Brayton-cycle engine is a possible option too (Mills 2004).

However, due to the high intermittency of solar radiation reaching the surface of the Earth, the CSP technology has a limited capability of replacing fossil fuels for power production. Natural phenomena, such as unstable weather conditions, variations of the elevation and azimuth angle of the sun through the cycle of the day, and also the year, and the necessity to pause the solar plant operation in nighttime have a strong negative impact on the availability of solar energy for utility- scale power generation. Thus, an average daily operating time of a CSP system throughout a year is approximately 6 hours only, while load demand from the utility grid normally continues 24 hours a day.

In order to stabilize power delivery and prolong daily operating hours, solar thermal electric power plants beside a CSP system comprise also a solar thermal storage and fossil fuel co-firing facilities, as is shown schematically in Fig. 1. For this purpose, the size of a CSP system must be increased by a factor called as solar multiple (Montes, et al. 2009) to allow operating of the power block simultaneously with charging the thermal storage on daylight hours when the insolation level is sufficiently high. This makes possible continuous electricity production at full load during the day by direct input of solar energy to the power block combined with utilizing the storage and/or fossil fuel backup when the solar radiation is low or not available, including some hours after sunset (Herrmann and Kearney 2002), (Müller-Steinhagen and Trieb 2004), (REN21 2009), (Steinmann, Eck and Laing 2005).

A share of solar energy in the annual electricity production capacity of hybrid solar-fossil power plants is called as solar fraction or annual solar capacity factor. The capability of hybrid systems without solar energy storage to match load demands typical for domestic and industrial areas is limited to a solar fraction $\alpha = 0.13 - 0.25$ (Jacobson 2009), (Müller-Steinhagen and Trieb 2004), (Trieb, et al. 2009).

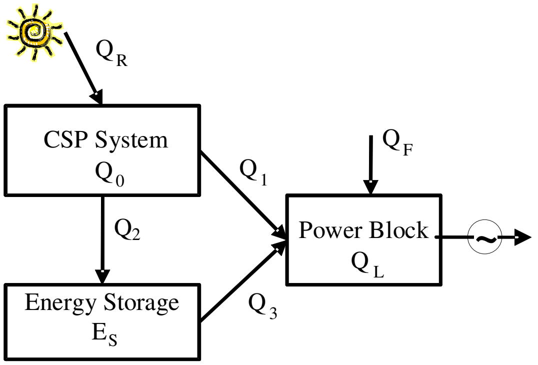

Figure 1. A schematic diagram of hybrid solar-fossil thermal power systems.

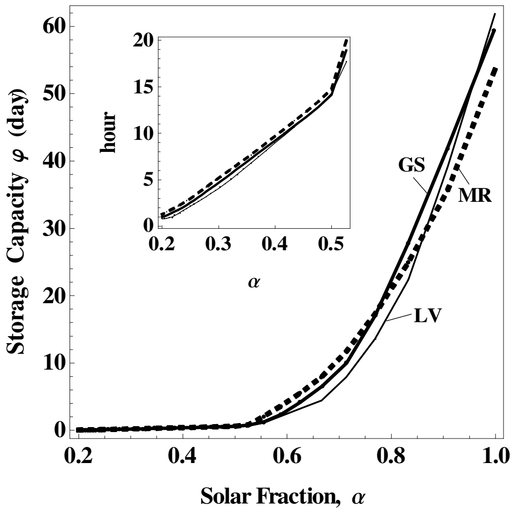

Figure 2. Nominal storage capacity φ as a function of solar fraction α for parabolic trough plants.

Simulation results for a parabolic trough solar power plant having thermal storage for 6 hours[1] full load capacity give $\alpha = 0.4$ versus 0.25 without storage (Price 2003). According to storage capacity estimates presented by (Price, Lûpfert, et al. 2002), a solar fraction resulting from 12 hours storage is $\alpha = 0.53$, and due to (Staley, et al. 2009), a larger storage of 15 hours capacity leads to a solar fraction $\alpha = 0.65$-0.71.

To minimize the fossil fuel dependency of hybrid power plants by making the most of solar energy, it is necessary to accumulate a large amount of energy during sunlight hours in order to retrieve the storage on a seasonal basis. Large-scale storage assessments found in the literature are scarce and sometimes contradictory. As it follows from a simulation study carried out by (Iannucci 1981) for solar thermal electric power plants, storage capacities ranging over several hundreds of full load hours are required to provide 100% ($\alpha = 1$) load demand with solar energy. At the same time, solar fractions as large as $\alpha = 0.8 - 0.9$ were predicted for moderate amounts of storage of about 50 full load operating hours, for the site of Albuquerque, USA.

In general, solar thermal energy storage (STES), as the factor increasing solar capacity of a power plant while improving its operating performance, has the potential to bring down the levelized cost of solar energy, which is still higher than most of fossil fuels. It is clear that a long-term (tens of hours and more) storage can be very expensive due to large capital investments in both the storage and the CSP system, taking into account a large solar multiple, up to 4-5 for a pure solar plant (Iannucci 1981). For a given hybrid plant location, the optimum storage capacity would mainly depend on trade-off between investments in CSP, storage and fossil fuel backup systems, taking into account the environmental factors as well. Undoubtedly, the availability of inexpensive and efficient thermal storage is one of the major issues faced today by the CSP technology in further deployment of solar power plants.

A characteristic feature of CSP storage systems is that they are widely diverse with respect to thermal storage technology, based on either sensible, latent or thermochemical heat. Different storage materials and heat transfer fluids are available for charging and discharging the storage (EPRI 2009). The variety of operation parameters includes temperature, pressure, power level, rates and durations of charge and discharge cycles, etc. The objectives of Task-1 was to provide a systematic approach to classifying and characterising various types of thermal storage systems in order to lay out a basis for a scientifically sound methodology of developing, designing and validating cost-effective thermal energy storage systems for large-scale solar thermal power plants.

This report is based on the analysis of solar thermal storage developments for electric power generation, with a special focus on such system characteristics categories as thermodynamics, storage medium properties, heat transfer capability and thermal efficiency, chemical stability and compatibility of materials, design and operational issues. It also underlines the role and importance of two basic parameters of solar power plants such as the solar fraction and solar multiple for characterizing thermal storage systems. The results of this report are supposed to

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[1] It is convenient to appraise storage energy in the units of time (hour), as an operating period during which a power plant can run at full load on the storage power only.

assist the other Tasks of WP-15 in developing the methodologies for standardized testing, evaluation and assessment of different energy storage systems.

2. System Analysis of STES Operation

2.1. Energy Flow Modelling

A mathematical-statistical model of hybrid solar-fossil power plants based on energy balance equations has been developed to simulate the operation of a thermal storage system in a wide range of storage capacities (Adinberg 2010). The results of this modelling study were significant to identify the distinction between the diurnal and seasonal storage scales.

The general model of solar thermal electric power plants shown in Fig. 1 consists of three major components: a solar collector (e.g. parabolic trough technology), a thermal energy storage unit (considered as a black box), and a power block (e.g. Rankine cycle, including fossil fuel backup). The plant employs also a power control system, as is explained in the following. Primarlly, the CSP sytem collects and concentrates the incident solar power Q_R (direct normal irradiation) to produce thermal power Q_0 in a form of a flow of high-temperature HTF (e.g. 300-400°C, thermal oil). Then, the available power is distributed between the power block, Q_1, and the thermal storage, Q_2. Simultaneously, some amount of power, Q_3, can go from the storage to the power block. In addition, fossil-fueled power generation, Q_F, might be required in order to maintain the power block operation at the specified load level, Q_L.

The power control system maintains the following energy balance of the plant being evaluated at every instant of operating time:

$$Q_1 + Q_3 + Q_F = Q_L \tag{1}$$

In the present analysis, heat losses and auxiliarly energy consumptions are not taken into account. The solar energy contribution to the continuous power generation over an annual operating cycle is expressed with the aid of solar fraction α as follows

$$\int_0^{yr} Q_0(t)\,dt = \alpha \int_0^{yr} Q_L\,(t)dt, \quad 0 < \alpha \le 1 \tag{2}$$

The amount of solar energy directly delivered to the power block is part of the total amount of energy provided by the solar collector:

$$\int_0^{yr} Q_0(t)\,dt = \beta \int_0^{yr} Q_1\,(t)dt, \quad \beta \ge 1.0 \tag{3}$$

Parameter β can be considered as some analogue of solar multiple (Montes, et al. 2009), a factor by which the solar field must be multiplied in order to supply energy for storage in addition to the amount of energy going directly to the power block at nominal conditions. The advantage of using the solar collector factor β is its accurate definition by equation (3) as compared to the solar multiple being dependent on the choice of the design point, such as solar noon on June 21.

The variable energy of thermal storage has the following integral form expression:

$$E_S(t) = \int_0^t [Q_2(\tau) - Q_3(\tau)]\, d\tau \tag{4}$$

At the begining and the end of the annual cycle, thermal storage is supposed to be empty:

$$E_S\,(0) = E_S\,(yr) = 0 \tag{5}$$

Power variables Q_1, Q_2, Q_3 and Q_F are to be resolved with account for the conditional relationship between solar power Q_0 and load demand Q_L, that either

$$Q_0(t) \geq Q_L(t) \quad \text{or} \quad Q_0(t) < Q_L(t) \tag{6}$$

Correspondingly, Q_1 is defined as either

$$Q_1(t) = Q_L(t) \quad \text{or} \quad Q_1(t) < Q_0(t) \tag{7}$$

Following the adopted control strategy, surplus solar power, Q_2, when available, as compared to load demand, is transferred to charge a storage unit, and under the opposite condition, when solar power is relatively low or entirely unavailable (at night time), the storage is discharged, $Q_3 > 0$, to secure the basic assumption (1). When the current storage energy E_S (t) is insufficient to meet load demand, the system makes use of the supplement (fossil fuel) source of power, Q_F.

2.2. Simulation results and discussion

Computations based on the above algorithm were carried out with the aid of the Mathematica program (Version 7.0, Wolfram Research). Hourly databases of direct normal irradiance (DNI) for the years 2004-2006 were used referring to three different geographical locations around the world including Granada, Spain[2] (GS), Mitspe Ramon, Israel[2] (MR) and Las Vegas, Nevada, USA[3] (LV) that have high total annual DNI values ranged between 2.0 and 2.5 MWh m^{-2}. The conversion from DNI values sets Q_R to the CSP system output Q_0 was calculated using the efficiency factor (except heat losses) for parabolic trough solar collectors operated on thermal oil as the heat transfer fluid (Quaschning 2004), (Price 2003), (Montes, et al. 2009).

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[2] Solar Radiation Series of Data: http://www.soda-is.com/eng/services/index.html [accessed April 2010].

[3] The National Solar Radiation Data Base: http://rredc.nrel.gov/solar/old_data/nsrdb [accessed April 2010].

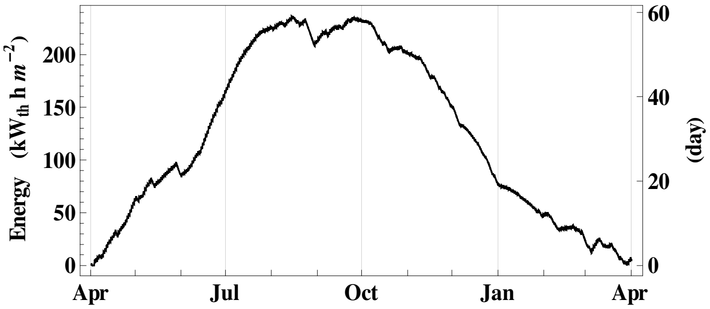

Figure 3. Thermal energy variations E_S (t) over a year for a seasonal storage of $\varphi = 59$ days providing pure solar operation of a power plant at the GS site ($\alpha = 1.0$, $\beta = 4.4$).

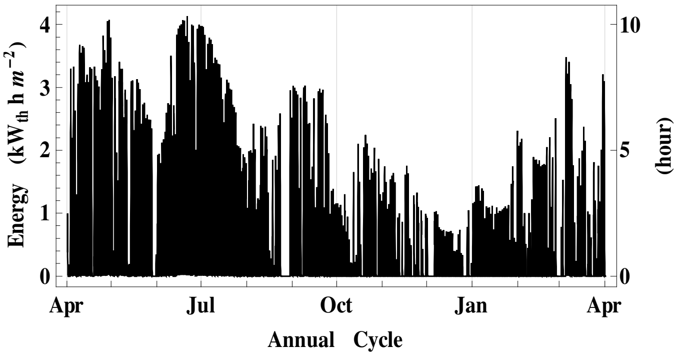

Figure 4. Thermal energy variations ES (t) over a year for a duirnal storage of $\varphi = 10$ hours at the GS site ($\alpha = 0.42$, $\beta = 1.8$).

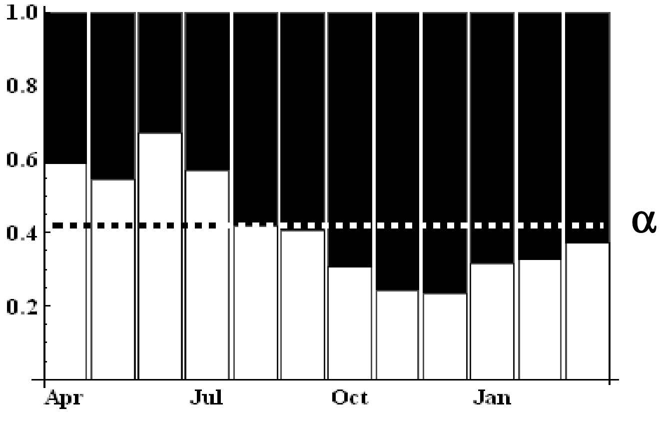

Figure 5. Month-mean fractions of solar energy (white bars) and fossil fuel (black bars) for the GS site.

For the sake of simplicity, the simulations of storage are presented for constant electric loads, as in the case of base load power plants, though some other load profiles have been estimated as well. All power-associated variables in the present calculations pertain to one square meter of the solar collector surface and have a 1-hour time resolution.

Figure 2 shows the dependence of storage capacity φ presented in days (24 hours a day) of full load operation on solar fraction α of power plants varying from near 0.2 (no storage applied, $\varphi = 0$) to 1.0 (pure solar power plants). In the inset graph of this figure, the function $\varphi(\alpha)$ is ploted within the range of several full load hours in order to demonstrate calculation results relevant to the state of the art concepts of thermal storage utilizing either sensible or latent heat of molten salts and various other storage materials (Pilkington Solar 2000), (Pacheco, Showalter and Kolb 2002), (Herrmann and Kearney 2002), (Tamme, Laing and Steinmann 2004), (Michels and Pitz-Paal 2007), (Adinberg, Zvegilsky and Epstein 2010)

It appears that the results of simulations for different plant locations are rather similar. Up to $\alpha = 0.5$, the nominal storage capacity is practically a linear function of solar fraction, extending to $\varphi = 14$ hours. However, the noted behaviour for $\varphi(\alpha)$ changes substantially in the next range of $0.5 < \alpha \leq 1.0$, where this function grows in an exponential-like manner up to a site-specific value of 50 to 60 days of storage capacity.

The major drawbacks of thermal storage systems are their relatively low energy density and significant heat losses in lengthy cycles of several days. For $\varphi = 14$ hours, the corresponding solar fraction parameter of power plants is $\alpha = 0.5$. Thus, with the best-expected result for existent thermal storage technologies, at least half of the energy input to the power block of hybrid base load power plants is to be provided by burning fossil fuels.

Time variations of storage thermal energy E_S (t) in a power system running continuously on solar energy only ($\alpha = 1.0$) are shown in Fig. 3. Since the beginning of the annual cycle, the energy contents of the storage grows strongly with time from zero to a maximum value reached after nearly half a year of the run. The highest quantity of thermal energy measured during the entire cycle indicates a fully charged state of storage and specifies the nominal storage capacity φ, which in the case of Fig. 3 is about 240 kWh per m^2 of the solar collector surface that is equivalent to 59 full operational days.

In contrast with that extrimely large, seasonal storage presented above, Fig. 4 shows a quite different behavior of a storage system rated at 10 hours nominal capacity. For this relatively short-term storage, diurnal-scale variability of thermal energy is obvious. As a result of its small capacity and full daily discharge, the diurnal storage has a consistently low energy level and quite irregular performance in the wintertime, when solar power conditions are very frequently inadequate to fully charge the storage during sunlight hours of a day (regarding the Northern Hemisphere). The significantly reduced performance of diurnal storage in winter season is clearly seen in Fig. 5, which demonstrates the relation between solar and fossil fuel energy inputs over a year based on thermal energy data of Fig. 4.

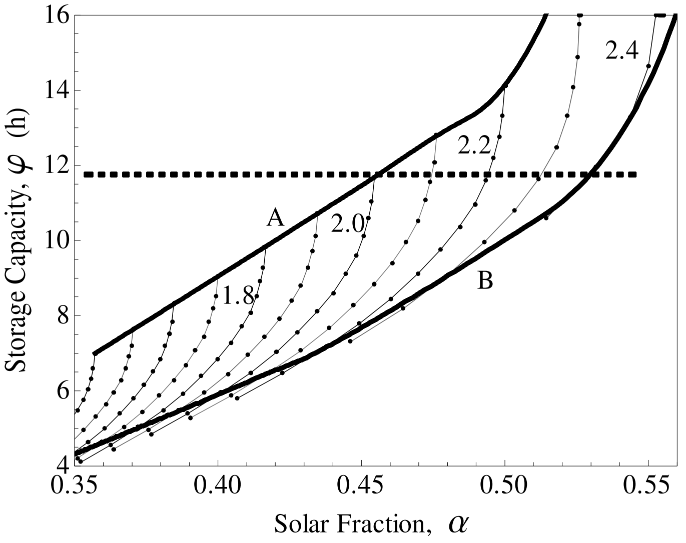

Figure 6. Storage capacity as function of solar fraction and solar multiple for a hybrid parabolic trough power plant (GS-site). The vertically oriented curves with numbers attached are the contours of solar multiple.

Table 1. Characteristic storage capacity scales for a base load plant at the GS site (Total quantities of energy $E_{i\ A}$ (i=1, 3, F, L) were computed by integrating the respective power variables Q_i (Fig. 1) over the annual cycle).

Scale	Storage capacity φ	Solar fraction α	Solar multiple β	Direct solar $E_{1\ A}$	Storage output $E_{3\ A}$	Fuel input $E_{F\ A}$
				% $E_{L\ A}$ (Total annual load demand)		
Diurnal	0 - 14 h	0.2 - 0.5	1.0 - 2.2	20 - 23	0 - 27	80 - 50
Intermediate	14 - 100 h	0.5 - 0.63	2.2 - 2.8	23	27 - 40	50 - 37
Seasonal	5 - 59 days	0.63 - 1.0	2.8 - 4.4	23	40 - 77	37 - 0
Annual	59 days	1.0	4.4	23	77	0

Figure 6 demonstrate the method of improving the efficiency of diurnal storage in terms of solar fraction by increasing the solar field size. The upper solid curve (A) represents a minimal size of the solar collector resulting from the annual energy balance, while the lower curve (B) corresponds to a bigger solar field, such that 3 to 6% of the concentrated solar power is rejected. The example with a storage capacity $\varphi = 12$ hours shows that the increase of a solar multiple from 2.0 to 2.4 results in rising of solar fraction from 0.45 to 0.53 respectively. The payoff of this would be about 4% of the annual amount of solar energy that is not utilized for power production but potentially available for another application. For a larger storage the effect of increasing solar multiple can be much more advantageous.

2.3. Storage capacity scales

Table 1 summarizes the main thermal storage scales identified by (Adinberg 2010) on the basis of statistical analysis of thermal energy variations throughout the annual operating cycle for various nominal capacity values. This includes diurnal, intermediate, and seasonal thermal storage scales. In addition, short-term storage of less than 1- h nominal capacity can be introduced considering it as a buffer aimed to protect the power system from excess solar power and surge loads. The seasonal storage providing pure solar operation of the power plant is called here as annual storage to distinguish it from the seasonal range with somewhat smaller capacity values. According to the simulation results for the GS site, the annual storage is capable of providing 74% of base load, while the balance 26% goes directly from the sun to the power block, without need for fossil fuel backup. The diurnal storage systems can only partially meet load demand and must be supplemented by combusting fossil fuels, at least 50% of the load.

2.4. Concluding remarks

This study covers the whole range of thermal storage capacities from a few hours to the order of magnitude of tens of days (about 2 months) full load operation of hybride solar-fossil power plants supported by storage. Although the modeling was specifically performed for parabolic trough systems operated as base load plants, the obtained results can be extended to most other CSP systems and also different continuous load profiles (except peaking power generation), since the dominating factor affecting system performance is the highly intermittent solar power source.

It follows that pure solar power plants should include storage capacities almost 2 orders of magnitude greater than what was recently achieved with the 2-tank molten salt system containing 28500 tons of the storage material to provide $\varphi = 7.5$ hours for the 50-MW Andasol-1 parabolic trough power plant in Spain (SolarPACES 2009). Presently, there seems little prospect for any known storage technology to achieve long-term thermal storage capacities beyond 14 hours for utility-scale solar thermal power plants, as this would require unreasonable large amounts of storage materials, such as many tens of thousands of tons.

The statistical analysis of storage operational parameters has shown that in the nominal capacity range of several full load hours the storage operation is strongly influenced by daily solar power conditions and its performance appears to be considerably less efficient in the low-sun season (winter) than in the high-sun season (summer). Respectively, the solar fraction of a power plant employing a storage unit within the diurnal storage range up to 14 hours is limited to about 0.5.

The state of the art thermal storage technologies utilizing either sensible or latent heat of molten salts and various other materials suffer primarily from a relatively low energy density of the exploiting storage materials and also from significant heat losses from the system during lengthy operating cycles. The problem of efficient long-term storage especially restricts the design of large solar power plants having production capacity over 50 MW (electrical). Therefore, development of vastly more powerful energy storage concepts appears to be a great challenge to the further advancement of CSP technology.

The potentially most promising energy storage approach in terms of capacity and duration is known to be based on reversible endothermic/exothermic chemical reactions (Cacciola and Giordano 1986), (Lovegrove, et al. 2004), (Steinfeld and Palumbo 2001). At the present state of development, a wide range of research activities is still necessary to validate the technical and economical feasibility of thermo-chemical storage for commercial scale solar thermal utilities.

3. Definitions for Solar Thermal Energy Storage (STES)

No.	*3.1. The Concept of STES**	.
1	STES is an integral component of solar thermal power plants that aims at accumulating part of the thermal energy provided by the solar collector field for later use. The stored heat is utilized on-demand to keep the power plant in operation for a few hours or longer when direct solar radiation is low (cloudy skies) or not available (after sunset). STES is applicable to all advanced CSP systems, such as Parabolic Trough, Power Tower, Linear Fresnel, and Parabolic Dish.	
2	STES is an ultimate engineering solution to the problems of solar power intermittency and load peaks due to both the capability of storage to smooth out the power output under transient solar radiation conditions during daytime and the feasibility of shifting the collected energy to the time after sunset in order to increase the efficiency and solar fraction of solar power plants. It can also protect the power system from excess solar flux and load surges.	
3	The mechanism of STES is based on a physical and/or chemical process that is accompanied with a strong thermal effect occurring in the heat storage material (HSM) due to either a temperature change, or phase transition, or reversible chemical reaction. Typically, a STES system is made-up of one or more storage vessels containing HSM. The system includes also heat exchange equipment used for thermal input (charging) and output (discharging) to/from the storage by means of heat transfer fluid (HTF).	
4	The size of a STES unit is expressed in terms of thermal capacity that is the amount of heat that can be extracted from a fully charged system. Storage thermal capacity is measured either in units of energy, e.g. MWh, or in units of time, such as hours of full load operation of the power plant.	
*	Considering power process temperatures above 200^{o}C.	

No.	*3.2. Utility-Scale Applications*	
1	Solar thermal electricity generation using steam- and gas-turbine power cycles.	(SolarPACES 2009)
2	Substitution of fossil fuels combustion by solar thermal technology in heat consuming industrial processes.	(Richter, Teske and Nebrera 2009), (Kalogirou 2004)
3	Solar-powered production of energy carriers, such as Biofuels, Syngas, Hydrogen, Metals, etc.	(Steinfeld and Meier 2004)
	3.3. Power Cycles Employing STES	
1	Hybrid Solar-Fossil-fuel power cycle combining CSP technology with fossil fuel co-firing. The integration of STES into hybrid power plants increases the annual solar fraction of about 20% without storage by factor 2 or more, depending on the storage capacity.	(Kolb 1998)
2	Integrated Solar Combined-Cycle using solar heat for steam generation and gas turbine waste heat for preheating/superheating the steam. Adding STES allows doubling of the solar contribution for this type of power plants.	(Dersch, et al. 2002), (Müller-Steinhagen and Trieb 2004)
3	Grid-connected or Stand-alone solar power plant with (Hybrid type) or without (Solar-only type) fossil fuel backup. STES is a vital component of solar-only plants for its ability of smoothing out the power output and increasing the operational time.	
4	Solar power cycle hybridized with another renewable energy source like wind, biomass, hydropower, etc. STES increases the solar fraction of the power plant according to its capacity value.	(Vosen and Keller 1999)

4. Classification of STES Systems

No.	*4.1. Thermodynamic Concepts*	.
1	**Sensible** heat storage, using the energy absorbed by a substance (HSM) during a change in its temperature.	
2	**Latent** heat storage, using the heat associated with phase change in HSM, mostly the solid-liquid transition of fusing (melting), and also the liquid-gas transition of vaporization.	
3	**Thermochemical** storage, using an enthalpy change occurring in the reacting medium (HSM) in the course of a reversible chemical reaction (the heat of reaction).	
	4.2. Storage Temperature Ranges (roughly)	
1	**Mid:** 200-400 ^{o}C (e.g. Parabolic trough technology using mineral/synthetic oil HTF, Direct steam generation in parabolic trough and Fresnel systems).	(Zarza, Valenzuela, et al. 2002), (Zarza, López, et al. 2008)
2	**High:** 400-600 ^{o}C (e.g. Parabolic trough/Power tower technologies using molten salt HTF, Direct steam generation in parabolic trough and tower systems).	
3	**Super-high:** > 600 ^{o}C (e.g. Power tower technology using gaseous HTF, Solar Dish/Stirling cycle engine).	
	4.3. Heat Storage Materials	
1	Homogeneous: Solid: Natural rocks, Sand, Ceramics, Concrete, Metals; Liquid: Mineral/Synthetic oil, Molten salts, Liquid metals, Pressured water; Gas: Air, Hydrogen, Helium.	(EPRI 2009), (Pilkington Solar 2000)
2	Heterogeneous: Liquid- Solid: Thermocline with Molten salt (Oil)/Solid filler materials; Gas-Solid: CaO/H_2O Thermochemical cycle; Phase change materials (PCM): Various inorganic salts eutectic systems, Metals; Composite solids: PCM/Expanded natural graphite.	

No.	*4.4. Storage Capacity Terms*	
1	**Short** (0.5-1.0 hour full load) – buffering surges of solar flux and peak loads to protect the power system from strong deviations.	
2	**Diurnal** (several, up to ~14 hours full load operation) – allows smoothing solar flux fluctuations and load irregularities during sunlight time, and a few operating hours after sunset daily (mostly in the summer and much less in the winter).	
3	**Intermediate** (up to a few (~ 4-5) days of full load operation) – additionally to the diurnal mode, provides several hours of continued operation for the power plant after sunset daily, throughout the year.	
4	**Seasonal** (up to 2 months full load operation) – approaches continued operation of the power plant based mostly on solar energy, with minimal fossil fuel support, during all year round.	

5. Major Technological Factors

No.	*5.1. Heat Transfer*	.
1	HSM thermophysical conditions: Stationary medium (e.g. Rock bed apparatus; Pressured water Ruth's system); Convective fluid flow (e.g. 2-tank oil/molten salt system direct); Stratified liquid (e.g. Single-tank thermocline system); Thermochemical reaction medium (e.g. Solar ammonia cycle).	
2	Comparison of HSM and HTF chemical substances: The same = Direct heating (e.g. 2-tank Thermal oil storage); Different = Indirect heating (e.g. Thermal oil HTF vs. Molten salt storage).	
3	HTF flow forced by: Pump, Natural convection, Gravity.	
4	Contact between HTF and HSM: Direct for chemically compatible substances, e.g. Air HTF and Rock HSM; RHTS (Thermal oil and metal PCM); Through wall for incompatible substances, e.g. Thermal oil HTF and Molten salt HSM.	
5	HTF-to-HSM Heat Exchanger: Embedded into HSM; Installed externally to the storage medium; Not Applicable.	

No.	*5.2. System Configuration*	
1	Modular charge/discharge arrangement of storage units to increase the total capacity of the system.	(Tamme, Laing and Steinmann 2004)
2	Cascade of a number of different PCM and sensible heat storage units to approach the optimum temperature range.	(Michels and Pitz-Paal 2007)
3	RHTS (reflux heat transfer storage) tandem of a boiler with a steam superheating unit to achieve isothermal steam generation.	(Adinberg, Zvegilsky and Epstein 2010)

No.	*5.3. Key Requirements for Developing STES Systems*	
1	High energy density capability of HSM.	
2	High thermal conductivity of HSM and efficient heat transfer between HSM and HTF provided by properly designed heat exchange equipment.	
3	Fast response to load changes in the discharge mode.	
4	Low chemical activity of HSM and HTF towards the materials of construction.	
5	Good chemical stability of HSM/HTF and temperature reversibility in a large number of thermal charge/discharge cycles comparable to a lifespan of the power plant, 30 years.	
6	High thermal efficiency and low parasitic electric power for the system.	
7	Low potential contamination of the environment caused by an accidental spill of large amounts of chemicals exploited in STES.	
8	Low cost of HSM, taking into account the embodied energy (carbon).	
9	Ease of operation and low operational and maintenance costs.	
10	Feasibility of scaling up STES designs to provide at least 10 full load operation hours for large-scale solar power plants of a 50 MW electrical generation capacity and larger.	

No.	*5.4. State-of-the-Art Designs*	
1	2-tank Thermal oil/Molten salt system	(EPRI 2009), (Medrano, et al. 2010), (Perez-Devis, McKissock and DiFilippo 1992), (Fernandez-Garcia, et al. 2010)
2	Single-tank thermocline system	
3	Rock bed apparatus	
4	PCM-Finned Tube structure	
5	Concrete storage module with cast-in pipes	
6	Combined Concrete/PCM storage system	
7	RHTS (reflux heat transfer storage) system	
8	Graphite block energy storage system	
9	Fluidized bed of particles (sand)	
9	Ruth's steam accumulator	
10	Solar ammonia dissociation/synthesis cycle	
11	CaO/H2O thermochemical cycle	

6. STES Design and Performance Characteristics

No.	*6.1. Basic Categories and Parameters for Comparing STES Systems*		
6.1.1. Thermodynamic & Physicochemical Properties of Storage Medium			
1	HSM/HTF	Chemical composition; Phase.	
2	Thermal effect	Sensible, Latent, Thermochemical.	
3	Temperature	Working range ΔT (^{o}C) ; T_{Min} & T_{Max} restrictions (e.g. points of freezing, decomposition, undesirable reactions, etc.).	
4	Pressure	Gas-, Vapor-medium of HSM/HTF at the upper temperature (bar).	
5	Physical density	(kg/m^{3})	
6	Energy density	(by volume: MJ m^{-3})	
7	Enthalpy change	c_p* ΔT – sensible; H_{lT} –latent; H_R – reaction (J/kg)	
8	Thermal conductivity	Effective value (W/m-K)	
9	Materials quality	Corrosiveness; Chemical/Mechanical stability	
10	Embodied energy	The conventional energy (carbon) needed to extract, elaborate, transform, ship, and integrate from natural resource to the recycling.	

No.	6.1.2. System Design Features		
1	Apparatus pattern	2-Tank, Thermocline, Concrete block, Packed bed, Ruths, etc.	
2	Amounts of HSM/HTF	(ton)	
3	Storage unit size	Module dimensions: e.g. height, diameter (m).	
4	Footprint of complete storage system	Area (m^2)	
5	Method of heat circulation in storage	Active vs. Passive; Active: Direct vs. Indirect.	
6	Heat transfer technique (heat exchangers)	Equipment applied to carry out and to enhance the processes of heat charge and discharge.	
7	System structure	Single/Multiple-stage layout; Serial/Parallel connection of units.	
8	Solar multiple	A factor by which the solar field must be multiplied in order to supply energy for storage in addition to the direct powering of the process at nominal conditions, e.g. 2.0.	
9	Auxiliary equipment	Pumps, heaters, valves, thermal insulation, foundations, etc.	
10	Power hybridization	Solar-only, Solar-Fossil hybrid, Combined cycle.	
11	Power cycle	Rankine (steam, organic); Brayton (gas turbine) process, Chemical process, etc.	
12	State of development	R&D project; Demonstration stage; Commercial plant.	
13	Particular limiting factors	E.g. Molten Salt freezing temperature; HTF upper working temperature; Corrosion rate; Secondary chemical reactions; etc.	

No.	6.1.3. Operational Performance		
1	Charge/Discharge temperatures	Mean values; Average difference (temperature lag); Variability. (^{o}C)	
2	Nominal capacity	(MW_t h; Full load hours)	
3	Power plant annual solar capacity factor	A share of solar energy in the annual energy balance of a power plant, e.g. 0.4.	
4	Full periods of Charge and Discharge	Nominal values (h).	
5	Power rating on charge/discharge	Nominal value/Working range (MW_t)	
6	Mass flow rate of HSM (the direct mode)/HTF (the indirect mode)	(kg/sec)	
7	Response time	Defines the capability of buffering fast solar and load power fluctuations (min)	
8	Minimal useful charge	The minimum energy (or temperature) level that can be utilized on discharge.	
9	Energy use strategy	Full/Partial load, Displacement in time	
10	Annual thermal efficiency	The net heat available for distribution as a fraction of the amount of thermal energy charged into the storage unit.	
11	Parasitic losses of energy	Operation of auxiliary systems.	
12	Technical availability	The percentage of annual operating time available without downtime.	
13	Lifetime	(E.g. 30 yrs.)	

No.	6.1.4. Economic and Environmental Issues	
1	HSM cost per unit mass/same in terms of embodied energy/kg, €/kg	
2	Total storage system investment cost per unit thermal capacity, including the date of price assessment, €/kW$_t$ h	
3	Potential for scaling up a STES system to suit large-scale solar power plants of 50 MW and larger.	
4	Technical risk and potential consequences of environmental contamination caused by an accidental spill of a large amount of storage chemicals.	
5	Legal problems referred to a country and the date.	

No.	*6.2. Specifics of Sensible Heat Storage*		
1	HSM	Solids (e.g. rock bed, concrete, cast iron); Liquids (e.g. thermal oil, molten salt, water); Mostly inorganic materials.	
2	Cost of HSM	Solids commonly are inexpensive.	
3	HTF employed	Thermal oil, Molten salt, Gas, Steam.	
4	Storage temperature	Wide range, up to 1800^{o}C (graphite block).	
5	Temperature lag	Large, > 100^{o}C.	
6	Energy density	Low, as compared to latent and chemical storage.	
7	Thermal conductivity of HSM	Normally low (rocks, concrete), except metals; graphite – high.	
8	State-of-the-art systems	Section 5.4, Nos. 1, 2, 3, 5, 8, 9.	
9	State of development	E.g., Commercial scale 2-tank molten salt system	
10	Storage capacity range	Diurnal, potentially up to 10-14 h, regarding large scale power plants, 50 MWe and more.	

No.	*6.3. Specifics of Latent Heat Storage*		
1	HSM	PCM: Pure-substance; Eutectic/Non-Eutectic mixture (e.g. inorganic salts, metals).	(Zalba, et al. 2003)
2	Phase change	Melting (fusion), Vaporization.	
3	Cost of PCM	May be expensive, as compared to sensible-HSM.	
4	HTF employed	E.g., Thermal oil, Gas (via a heat exchanger, except RHTS using direct contact between PCM and HTF).	
5	Storage temperature	Melting (eutectic) point, °C	
6	Temperature lag	Small, ~ 20°C; Nearly isothermal process (if not limited by thermal conductivity).	
7	Energy density	High, as compared to sensible heat storage.	
8	"Side effects"	Supercooling, Volume change.	
9	Thermal conductivity of HSM	Normally low (salts), except metals. Means of enhancement: Macro-encapsulation; Embedded heat exchanger; Metal fins; Expanded graphite sandwich.	
10	State-of-the-art systems	Section 5.4, Nos. 4, 6, 7.	
11	State of development	Mostly R&D projects.	
12	Storage capacity range	Diurnal	

No.	*6.4. Specifics of Thermochemical Storage*		
1	HSM	Reactants, including catalyst, if applied.	
2	Reactions	Endothermic for charge and Exothermic for discharge.	
3	Costs of HSM and the whole system	HSM may be inexpensive, as for the CaO/H_2O thermochemical storage. However, the storage system could require a high capital investment due to the complexity of equipment used.	
4	Storage temperature	Reaction temperature, ^oC; All ranges.	
5	Charge/Discharge temperature lag	Relatively large, in order to shift the reactions away from equilibrium.	
6	Energy density	High, as compared to the other storage concepts.	
7	“Side effects”	Secondary reactions should be excluded to guarantee cycle reversibility.	
8	System design	In general, it is a tandem of solar endothermic and conventional exothermic reactors; e.g. the Ammonia based cycle (450-650^oC) designed for a parabolic dish collector.	
9	State-of-the-art systems	Section 5.4, Nos. 10, 11.	
10	State of development	R&D projects.	
11	Storage capacity range	Diurnal-Intermediate; A potential for developing seasonal storage in the future. The advantage is that the heat can be stored during a long time until the reaction is restarted without thermal loss (provided that the sensible heat of the reactants is utilized efficiently).	

7. Summary

This table summarizes the most common attributes of STES systems considered in the report. The chosen characteristics have been applied to describe well-established storage technologies in a separate attached Excel worksheet.

Meanwhile, it is a rather short list of sensible and latent heat storage systems, for which the relevant data could be found in the literature. That file is aimed to be updated from time to time on the basis of new information derived from R&D studies, proven technologies and feedback from commercial experience.

1	Thermodynamic concept of storage	Sensible/Latent/Thermochemical heat
2	Heat storage medium (HSM)	Material; Chemical composition
3	Working temperature (WT)	High & Low limits; Optimal range
4	Thermochemical properties of HSM @WT	Phase change; Density; Pressure; Chemical reactions
5	Storage capacity factors	HSM amount; Energy density; Nominal capacity; Diurnal/Intermediate/Seasonal type
6	Heat transfer means and technique	HTF/HSM; Active/Passive; Direct/Indirect; Heat exchangers
7	Storage system structure	Tank design and dimensions; Single/Multiple-stage layout
8	Integration into power plant	Power cycle; CSP system; Solar-Fossil hybrid; Grid connection
9	The performance impact	Solar fraction; Solar multiple
10	Operating performance parameters	Charge vs. Discharge temperatures (difference and variability) and periods of time; Power rating; Annual thermal efficiency; Technical availability; Lifetime
11	Economic and Environmental Issues	Investment costs; Scale-up feasibility; Risk of environmental contamination.

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