THERMAL STORAGE CSP TECHNOLOGY

STATE OF THE ART AND MARKET OVERVIEW

PROJETO Energia Heliotérmica

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A study produced by the project DKTI-CSP (German Climate Technology Initiative on Concentrating Solar Power), which is managed by the Ministry of Science, Technology and Innovation (MCTI) and the Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The project focusses on the promotion of climate technologies, in particular Concentrating Solar Power. Its objective is to ensure that required conditions to implement and disseminate Concentrating Solar Power are established in Brazil.

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CONTENT

1 INTRODUCTION

Solar thermal power plants for electrical energy production are built worldwide since several years, with main focus on Southern Europe, North and South Africa and the United States.

The key components of these plants are independent of the used technology: A system of mirrors is used to concentrate the direct irradiation from the sun on a receiver. Inside the receiver system a medium is heated up and transferred to a power block. There, the heat is used to produce steam, which is used in a steam turbine to produce electricity. Using the sun as a renewable energy source, CSP-plants are delivering reliable and eco-friendly electricity.

The possibility to implement a thermal storage system is one of the key advantages of CSP-plants. Based on the plant setup the storage system could be integrated in each of the big-scale commercially available CSP-technologies, shown in Figure 1.

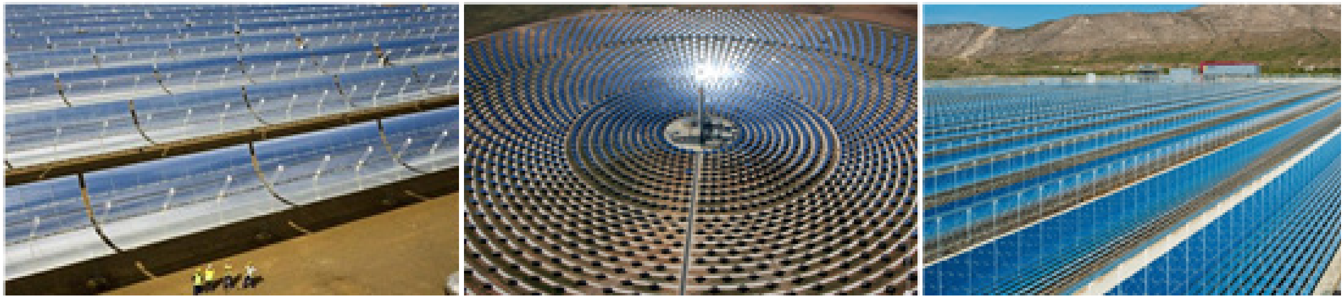

Figure 1: Considered CSP-Technologies (from left to right): Parabolic Trough (PT), Solar Tower (ST) and Linear Fresnel (LF)

Energy storage systems have an essential role in every electrical system. Due to the fact that electrical energy must be consumed when it is produced, every energy system needs reliable and flexible energy generation units. Such energy generation units are directly controlled by an operator and called "dispatchable" energy generation units. Additional energy storage systems support the electrical grid by providing the possibility to shift energy over the time. With an increased share of non-dispatchable energy generation units (like wind farms or hydro plants without reservoir) the importance of storage systems rises.

Concerning the development of the electrical system in Brazil, the need for new electrical storage systems is foreseeable. With the further increase of non-dispatchable wind energy and the lack of reservoirs for new hydro plants in the Amazonas region, the reservoir regulation capacity is decreasing, as shown in Figure 2. As the hydro production becomes more dependent on rainfalls, the ratio between energy storage and energy load decreases. To avoid critical situations in the grid, new generation units are necessary to guarantee energy and peak power supply. Energy storage systems are able to take this role.

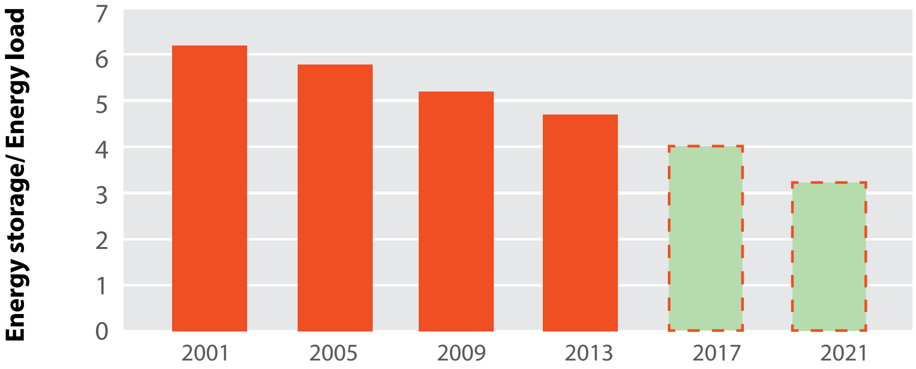

Figure 2: Development and estimation (2017; 2021) of the reservoir regulation capacity in Brazil, based on ONS

There are different ways to realize energy storages like mechanical, (thermo-) chemical, electrical or thermal systems. A short overview of these systems and typical application are given in Appendix A. Well known systems are hydro plants with big water reservoirs to store energy over days or even months. Batteries or accumulators are another common method to store electrical energy in small scale.

Thermal storage system works with another storage principal than the above mentioned methods. Heat is produced and stored using a storage material, before the electrical energy is produced. As the produced thermal energy by a power plant could be stored very easy in different materials, these storage systems offer an easy to implement and high efficient method especially for thermal power plants like conventional coal plant or CSP-plant. In comparison to battery systems the energy could be stored before the electrical energy is produced. With this approach, CSP-plants act like a common steam boiler with a varying, but foreseeable and storable fuel supply: the sun.

The size of the thermal storage is one key parameter in the development phase of the CSP system, described in detail in chapter 2.1.1. As current state of the art, short term storage systems with a capacity of about 1 hour (of full load operation) are used to guarantee the energy production on a cloudy day. Mid-term storage sizes of about 5 hours are used to cover peak demand periods in the evening. For long term storage systems, storage capacities between 8 and 16 hours are commercially available, allowing a base load operation of the CSP-plant over the whole night. The size of the solar field is always related to the size of the storage. The solar field must be big enough to charge the whole thermal storage and produce electrical energy in parallel.

About half of the CPS-plants in worldwide operation and nearly all CSP-plants that are under construction are equipped with a thermal storage system. These figures show that thermal storage systems are an important key part of the CSP technology. In comparison with other renewable energy generation units, the ability to integrate a storage possibility is a huge advantage of the CSP-plant. For the further development and to ensure the success of the technology, thermal storage systems have a crucial role, providing the ability to supply energy when it is demanded.

With this report the current state-of-the-art of thermal storage systems is described. For every technology, a short overview of the functional principle is given and the main technical parameters are described. As current technologies the molten salt system, the steam accumulator (so called Ruth's storage) and the honeycomb ceramic storage are considered.

The main industrial players related to the whole system and key components are presented. A short overview of the further technical development is given at the end of the report. In this chapter the development paths of existing technologies and new storage materials for the next 3-5 years are described.

Main objective of the report is to create a basic understanding of the different technologies and to provide an outlook on the potential of thermal storage system, not only for CSP-plants but for the whole energy sector.

2 STATE OF THE ART

In this chapter the current state of the art of the thermal storage technologies commercially available for CSP-plants is described. These systems operate in a range between 200 °C and 800 °C. As the different CSP-systems operate on different temperature levels (Figure 3) different thermal energy storage system are necessary, relevant for different temperature levels.

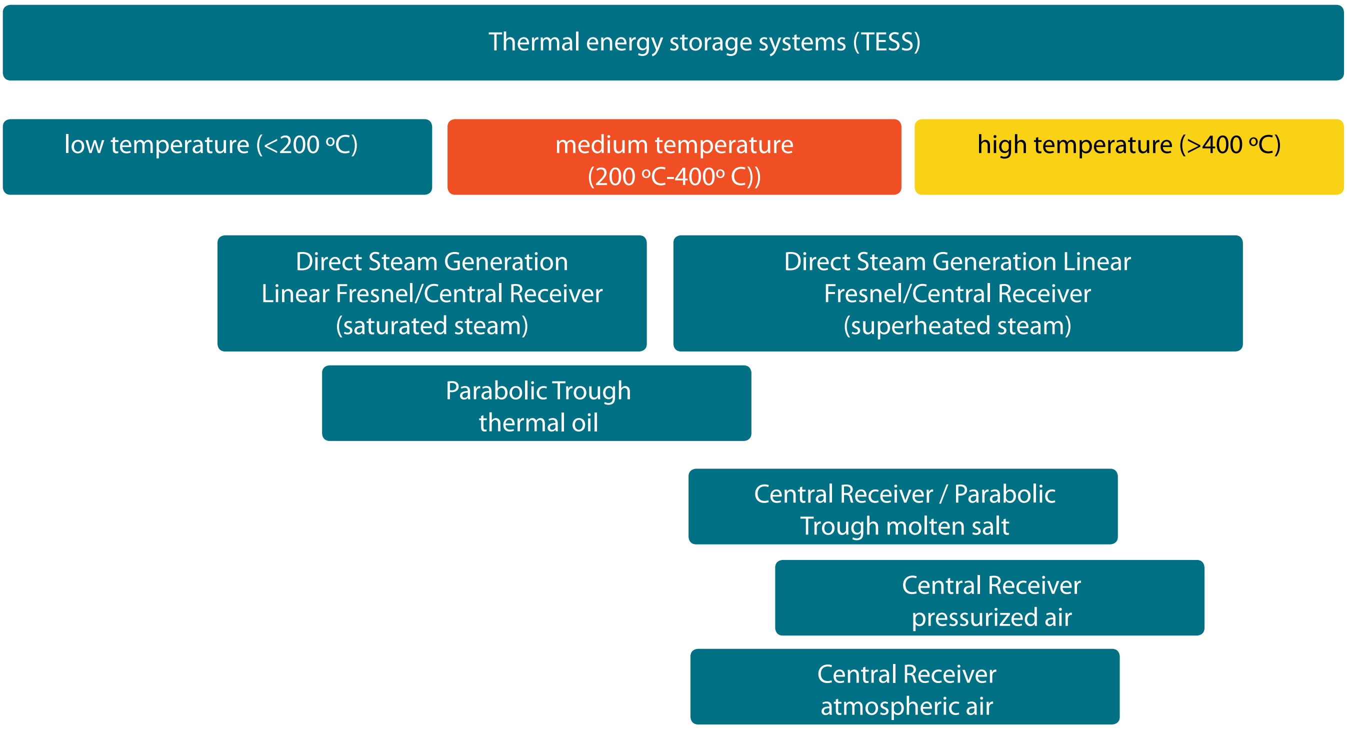

Figure 3: Overview of the different CSP-technologies and the relevant temperature range

Based on the thermal stability of the used medium, systems with thermal oil used as heat transfer medium in the solar field are limited to temperatures slightly above 400 °C. CSP-plants with molten salt as heat transfer medium in the solar field are limited to temperatures up to approximately 570 °C. Air as heat transfer medium allows for much higher temperatures, however, limitations are given by the thermal stability of the equipment (e.g. valves, channels etc.) especially regarding the long operation periods at high temperatures.

2.1 TECHNICAL SPECIFICATIONS

The overall target in the design phase of a thermal energy storage system is the cost efficiency of the systems and the enhancement of thermal efficiency and reliability. Therefore several technical parameters have to be considered. These parameters are described in the following chapters.

2.1.1 Main technical parameters

In order to describe thermal storage systems as well as to define the performance it is necessary to define characteristics and technical parameters. With these parameters, a comparison of different systems is possible, considering the pro´s and con´s for a certain thermal storage system.

In order to make different systems comparable, it is further necessary for those characteristics and technical parameters to be defined in a common sense and to be valid for all types of systems. Within the following chapter, these characteristic parameters are defined and described the way they are understood within this study. If applicable, typical ranges and values are given referring to the different state of the art technology.

Latent and sensible heat storage systems

The differentiation between latent and sensible heat storage systems indicates whether the storage medium changes between solid, fluid or gaseous state during the storage cycle or not. If the state of the storage medium doesn't change within the charging and discharging cycle, only sensible heat is transferred and though the system is part of the category of sensible heat storage systems. If the storage medium changes its state during the charging-discharging-cycle, sensible and latent heat is transferred and the storage system is then called latent heat storage system. With the expression latent heat, the heat released or stored during the phase change is described. Very common example for a latent heat medium is water.

The main difference between both systems is the temperature change during charging and discharging. Charging of sensible heat storage always results in an increase in the temperature of the storage medium, described at Figure 4a. Discharging of sensible heat storage always results in a decrease in the temperature of the storage medium.

With latent heat storage, the transferred heat is used to perform a phase change within the storage medium. During the phase change, the temperature of the storage medium does not change if pure materials are used. In case of mixtures of several materials only slightly temperature changes can be expected during the phase change. To charge latent heat storage a heat source with high temperature is necessary. Due to the fact that the temperature of the primary medium has to be always higher than the temperature of the storage medium, the temperature gradient must be very high at the beginning of the phase change. The typical profile of the resulting temperature is shown in Figure 4b. Before and after the phase change, sensible heat is transferred. With the start of the phase change, the transferred thermal energy is used to realize the phase change. The temperature of the phase change material remains at the same level.

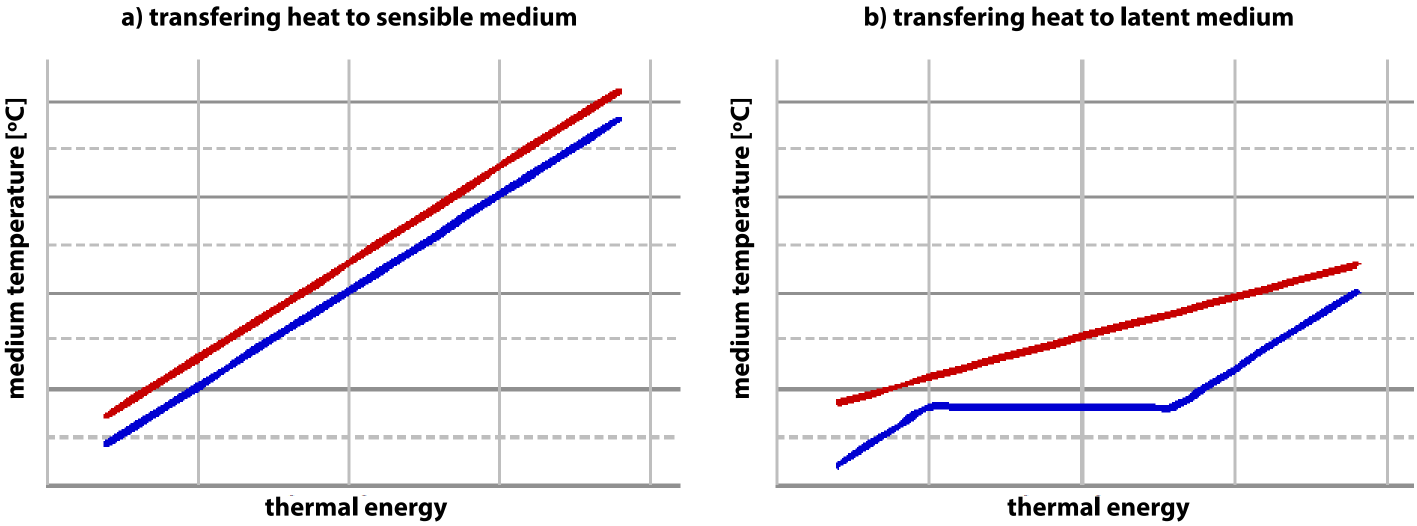

Figure 4: Transferring heat to sensible (a) and latent (b) medium

Storage temperature

The operating temperature range is one key parameter for the thermal storage system. The operational temperature is depending either on the storage material itself or on the temperature limits of the heat transfer fluid. The upper temperature limit of the material is often defined by the thermal stability of the storage material (solar salt and thermo-oil) or the storages vessels (ceramics and water/steam).

A higher useful temperature range results in a higher storage capacity and a higher efficiency of the power block. Based on [1] the temperature ranges of the main materials used in the CSP-industry are summarized in the following table.

Medium	Lower temperature limit [°C]	Upper temperature limit [°C]	Average density [kg/m^3]
mineral oil	200	300	770
synthetic thermal oil	180	410	900
nitrate salts	265	565	1870
ceramics	--	900	2000

Efficiency of the storage system

Efficiency values are used to describe the performance of an energy system. In general the ratio between the useful output of a system and the energy input into the system is defined as the efficiency value. Considering the CSP-plant several efficiency values can be found in the technical literature, using different system borders and therefore different definitions of the energy inputs and outputs.

In order to provide a general overview of the storage systems without regard to the auxiliary systems, the storage efficiency used in this report is defined by the ratio between the thermal energy output and the thermal energy input of the storage system. Therefore only thermal losses within the heat transfer and through the surface of the storage vessels are considered.

Another critical factor in the design of the storage system is the energy necessary to operate the storage, the so called own consumption of the system. The electrical own consumption is mainly influenced by pumps or fans necessary to transport the HTF/storage fluid and by auxiliary heating systems. As the overall storage efficiency is given by the ratio of energy flows, it is not easily possible to include the electrical own consumption. Therefore typical ranges of this value are given separately.

Heat capacity and volumetric storage capacity

Heat capacity, or thermal capacity, is the amount of thermal energy required to change the temperature of a medium. The heat capacity often is given as a specific heat capacity.

To analyze and asses different storage materials, it is not sufficient to focus o the heat capacity only. The relevant temperature range is also a very important factor, describing the useful operation range of the medium. In order to calculate the storage capacity of a storage system, the specific heat capacity of the storage material has to be multiplied by the possible temperature gradient during operation. The result is the mass specific storage capacity in kWh/kg. Further multiplied by the density of the material, the specific volumetric storage capacity is given. When using solid storage material a free cross section is necessary to allow a flow of the HTF trough the storage material. For the calculation of the volumetric storage capacity, this free cross section always has to be taken into account, e.g. by using the apparent density.

Summarized, the volumetric storage capacity describes the ability of a given volume of a medium to store a certain amount of thermal energy while performing a temperature change.

Storage vessels

Storage vessels are forming the containment for the storage material. Based on the design of the storage system, the requirements for the storage vessel vary.

For pressurized systems thick storage walls are necessary and special equipment for the manufacturing process is necessary. Systems with a liquid storage material cannot be equipped with a thermal insulation between the storage material and the vessel. In this case the vessel must be able to withstand the load of the material at the operation temperature and pressure. This often results in the need of high-quality steel which is more expensive.

Nevertheless the requirements of thermal storages for CSP-plants do not differ from other industrial applications dealing with high temperatures and pressures. Therefore it is possible to build these components without any additional effort directly at the country.

Storage size

The size of the storage system is a main parameter in the development phase of the CSP-plant. With the thermal storage capacity, important parameters for the economics of the plant like the capacity utilization factor (amount of hours the plant is running under full load) and the yearly income are influenced. Storage size often is given as an hourly number, although the storage size is defined as stored thermal energy. Using an hourly number allows a direct comparability of different systems. Therefore the storage size is defining the amount of hours the CSP-system is able to run on full load without any additional heat from the solar field. Assuming a typical parabolic trough plant with power block efficiency of 37 % at design conditions and an installed electrical power of 50 MWel, the storage system with a capacity of 7.5 h must be able to store around 1000 MWhth of thermal energy.

As already mentioned, the size of the thermal storage has direct influence on the size of the solar field. This influence is reflected in the "solar multiple (SM)". The SM is a factor describing the ratio between the installed solar field size and the solar field size necessary to run the CSP-plant in full load under defined terms for irradiation conditions. In order to parallel charge the storage and produce electrical power, a surplus of energy is necessary resulting in a bigger solar field. For example, with a solar multiple of 2, the solar field is two times bigger than necessary for a pure electricity operation. The principal relations between SM, storage size and capacity factor is shown in Figure 5. This analysis was done based on [2] for a 100 MWel parabolic trough plant in the US. Of course this analysis must be performed for every site and technology, but the principal behavior is valid for nearly every place in the world.

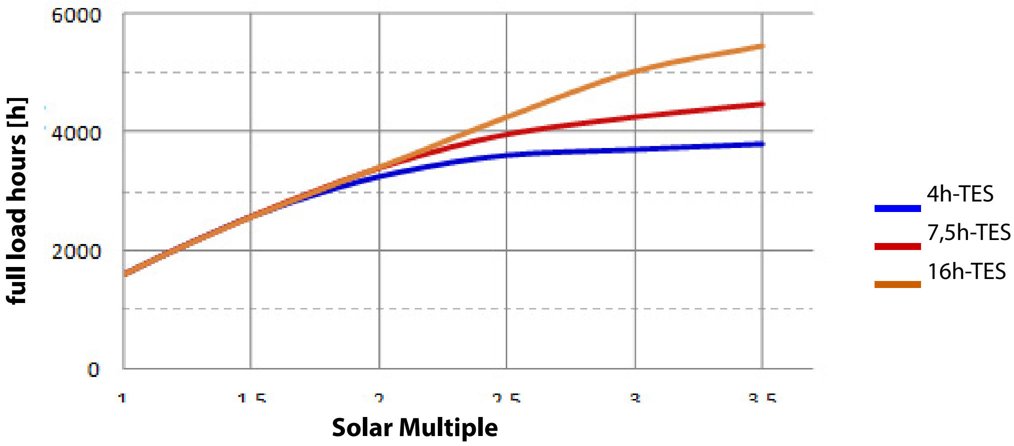

Figure 5: Principal relations between Solar Multiple (SM), full load hours and storage size

Based on this relation, it is not suitable to build a 4h-TES with a solar multiple above 2, because there is no additional benefit in increasing the full load hours. On the other side, for a storage system with 16 h capacity a solar multiple of 3 or higher is necessary.

There are also economical parameters affecting a suitable size of the thermal storage. Based on the market design it could be suitable to build only small storage sizes (like in South Africa and the US with their peaking tariffs) or to build big storage sizes for base load operation (like in Spain with time independent feed-in tariff).

Conclusion:

The relevant factor for the development and assessment of thermal energy storages are:
Usable temperature range: The storage material is limited to an upper and lower temperature bound, either defined by its own material properties or by the storage system.
Efficiency of the storage system: The efficiency of the storage system is calculated by the ratio between the usable heat output and the heat input in the storage system. As second key parameter the electrical own consumption is considered.
Specific volumetric storage capacity: Describes the ability of the storage medium to store thermal energy in a given volume.
Storage size: The size of the storage system is strongly depending on economical or grid connected reasons. The size of the storage system is connected with the size of the solar field. Storage sizes of up to 16 hours are possible.

2.1.2 Integration into CSP-plants

Considering the integration of the thermal storage system into a CSP-plant there are two possibilities, presented in Figure 6. The storage system always is placed between the solar field (or the solar receiver) and the power block. To simplify the diagram, these components are not shown in this figure and just the interconnections are given.

With the direct method (Figure 6a) one medium is used as storage material as well as heat transfer fluid (HTF). The medium is stored in a cold tank, heated up in the receiver and is afterwards stored in the hot tank. The hot medium is then forwarded directly to the power block.

The indirect method (Figure 6b) must be used if the storage material and the HTF used in the solar field are different. The heat is transferred from the HTF (heated up in the solar field) to the storage material with special heat exchangers. This method is resulting in two different closed material cycles. In order to discharge the storage the heat is again transferred via the heat exchanger from the storage material to the HTF.

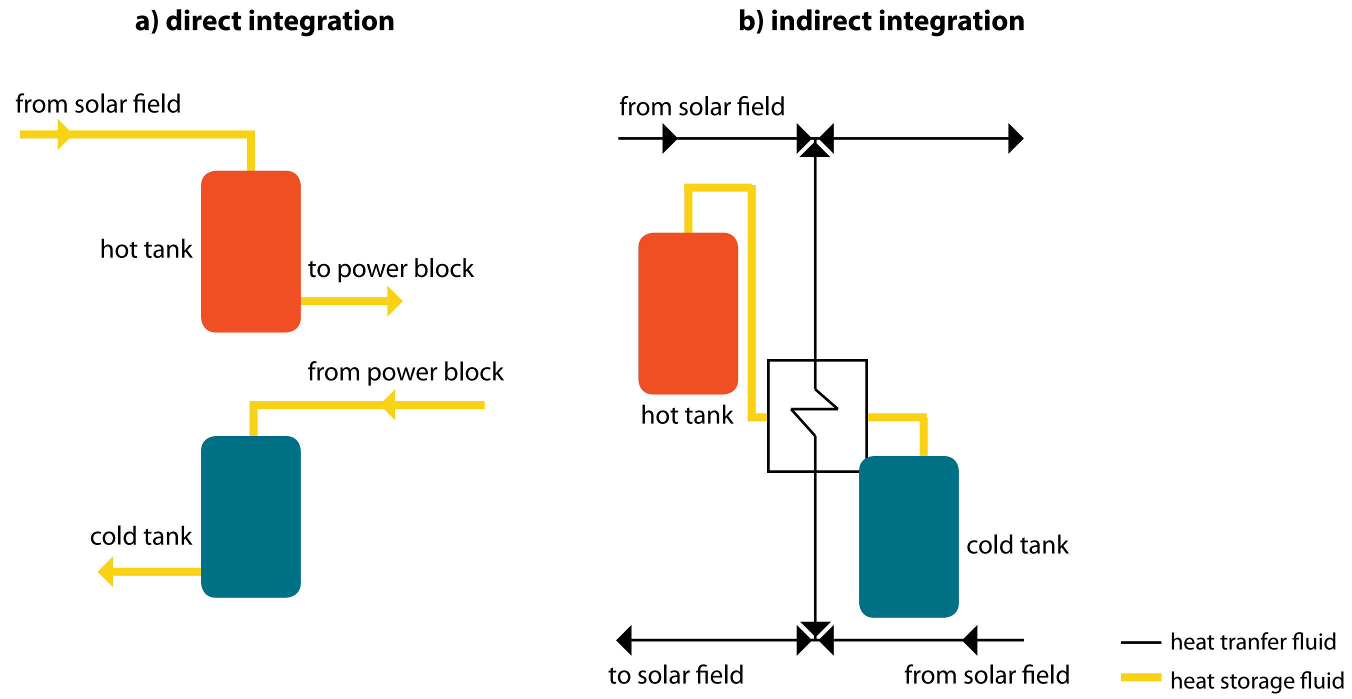

Figure 6: Schematic layout of the storage integration into a CSP-plant

The main challenge of the indirect method is the efficiency of the heat exchanger between the storage material and the HTF from the solar field. To increase the efficiency, heat exchangers are designed to maximize the surface area of the wall between the two fluids, while minimizing resistance to fluid flow through the exchanger. Nevertheless there is always a temperature gradient necessary between the primary and the secondary medium, resulting in a drop of the overall system efficiency.

Conclusion:

With the indirect integration of the thermal energy storage heat exchangers are necessary. There are different materials for the Heat-Transfer Fluid necessary.

State of the art of the different storage systems that could be integrated are:

- **Solar Tower Systems**: direct storage methods
- **Linear-Fresnel Systems**: direct storage methods
- **Parabolic Trough Systems:** indirect storage methods

2.2 HISTORICAL DEVELOPMENT OF THERMAL STORAGE SYSTEMS

Since the implementation of the first CSP systems in the early years of the 20th century, thermal storage systems are a key element in the design of CSP systems. The first parabolic trough plant build in Egypt used tanks to store saturated water, similar to the nowadays used "Ruth's storage".

In the 1980s the first commercial CSP-plants using parabolic trough with thermal oil as Heat-Transfer fluid (HTF) were build in the United States. Within the first plant SEGS 1 a thermal-oil storage was included, using a direct 2-Tank system. In the first tank, the cold thermal-oil is stored and pumped to the solar field. The HTF is heated up passing the solar field and is stored in the hot tank. From the hot tank the thermal-oil is delivered to the power block. With this system the first implementation of a 2-Tank system into a commercial CSP system was realized. The system was damaged by a fire in 1999 and was not replaced.

With the development of CSP-plants, higher efficiency values for the whole system gained on importance. One way to increase the efficiency is the use of HTF that can reach higher temperatures. The thermal-oil system, especially the mineral based thermal oil used in SEGS 1, is limited in its upper temperature range. The storage system installed at SEGS 1 was limited to temperatures up to 307 °C. The heat capacity was at 25 kWhth/m^3 with material costs of about 4.2 US$/kWhth [1]. In SEGS 1 mineral based thermal oil was used, that could be stored in non pressurized vessels. With the further development of the thermal-oil to higher temperature values, new synthetic thermal-oils were used. This new thermal-oil has a high vapor pressure. Therefore pressurized tanks would be necessary, that are very expensive or even not able to manufacture in the size needed for big CSP-plants, signifying the end of thermal-oil storage systems.

In order to find a new way of storing the heat, indirect methods were implemented. With the 2-Tank system based on molten salt the first indirect storage method was installed at the Andasol 1 plant in Spain. The hot HTF from the solar field passes a heat exchanger, where the heat is transferred to molten salt from the cold tank. The hot molten salt is stored in a hot tank. The solar salt is stable at high temperatures and could be stored in non-pressurized vessels. With this system temperatures up to 550 °C in the storage system are theoretically possible. Assuming an upper temperature level of 400 °C, a volumetric heat capacity of 83 kWhth/m^3 with material costs of about 16 US$/kWhth [1] could be achieved. The challenges for molten salt systems are the heat transfer from the HTF to the molten salt and the solidification temperature of molten salt at 270 °C. A first direct method of storing heat based on a molten salt receiver was implemented in the Solar Two demonstration solar tower plant in 1999. The molten salt was directly pumped from the cold tank to the receiver, heated up to 565 °C and than stored in the hot tank.

Since the realization of the first molten salt storage, further developments in the design of the storage systems were implemented considering the position of the heat exchangers or the use of new materials for the tanks.

Most storage technologies implemented in CSP-plants also have industrial applications. These applications are often focused on a lower temperature range, for example as waste heat recovery systems. Experiences gained in this sector are transferred to the development of storage systems for CSP-plants.

To give an overview of the current state of thermal storage systems for CSP, the main developments are shown in Figure 7. The development states of the technologies are divided in "Basic research" with first developments and demonstration plants, "commercial operation" with first plants in operation and "further development" describing a mature technology that is further optimized based on operational experiences. Developments that are expected within the next five years are marked with a dotted line.

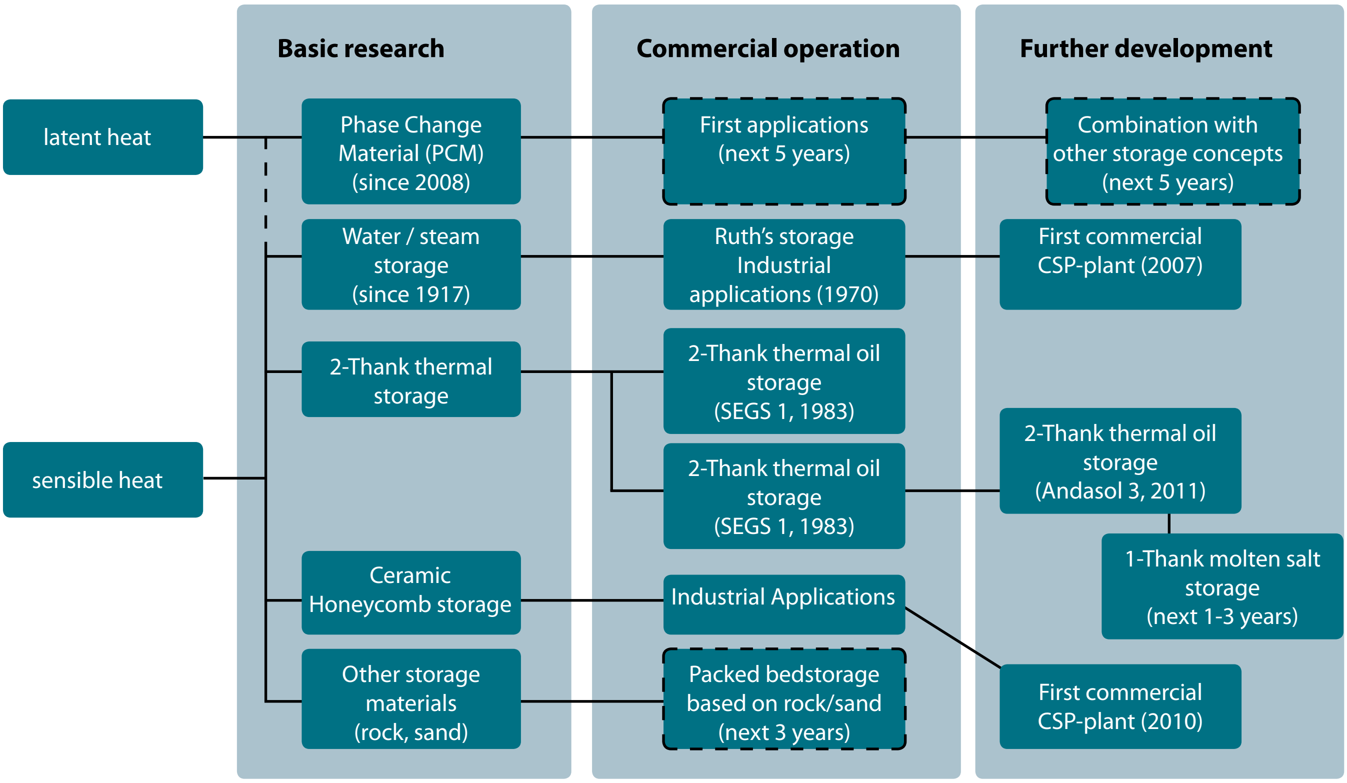

Figure 7: Overview of the main storage concepts and their development (dashed: development expected)

As "state of the art" technologies storage systems are considered that are included in commercial CSP-plants and that are used in daily operation. These technologies (Ruth's storage, molten salt storage and the ceramic honeycomb storage) are described in detail in the following chapter.

Conclusion:

Since the first CSP-plant thermal storage systems are an essential key part of the technology. With the development of the CSP-technology towards higher temperatures and efficiency values, new thermal storage concepts were integrated. As state-of-the-Art the following technologies are considered:

- **Molten salt storage systems**: indirect storage method for large capacities
- **Ruth's storage system:** direct storage methods as short time steam accumulator
- **Ceramic honeycomb storage system:** direct storage method for air based systems

2.3 TECHNOLOGY OVERVIEW

Based on the current commercial realization, the three implemented storage system are described in the following chapters.

2.3.1 Molten Salt storage system

The best known storage system in the CSP sector, due to their application in several CSP-plants around the world, is the molten salt storage system. Up to now, this storage is also the only commercially applied long-term thermal storage system for CSP-plants. The commonly used storage medium, often called “solar salt”, is the eutectic mixture of 60 % NaNO3 (sodium nitrate) and 40 % KNO3 (potassium nitrate). The melting point of this mixture is in the range of approx. 220 °C where the eutectic minimum melting point is at approx. 210 °C for a mixture of 50 % NaNO3 and 50 % KNO3. The solar salt is chemically stable for temperatures up to approximately 570 °C.

Storage principle

The storage principle depends upon the heat transfer medium used for the CSP technology. If molten salt is the heat transfer medium, the storage system is directly integrated into the heat transfer mediums cycle (direct molten salt). For other mediums, an external storage system cycle is applied (indirect molten salt).

Application for molten salt used as heat transfer medium (direct molten salt)

The direct molten salt storage consists of two storage tanks integrated directly into the molten salt cycle of the plant. One so called hot tank stores the hot salt (approx. 565 °C) and one cold tank stores the “cold” salt (approx. 290 °C). With this configuration the maximum operational range of the solar salt is used. Figure 8 shows the integration of a two-tank direct molten salt storage. The cold tank is shown here in orange and the hot tank is shown in red. The direct integration into the molten salt cycle ensures a constant volume of hot salt and cold salt inside the tanks. During normal operation there is a constant flow in and out of both storages. During the night, the molten salt cycle is continued, while no heat is transferred from the receiver into the cold molten salt. The stored hot molten salt from the hot tank is used to keep the steam production running, while the cold sat replaces the extracted hot salt inside the hot tank. This system has been applied at the Gemasolar power plant in Spain.

The two molten salt storage tanks built in Gemaolar have a diameter of 23 m and a height of approx. 10.5 m. The different (cold and hot) pumps for the molten salt are placed near the corresponding tank. Additional heat tracing units for the piping and the heat exchangers are installed, in order to prevent the freezing of the system. These heaters are also installed in both tanks [3].

With the integration of a thermal system into a solar tower plant, all necessary fluids (HTF if necessary and storage medium) are concentrated in a small area. Compared to the indirect integration of a thermal storage system into a parabolic trough plant this results in a less thermal losses and lower maintenance costs of the system.

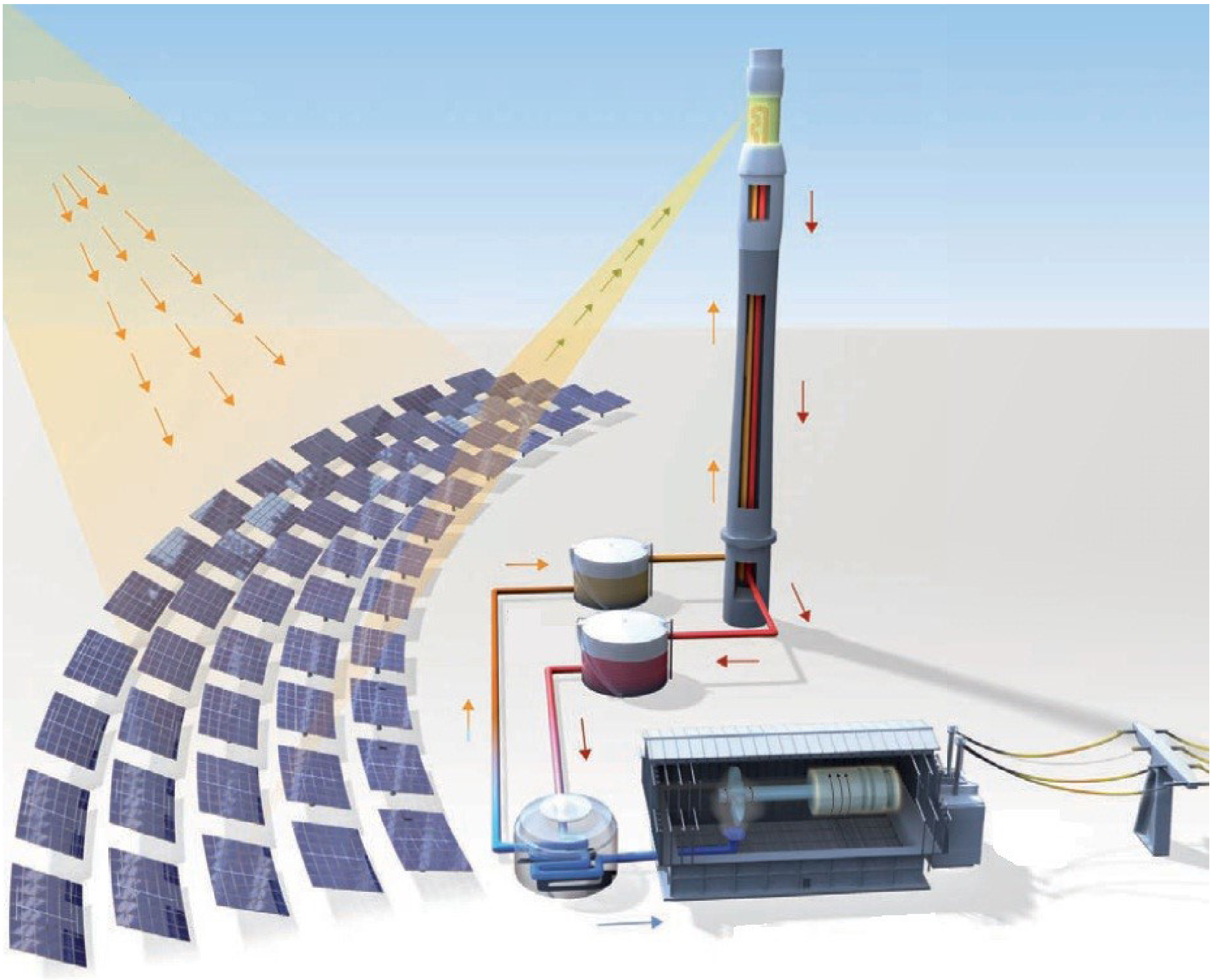

Figure 8: Integration of a two-tank direct molten salt storage system into a Solar Power Tower plant (here: Gemasolar plant) [4]

Application for other heat transfer mediums (indirect molten salt)

The indirect molten salt storage is not directly integrated into the heat transfer cycle. The system consists of two storage tanks for the salt with molten salt pumps in each. Between the tanks is a pipeline connection with several heat exchangers. The heat exchangers serve as a means to transfer the heat from the heat transfer medium (e.g. synthetic organic fluid or water/steam) to the molten salt and vice versa. This system has been applied at the Andasol 1-3 power plants in Spain. The schematic layout of a typical design is shown in Figure 9.

The left tank is described as the cold storage tank and the right tank as the hot storage tank. The molten salt, when cold, is stored inside the cold storage tank. In this state the molten salt has a temperature of approx. 290 °C in order to maintain a temperature distance to the crystallization point of the salt mixture of approx. 220 °C. If the molten salt should reach this temperature, crystallization of the salt will occur, damaging the system and making it non-operational.

Especially the containment of the hot tank of the system is made of stainless steel, due to the thermal stresses and the presence of the storage material.

From a principal point of view, the cold tank could be manufactured with carbon steel. To enable the system to store the whole molten salt in one tank in case of emergency, often both tanks are built of stainless steel.

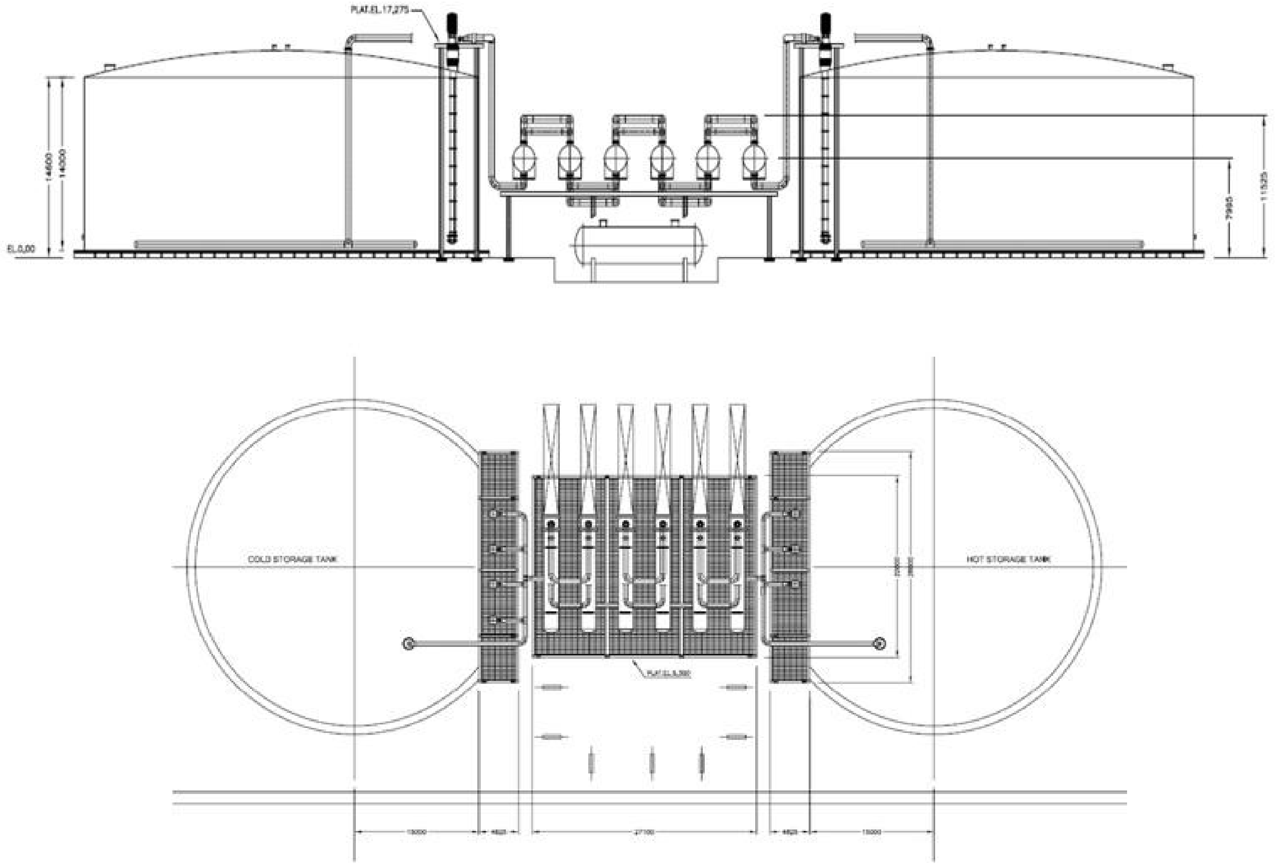

Figure 9: Schematics of a molten salt two tank thermal energy storage system, side view and view from above, Andasol 1 plant [5]

For the charging process, the molten salt from the cold storage tank is pumped through the pipeline with the heat exchangers “batteries”, where the heat from the heat transfer medium is transferred to the salt. To increase the part load performance of the system, two parallel pipelines are installed, allowing the use of only one pipeline in part load and both pipelines in parallel operation on full load conditions. The hot salt is stored inside the hot storage tank in the process. For the discharging, the process is reversed. The heat is transferred back to the heat transfer medium and the now cold molten salt is stored in the cold storage tank again.

Comparison of the two methods

Both systems could be compared considering the plants Gemasolar and Andasol 1, both with different storage capacities and installed electrical power but with similar thermal heat capacity of about 1000 MWhth. The technical parameters for both systems are given in the following table, based on [6]. The effect of the useful temperature range of the storage medium is obvious. With the indirect method, three times more molten salt is necessary resulting in higher system costs.

Project	Storage method	Thermal capacity [MWhth]	Inventory mass [tones]	Temperature [°C]		Volumetric heat capacity [kWh/m^3]
				cold tank	hot tank	
Gemasolar	direct	1000	8’500	290	565	210
Andasol 1	indirect	1010	28’500	292	386	75

Technical parameters

This technology is so far the only commercially available, applied and proven long-term thermal energy storage system. This technology however has, as well as other storage technologies, a few drawbacks. For example, the price of the molten salts is highly volatile and depends strongly on the market and availability. This causes fluctuations in the investment costs of this system. During operation of the storage, it is very important not to reach the crystallization point of the molten salt. Crystallization of the salt within the tanks can have drastic impact on the entire system, making it unusable. The crystallization point of the salt mixture 60 % NaNO3 and 40 % KNO3 is at approx. 220 °C and thermal stability is up to approx. 580 °C. For safety reasons, a temperature distance is kept to these two significant points. The tanks for the approx. 1000 MWhth capacity system each have a diameter of approx. 38.5 m and a height of approx. 14 m with a system mass of around 31’000 t, thus requiring significant space. Based on the construction and operational experiences this is somehow the maximum size of molten salt storage. To achieve a higher capacity, several 2-Tank systems are built in parallel, allowing a limited modularity of the system. With the Solana Generation Station (Arizona, USA; 2013) the biggest thermal storage system was implemented, offering a storage capacity of 6 hours for a plant with an installed capacity of 280 MWel. The thermal storage system consists of six parallel 2-Tank molten salt systems.

The storage efficiency is defined by two main factors: At first, losses due to the thermal losses and second losses due to the energy transfer via the heat exchanger. Both factors are strongly depending on the storage design, for direct methods without heat transfer, only the thermal losses for the tanks and piping are relevant.

Heat loss of the storage tank consists of convection to the environment over the walls of the storage tank and conduction to the foundation. Applying a highly effective thermal insulation, for all relevant parts (tank, piping, heat exchanger, etc.) the heat losses could be minimized to values between 2 % and 6 %.

As already explained, a certain temperature gradient is always necessary to transfer the heat with the heat exchanger. Therefore the temperature of the HTF after discharging is always lower than the HTF from the solar field. This effect is described as a decrease of the exergy through the storage. To quantify this decrease, the ratio of the Carnot cycle efficiencies during charging and discharging is used. With a typical temperature gradient of 10 K each, round trip efficiency values for the heat exchangers of around 99.5 % could be achieved. Combined with the thermal losses, overall storage efficiency values around 95 % are achieved with commercial systems [7].

The electrical own consumption of the molten salt system is dominated by two main consumers: the electrical trace heaters necessary to prevent the freezing of the system and the molten salt pumps, providing the flow through the heat exchangers. The pump energy is depending on several factors like the pump efficiency and the flow rate, for a Andasol like system the necessary energy for one cycle (charging and discharging) is estimated with 1.8 MWhel. [8].

The foundation of the tank is a critical part of the system, due to the fact that is has to resist the huge masses of the system and the high temperatures of the system. The concrete used for the foundation has a thermal stability limit at around 80 – 90 °C. Therefore a separate insulation and additional air-cooling systems are necessary to avoid an increase of the concrete temperature, shown in Figure 10.

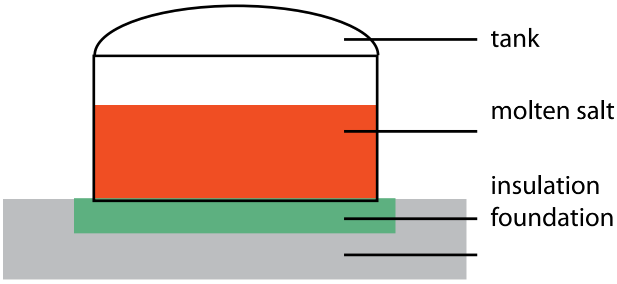

Figure 10: Schematic layout of the molten salt tank and the foundation

In the design phase of the foundation, the long term effect of the always shifting hot molten salt mass must be taken into account. The weight and charge/discharge cycle of the molten salt mass may cause a thinning of the insulation or a deformation of the tank bottom, resulting in higher concrete temperatures.

Operation and maintenance

Two-tank molten salt storages have long operational experience. Referring to information from a molten salt storage supplier with more than 20 accumulated years of operational experience, the maintenance effort is very limited and carried out as follows:

Pumps: Predictive maintenance and analysis of vibrations during operation are carried out. An inspection every 5000 hours of operation is recommended.

Piping/ trace heating: A weekly check of the piping / trace heating and its distribution cabinets is carried out.

Instrumentation: The Instrumentation is checked annually

Heat exchangers: An annually inspection to the heat exchangers including predictive maintenance, analysis of working conditions and performance is carried out.

Most of the maintenance works can be carried out during daily operation and with that the impact on plant operation is kept at a minimum; the availability of the molten salt system exceeds 99 % and is higher than all other parts (power block and solar field) of the CSP-plant [3]. No special equipment is necessary for the maintenance.

The replacement of solar salt during a considered 20 year runtime of the plant is not expected by the supplier and the operational experience up to now confirms this hypothesis.

Two tank molten salt storage systems are at the moment the number one choice for storage implementation in CSP-plants. However, new storage systems are coming up, slowly but steady making their way from the development and demonstration stadium to a soon competitive storage alternative. In order to stay competitive even for future storage systems, molten salt storage suppliers are steadily trying to improve their system. Improvements of molten salt storage systems mainly take place in two categories, the improvement of the storage material and the plant design. These developments are described in the chapter 5.1.1.

CSP-Track record (extract)

Project name	Storage capacity	In operation	CSP- Technology	Owner / EPC Contractor
Andasol 1	7,5h ~1000 MWhth	11/2008	Parabolic Trough	ACS Cobra Group / UTE CT Andasol
Andasol 2	7,5h ~1000 MWhth	06/2009	Parabolic Trough	ACS Cobra Group / UTE CT Andasol
Andasol 3	7,5h ~1000 MWhth	08/2011	Parabolic Trough	Ferrostaal/Solar Millenium/RWE/Rhein E./ SWM
Archimede	~ 8h ~100 MWhth	07/2010	Parabolic Trough (Direct Molten Salt)	ENEL / ENEL
Solana	~6h, ~4500 MWhth	10/2013	Parabolic Trough	Abengoa Solar / Abengoa Solar
Gemasolar	15h ~800 MWhth	04/2011	Solar Tower (Direct Molten Salt)	Torresol / UTE C.T Solar Tres

Summary:

The molten salt storage system is a system that stores sensible heat in a mixture of nitrate salts. Based on the used heat transfer fluid, it could either be implemented as a direct or an indirect storage method. The nitrate salts have to be kept in a liquid phase over the whole operational runtime of the storage system, which means that a decrease of the systems temperature below a certain limit will have to be avoided in any case.
Two-tank molten salt storage system is the state of the art long term thermal storage type available for application to different CSP technologies as direct storage as well as indirect storage solution. It can supply all kinds of capacity ranges necessary for solar energy production. Due to the long track record and the operational experience with this system, it is almost the only bankable long term thermal storage solution on the market at the moment.
Costs for storage materials are high and volatile depending on the market behavior. The efforts for operation and maintenance are well predictable and economically justifiable.

2.3.2 Ruth's storage system

CSP-system with direct steam generation (DSG) needs a direct method of storing the heat, due to the challenges transferring latent heat (see chapter 2.1.2.). Using pressure vessels for the direct storage of saturated or superheated steam is not economical feasible. As current state of the art, steam accumulators are used. Within this system the heat is stored in pressurized, saturated liquid water. Due to the thermodynamic properties, there is a big difference between the volumetric heat capacity of saturated steam and saturated water, resulting in a much smaller vessel when using saturated water. Although it is technical feasible to build steam accumulators with a big capacity, the costs are very high. Therefore only small capacity factors up to 1 h are installed at CSP-plants.

The scheme of a steam accumulator is shown in Figure 11. The design and the capacity of the Ruth's storage is mainly influenced by the pressure in the storage. A higher pressure is resulting in a higher volumetric capacity but requires on the other side a very thick vessel to resist the forces, resulting in a typical economical limit up to 70 bar.

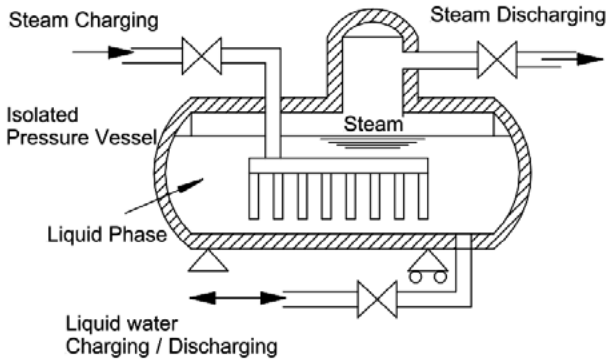

Figure 11: Scheme of sliding pressure accumulator [9]

In order to charge the accumulator, steam is blown into the liquid phase. The incoming steam condenses in the liquid or passes into the steam phase. The steam that is reaching the steam phase is increasing the pressure in the vessel, resulting in a higher saturation temperature. With higher saturation temperature, more steam in condensing in the liquid phase. With this principle the amount of steam in the system is always kept at the same level (about 10 %).

By lowering the pressure in the vessel, saturated steam is produced and the storage is discharged, resulting in a continuously decrease of the pressure. As the storage medium and the working medium is the same, high discharge rates could be achieved, only limited by the design parameters of the pipes.

Another method to charge or discharge the storage is the exchange of saturated water at the bottom of the vessels, also shown in Figure 11, although this is not the primary way.

Technical parameters

The volumetric storage capacity of the steam accumulator is depending on the thermodynamical properties of water. Assuming that the storage could be discharged to a pressure of 20 bar the resulting storage capacities for different pressure levels is shown in Figure 12.

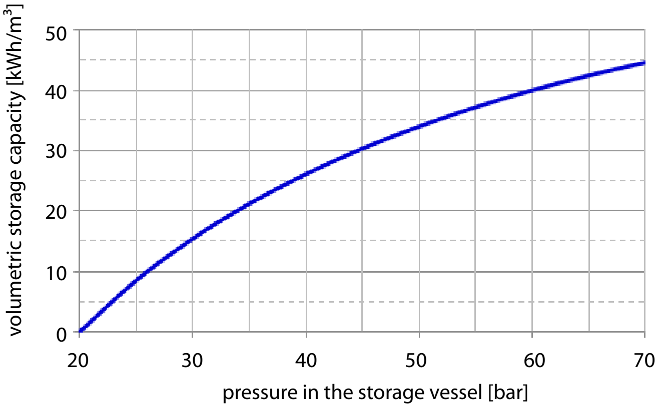

Figure 12: Volumetric storage capacity for a Ruth's storage system

As the water in the storage is always kept on saturated level, the temperature ranges within the storage is between 210 °C (20 bar) and up to 285 °C (70 bar).

As typical "state of the art" Ruth's storage systems with 55 bar as maximum pressure are used. Assuming a storage volume of 100 m^3, about 3.5 MWhth of thermal energy could be stored in such a system, resulting in an approx. system weight of about 90 t. The main challenge building this system is the huge pressure within this system. Therefore high-quality steel (e.g 1.6368) is necessary in order to keep the wall thickness in an economical feasible range (below 75 mm). A thermal insulation reduces the thermal losses of the system to a minimum of about 2 % related to the energy stored within the whole load range. Compared to the energy produced by the solar field, the thermal losses are below 0.1 %. The electrical own consumption is negligible [10].

The storage vessels are constructed at the facility of the manufacturer and delivered to the side, reducing the construction time on the side to a minimum. At the side the vessels could be placed on the ground level with concrete foundation (like it is done at Planta Solar) or even on a steel structure at a higher level (like it is done at Puerto Errado 2). Besides the weight of the storage vessel there are no additional requirements on the foundation.

As already mentioned, it is economical not feasible to build huge storage vessels. To increase the storage capacity the number of storage vessels is increased, resulting in a very high modularity and availability of the storage system. As there are no movable parts included in the system, almost no maintenance work is necessary besides regular inspections.

The steam accumulator could be directly integrated in a plant using direct steam generation, shown in Figure 13.

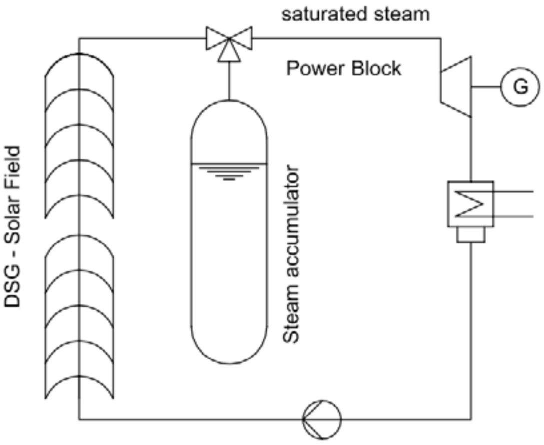

Figure 13: Scheme of a DSG solar thermal plant with integrated steam accumulator [9]

A surplus of steam from the solar field is stored in the steam accumulator. If the steam demand from the turbine is higher than the actual produced amount of steam in the solar field, steam is taken out of the storage in order to support or even replace the steam from the solar field.

CSP-Track record (extract)

Project name	Storage capacity	In operation	CSP-Technology	Owner / EPC Contractor
PE 2 (Puerto Errado 2)	0.25 h	2012	Linear-Fresnel	Novatec Solar
Alba Nova 1	1 h	Under construction	Linear-Fresnel	Solar Euromed
Planta Solar 10	1 h	2007	Solar Tower	Abengoa Solar
Planta Solar 20	1 h	2009	Solar Tower	Abengoa Solar
Khi Solar One	2 h	Under construction	Solar Tower	Abengoa Solar

Summary:

Ruth's storage is a direct storage method storing saturated steam. The system is implementable in CSP-systems using direct steam generation (like Linear Fresnel or Power Tower). The system is limited to capacity factors of up to 1 h and is used as medium term storage in CSP-plants. The storage system consists of several vessels, allowing a high modularity and availability of the system.
The storage principle was implemented in the early years of the 20th century and is common in the process industry. It is implemented in several CSP-plants like PE2 (Linear Fresnel) or PS10 & PS20 (Power Tower).

2.3.3 Ceramic honeycomb storage system

In order to store heat at a high temperature level, the honeycomb storage system could be used. This storage method combines a gaseous heat transfer fluid (often air) with a solid storage medium. Both mediums are in direct contact to each other and the heat is exchanged as the HTF flows along a flow-path through the storage medium.

Within several high temperature industrial applications, this principle is used for regenerator-type storage systems, like regenerative thermal oxidizer (RTO) in industrial air purification systems or as regenerator chambers in the glass industry. Different materials could be used to form the inventory, like alumina-silica or other ceramics. The main challenge of this system is the low heat transfer coefficient between the gaseous HTF and the solid material. Therefore the surface of the solid storage material must be increased. This could be done by a honeycomb structure or other innovative spheres.

The storage itself is built of several parallel modules, shown in Figure 14. The modules are connected through a dome and connecting piping. The hot air enters at the top of the system and flows through the ceramic storage material.

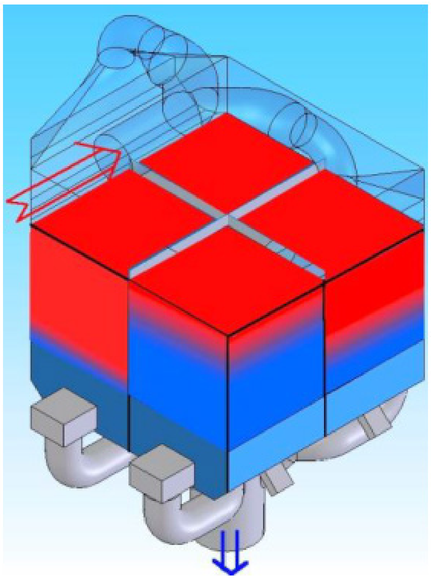

Figure 14: Modular storage design (KAM)

To increase the flexibility of operation, the storage is equipped with control valves at the cold end of the system (to reduce the material effort and the costs). With these valves it is possible to adapt the storage operation to different part load operations by closing some chambers. It is even possible to transfer the heat from one chamber to another with the help of an additional fan.

One key parameter in the design phase of the system is the electrical own consumption. The electrical energy necessary for the fans is depending on two main factors: the flow rate and the pressure drop. Due to the low heat capacity of the air a high flow rate is necessary to transfer the necessary heat. The pressure drop over the system is a key element in the design of the storage structure. The challenge is to reduce the pressure drop while increasing the surface.

Technical parameters

The storage system itself is operating at a temperature range between 120-150 °C (cold end) and 680 °C (hot end). In discharging mode outlet temperatures of approx. 640-670 °C could be achieved. As the heat transfer from the air to the storage media requires a huge heating surface, the storage material (alumina porcelain) is arranged in honeycombs. In the system in Jülich, a heating surface of 1180 m^2/m^3 could be achieved. With a total capacity of almost 9 MWhth and a total volume of the inventory of 120 m^3 a volumetric storage capacity of 75 kWhth/m^3 is achieved, with a specific system mass of around 13 kg/kWhth [11]. The maximum size for a single module is assumed with around 250 MWhth. By taking the whole temperature range into account (from 120 °C-1100 °C) specific volumetric storage capacities of up to 150 kWhth/m^3 could be achieved.

Thermal losses of the system are reduced by an inner insulation of the system made of 0.25 m thick ceramic fibre blankets. Due to the inner insulation no specific requirements on the thermal stability of the storing housing are necessary. It is made of mild steal with a surface temperature below 60 °C. The heat losses of the system depend strongly on the system configuration. They are mainly influenced by the thermal losses over the storage vessel and by the convection effects at the top of the storage. According to test measurements at the demonstration plant in Jülich [12], the thermal losses are mainly influenced by the convection effect. If it is possible to close the system with valves at the entrance and the output of the system, it is possible to reduce the overall thermal losses to a minimum of around 6 % of the thermal capacity over one day.

In order to transfer the heat from the air to the storage material, a specific temperature gradient between the two mediums is necessary. For the demonstration plant in Jülich, this temperature gradient is assumed with 15 °K. This temperature gradient effect the thermal efficiency of the thermal storage system. Theoretically, efficiency values up to 97 % could be realized, for a useful integration into CSP-system values around 90 % for all load factors are achieved, according to KAM.

Similar to the Ruth's storage, the thermal insulation of the systems allows a very simple foundation. In order to avoid thermal and pressure losses, it seems suitable to integrate the thermal storage system in the solar tower with short connections to the receiver and the steam boiler. If more space is necessary for the storage system, the storage vessels could be placed around the basement of the tower. For module sizes like the mentioned 250 MWhth system, foundation loads of around 3'000 t are estimated. Based on information from KAM, a construction time at the side of around 3-4 months for a storage system with 4 h storage capacity is necessary.

As there are no moving parts, the maintenance effort for the system is very low and the availability of the system is very high. As there is almost no time-depending degradation of the storage material longer downtime periods of the system are not expected. Based on operational experiences from the system in Jülich and similar industrial applications no additional maintenance work considering pollution of the honeycomb is necessary.

The honeycomb storage could be integrated directly in a CSP system using ambient air as heat transfer fluid. For charge operation the hot air from the receiver enters the storage at the top of the system and flows downwards through the storage, shown in Figure 15. The heat is transferred from the air to the storage material, resulting in a moving temperature profile in the storage.

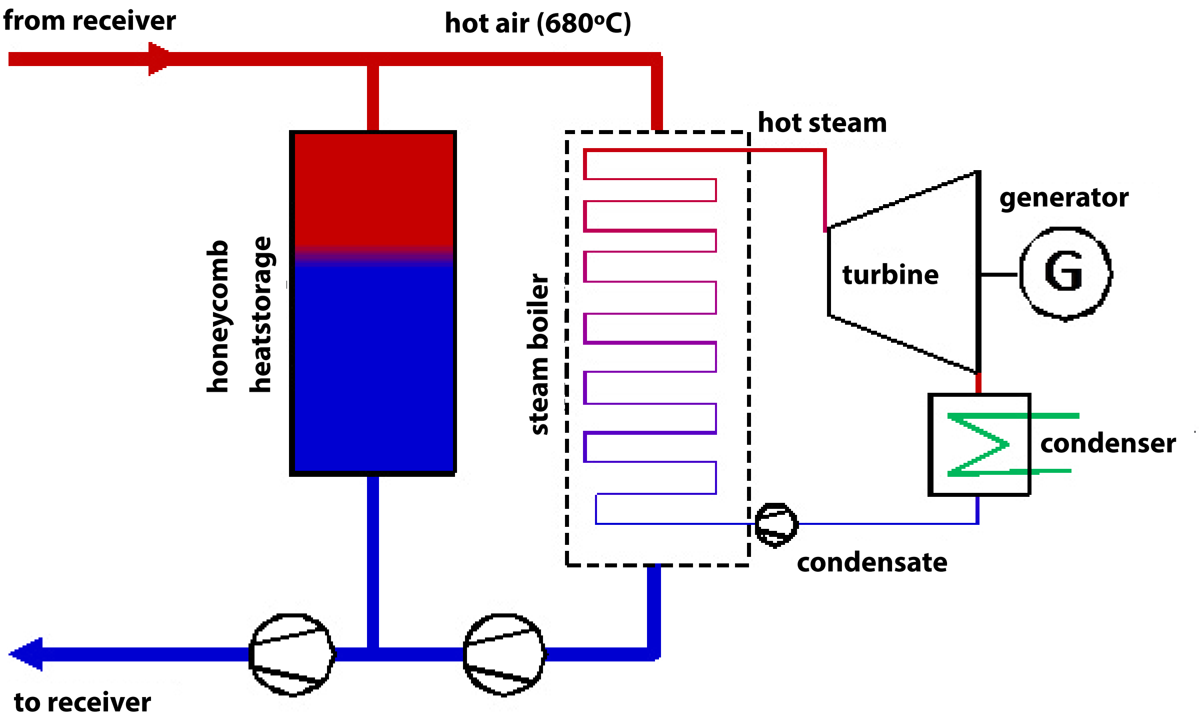

Figure 15: Scheme of a heat storage integrated in an ambient air receiver plant, based on [11]

By reversing the flow direction the discharge operation is started. Heat is supplied from the storage to the air and is transferred to the steam generator.

CSP-Track record

Project name	Storage capacity	In operation	CSP-Technology	Owner / EPC Contractor
Jülich Solar Tower	1.5h ~ 9 MWhth	2009	Solar Tower	Kraftanlagen München

Summary:

The ceramic honeycomb storage system is a direct storage method, applicable in CSP-systems using ambient air as heat transfer fluid (like the solar tower). The capacity of the system is limited by the available space. The system is nearly maintenance free. The main challenge in the design of the storage is the creation of a huge surface to guarantee a good heat transfer from the air to the storage material. The pressure loss over the storage system must be limited, to reduce the electrical own consumption of the storage system.

The storage principle is common in the process industry and was implemented in 2009 at the solar tower demonstration plant in Jülich, Germany.

2.3.4 Comparison

The parameters given here are explained in chapter 2.1.1 For a detailed description of each technology please refer to the different chapters.

Parameter	**Technology**		
	Molten salt system	**Ruth's storage**	**Ceramic honeycomb storage**
	chapter 2.3.1	**chapter 2.3.2**	**chapter 2.3.3**
In CSP-operation	Since 2007	Since 1917	Since 2007
Method	indirect/direct	direct	direct
Typical storage size	4, 8 and 16 h	0.5 h – 1 h	1.5 – 4 h
Storage capacity	huge	low	medium
Energy density	~75 kWh/m^3 (indirect) ~200 kWh/m^3 (direct)	30-45 kWh/m^3	70-80 kWh/m^3 (680 °C) 140 kWh/m^3 (1100 °C)
Own consumption	high	low	low
Modularity	low	high	medium
Temperature range	up to 550 °C	up to 285 °C	up to 680 °C (1100 °C)
Foundation	complex	basic	basic
O&M-effort	medium	low	low
Track-record in CSP	Very high	good	one plant
Main technology	PT- and ST-plants using thermal oil and molten salt as HTF	LF- and ST-plants using direct steam generation	ST-plants with ambient air receivers
Key points	• Only available long term storage system • Long track record and operational experience • Foundation is one key part • High availability, medium O&M-effort	• Only available direct storage method for direct steam generation (DSG) • Short term storage solution • High modularity	• Applicable for direct integration into air systems and indirect integration with heat exchangers• Heat is stored in solid material • Almost no mainte-nance necessary, even after longer still stand periods

Thermal storage systems are available for every CSP technology. The different storage technologies are economically feasible for different storage capacities. CSP-plant is not the only application for all considered technologies. All storage methods are also integrated into industrial applications.

The most mature thermal storage technology for CSP-plants is the 2-Tank molten salt storage, implemented in several CSP-plants with different sizes (from 20 MWel-280 MWel) worldwide. Taken into account the current operational experiences, the thermal storage system has a greater availability than all other parts of the CSP-plant. Due to the thermal insulation, the storage efficiency of every technology is very high.

The integration of storage systems with capacities >8 h into direct steam generation systems and the cost reduction of the overall system are further challenges thermal storages have to face with. Therefore, the already existing technologies are further developed and also new storage concepts are investigated.

3 ECONOMICAL ANALYSIS

Reliable information on the relative costs of the thermal storage system of a CSP-plant is an important point in the assessment of each technology. Within this chapter, costs of the presented storage systems are estimated, with a special focus on the molten salt system.

The thermal storage system of a commercial scale CSP-plant represents a share of 10 %-18 % of the total CSP-system costs, strongly depending on the used technology and the storage size. Nevertheless the storage system enables the CSP-plant to increase its capacity factor considerably. With this production surplus, a storage system in a suitable range always reduces the specific energy productions costs, the so called "levelized costs of electricity".

Within this chapter, the investment costs of the already described state-of-the-art technologies are estimated.. In a second step, the costs for operation and maintenance of the molten salt storage system are analyzed.

3.1 INVESTMENT COSTS (CAPEX)

In the first stage, the necessary investment costs of the equipment of the thermal storage system are estimated. A general estimation is done for the three considered state of the art technologies. As the molten salt system is the most mature technology, it is considered in a detailed cost breakdown.

Cost reduction of CSP-plants is one key point in the current development of CSP-plants worldwide. Besides the improvement of the plant efficiency, the reduction of the specific investment costs is an important goal of this development. In general, it is assumed, that an increase of the plant capacity will reduce the specific costs of the whole CSP-plant. Especially regarding the power block this so called "economy of scale"-effect is obvious. As the main components remain the same, a doubling of the installed capacity will not result in a doubling of the investment costs.

As the economy of scale is an important factor for the development of the CSP-plants, it is also analyzed in particular for the thermal storage within the following chapter.

3.1.1 Overall installation costs

The investment costs for a thermal storage system are analyzed in several papers. Among them, there are experiences from other projects and indications from EPCs. Compared to the overall system costs of the CSP, the costs of the thermal storage system are not directly depending on the location of the side.

To give an overview over the overall investment costs, the different state of the art systems are analyzed regarding their typical size of application. Data used from public available sources are tagged and are adapted on a common scope of supply in this analysis, in order to allow the comparability. The estimated specific storage costs are given, to allow the comparability of the figures. All data refer to plants developed/constructed between 2010 and 2013.

Storage System	Boundary conditions[1]			Estimated storage system costs [€/kWhth]	Source
	Storage size [h]	system size (MWel]	storage capacity [MWhth]		
Ruth's storage	0.5	50	114	**65-70**	Based on a LF-CSP-plant in MENA region
Ceramic honeycomb	--	--	2	**~60**	Information provided by KAM (ST-CSP-plant)
Ceramic honeycomb	--	--	250	**~30**	
Molten salt (direct)	6	100	1560	**30-36**	[13]
Molten salt (indirect)	7.5	50	1010	**41-45**	[14]
Molten salt (indirect)	8	100	2200	**~40**	Based on a PT-CSP-plant in the US
Molten salt (indirect)	14	100	~3800	**42-45**	[15]

For the estimated storage system costs, all necessary equipment for the storage system itself is included, as described in the different sections of chapter 2.3. Summarizing, all equipment for the heat transfer (if necessary), storage material, storage vessels and pumps or fans are included, also the risk and profit of the EPC. Only the storage system itself is considered, no additional solar field ("solar multiple") for charging is included in these figures, in order to allow a comparability of the figures without influences of the used solar field technology. Costs and preparation of the site are also not considered in this analysis.

3.1.2 Cost breakdown of indirect molten salt system

As the molten salt system is the only technology commercially available for large scale storage capacities, the cost structure is analyzed in detail within this chapter. As basis for this cost breakdown given in Figure 16, a parabolic trough plant with 100 MWel installed electrical capacity and a storage capacity of 8 h is assumed, resulting in a thermal storage capacity of about 2200 MWhth. The assumed system contains two lines of a common 2-Tank system. The data are based on a real CSP-plant project in the United States, developed by an experienced EPC-company.

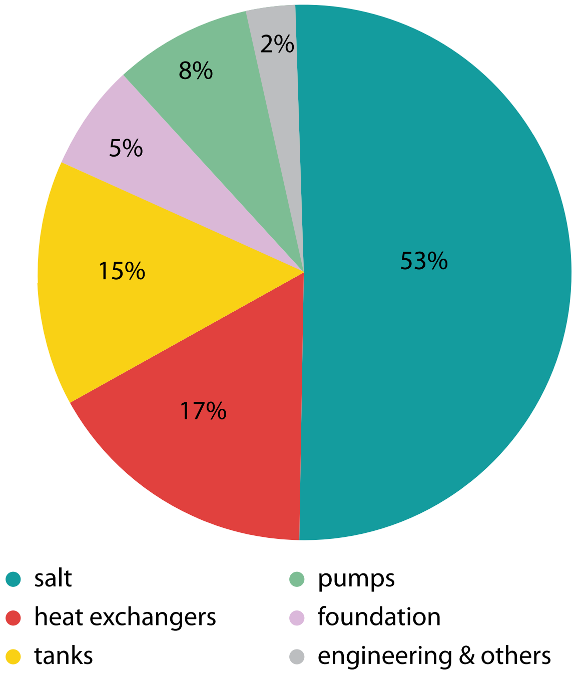

Figure 16: Cost breakdown of a 2200 MWhth indirect molten salt system

With more than 50 % the solar salt and the related components represent the largest share of the system costs.

To get a closer look into this share, the costs of the solar salt is detailed in its main components, shown in Figure 17.

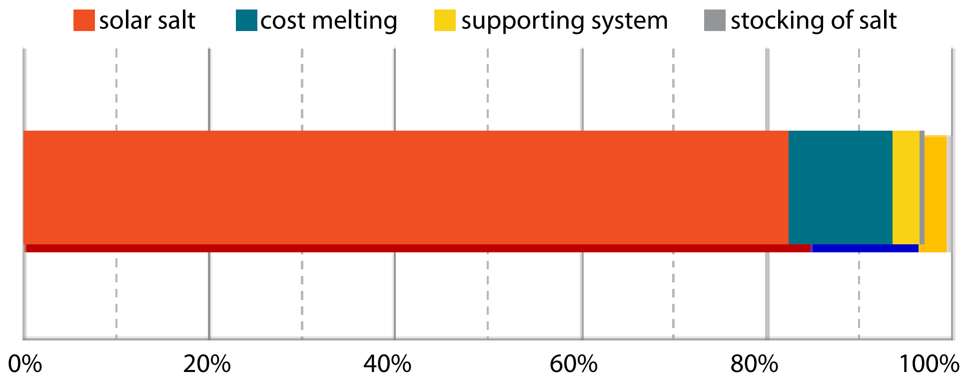

Figure 17: Detailed cost breakdown of the salt-costs

With more than 80 % the material costs of the solar salt has the main share on the salt costs, with specific costs of around 750 €/t. As the solar salt is a material component, it is not expected to achieve a huge cost reduction, ordering a greater amount. Therefore the "economy of scale"-effect for the solar salt is nearly negligible or even negative. Besides thermal storage systems also other industrial applications are demanding for the two components of the solar salt sodium nitrate (NaNO3) and potassium nitrate (KNO3).

The second largest share of the investment costs is the initial melting of the salt. As the salt is delivered as solid material, it must be preheated and melted at the side, including a special crushing, preheating and melting unit and the necessary amount of gas (or other fuels). Assuming gas costs of 35 €/MWh (current level Spain, [16]) specific melting costs of about 115 €/t are necessary.

The storage tanks (15 %) and the foundations (5 %) represents together the second largest share of the system costs. As the size of the storage tanks is bounded, an increase of the system capacity results in additional tank systems. If several 2-Tank systems are installed at one side, the construction infrastructure could be used several times. Due to this fact, the economy of scale effect on the cost reduction is given, but limited.

Cost reduction possibilities for the system include of course reducing costs for the tanks, also influencing the foundation costs. With the 1-Tank thermocline system (described in chapter 5.1.1) a promising concept is developed. The influence of a thermocline system on the costs of the overall system is not easy to estimate at the moment, due to the fact that several new components (like the moving barrier) and load factors have to be considered.

As the amount of necessary salt is depending on the useable temperature difference, any increase of this temperature range results in a saving of molten salt. As the molten salt has the highest share of the system costs, this leads to an enormous cost reduction. Therefore several developments are in progress, considering on the one hand the improvement of molten salt mixture (see chapter 5.1.1) and on the other hand the integration of direct molten salt receivers in parabolic trough and Linear-Fresnel plants.

Summary:

The thermal storage system represents a share of 10 %-18 % of the total investment costs of the CSP-plant. The specific storage costs for the Ruth's storage are the highest, followed by the costs for the honeycomb storage.
The investment costs for the molten salt storage have been analyzed in detail within different studies. Due to the higher temperature range, direct molten salt systems offers a cost advantage

compared to indirect molten salt systems.
The costs of the molten salt system are dominated by the costs of the solar salt, followed by the costs for the tanks and the foundation.
Further developments (like a 1-Tank system or further material developments) offer a cost reduction potential.

3.2 OPERATIONAL COSTS (O&M-COSTS)

In general O&M-costs of a CSP-plant are always given for the overall system. The O&M-costs of the thermal storage system are embedded in these costs. To give a rough estimation of the specific O&M-costs of the thermal storage, a top-down approach is performed, using the overall O&M-costs of the CSP-plant and the relevant shares of the thermal storage.

Based on [14], the total O&M-costs of a parabolic trough CSP-plant in the United States are estimated to values between 20 US$/MWhel and 30 US$/MWhel. In the same study, the O&M costs for a comparable plant in South Africa are estimated to values between 30 US$/MWhel and 40 US$/MWhel.

In principle the O&M-costs are influenced by two main factors:

- Fixed O&M-costs, representing around 90 % of the overall O&M-costs: Based on the costs for the staff and fixed costs for spare parts and wear and tear parts. Costs for insurances are also included in this cost block.
- Variable O&M-costs, representing around 10 % of the overall O&M-costs: Dominated by miscellaneous consumables, like the own consumption of the molten salt pumps, the fans or the additional trace heating of the piping and the tanks.

Within the following chapter, the O&M-cost of a molten salt system are considered in detail. As the track record of the honeycomb storage is very short, it is not possible to estimate these costs. The O&M-costs for the Ruth's storage are negligible and could be included into the O&M-costs of the power block, due to the similar components (pressurized vessels).

Based on [17] a cost breakdown of the maintenance and repair costs for a 100 MWel with 7 h molten salt storage system is shown in Figure 18. This CSP-plant is comparable to the regarded CSP-plant in chapter 3.1.1 concerning used technology, investment costs and location of the side. The thermal storage system is slightly smaller (7 h instead of 8 h) but includes also two lines of a common 2-Tank system. The thermal storage system represents a share of around 10 % of the overall maintenance and repair costs.

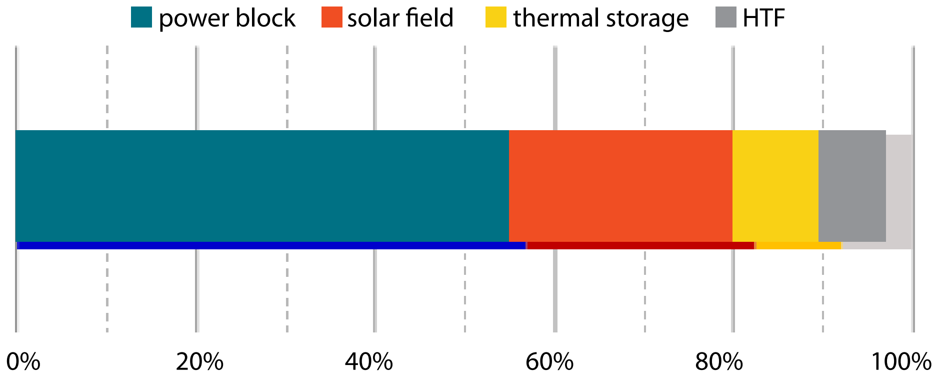

Figure 18: Cost breakdown estimated maintenance and repair costs of a CSP-plant

In order to estimate the total O&M-costs of the thermal storage system, some base assumption are taken into account.

- Maintenance & Repair costs as shown in Figure 18
- 20 % of the onsite staff is dedicated to the operation of the thermal storage
- 35 % of the variable costs are dedicated to the operation of the trace heating and the pumps
- Based on the share of the thermal storage on the total investment costs, 15 % of the other costs are taken into account
- CSP-plant (based on [17]): 100 MWel, Parabolic trough system, 7 h molten salt storage system (2000 MWhth), annual net production of 425 GWhel, operated in the US.

Base on these assumptions, the O&M-effort of the thermal storage system is estimated with a share of the total O&M-costs of around 18 % (1.9 mio US$), or a specific value of 4.5 US$/MWhel.

Transferring these values to Brazil additional assumptions are necessary. On the one hand, the wage level in Brazil is significantly lower than in the US. Compared to the operational staff necessary for the whole CSP-system, the operation of the thermal storage system requires well trained staff like technicians and engineers. Based on [18] the wage level for engineers in Sao Paulo (Brazil) is about 1/3 compared to Los Angeles (US). On the other hand, the price level for energy supply like gas is nearly at the same level.

In order to provide an independent view, again several assumptions are taken into account:

- Compared to the United States, the wage level is reduced on 1/3.
- Due to the lack of operational experience with CSP-plants in the first years, the necessary staff for O&M is raised by 50 % and additional external training stuff is included to provide a sustainable training "on the job".
- Variable costs remain on the US level
- Costs for spare parts are raised by 50 % due to the lack of a local industry for special equipment (molten salt pumps & heat exchangers).

Based on these assumptions, a slightly reduction of the O&M-costs for the thermal storage system of about 10 % is estimated. Together with the uncertainties of the used assumption, it could be concluded, that no significant change in the O&M-costs of the thermal storage system is estimated on a short-term base. Of course, initial plants have to deal with higher O&M-costs, due to the higher initial risks. Assuming a well establish CSP-industry and a sustainable training of local, the necessary staff could be further reduced. This results in significant lower costs for the O&M-cost of the thermal storage based on the lower wage level in Brazil.

Summary:

It is only possible to estimate the O&M-costs of the thermal system with several assumptions, because the O&M-costs are usually given for the whole CSP-plant. As the O&M-costs of a Ruth's storage are negligible and the O&M-costs for the honeycomb storage system could not be estimated due to the short track record, only the molten salt system is considered.
Based on several assumption, the O&M-costs of a molten salt thermal storage system have a share of the total O&M-costs of around 18 % (specific: 4.5 US$/MWhel).

4 WORLDWIDE MARKET PLAYERS

In this chapter, some main worldwide players active in the field of thermal energy storage are presented.

To provide a common understanding, all sales values provided in US$ or €. If the annual report of the company is given in another currency, the sales values are adopted with a fixed exchange rate. This is mentioned, including the used exchange rate.

4.1 STORAGE MATERIAL

4.1.1 SQM

Short company description

SQM is the world's largest producer of lithium chemicals, iodine, potassium nitrate and industrial nitrates used for thermal energy storage. SQM is based in Chile, where also nearly all mines are placed.

The company is dominating the market for industrial sodium nitrate (60 % market share) and potassium nitrate (40 % market share) which are the two components for the so called "solar salt". SQM is delivering "solar salt" since 2008. The sales volume in this sector ("Industrial Nitrates") was increased from 2011 to 2012 by 50 % and is expected to be increasing again in 2014.

Keydata (*based on companies annual reports 2008-2012*)

Year	Employees (overall)	Employees (CSP)	Sales (overall) million US$	Sales (CSP related sector) Million US$
2012	5643	n.A.	2'429	277
2011	4902	n.A.	2'145	182
2010	4327	n.A.	1'830	198
2009	4387	n.A.	1'439	--
2008	4561	n.A.	1'744	--

The main shareholders of SQM are:

- Inversions el boldo LTDA	23 %
- Sociedad de inversions Pampa calichera	20 %
- The Bank of New York Mellon ADRS	18 %

SQM is present in Brazil with offices in Sao Paulo and Las Condes-Santiago.

Track Record in CSP

SQM is the market leader in supplying solar salt for molten salt storage systems. Since 2009 SQM delivered solar salt to approx. 3 CSP-plants with 50 MWel per year (in total more than 750 MWel).

Some reference projects in Europe are Andasol 1 and 2 (Almeria, Spain, 2008-2009), Extressol 1,2 and 3 (Extremadura, Spain, 2009-2011) or L'Africana (Andalucia, Spain, 2012). Outside of Europe, SQM delivered its salt to the largest CSP project in the US (2012) and is already awarded a contract to deliver its salt to a 100 MWel plant in South Africa in 2014.

4.1.2 BASF

Short company presentation

BASF is a globally acting chemical company, active in the main sectors chemicals and petrochemicals, biotechnology, agricultural solutions and functional materials. The company delivers its products across all industries. BASF is headquartered in Ludwigshafen (Germany) and is considered as the largest chemical company in the world.

BASF has over 40 years operating experience in the use of molten salt as HTF in chemical processes. The company is also providing high purity alkali nitrates and nitrites. During the last years, BASF has established an intense R&D work in the field of high temperature HTF and thermal storage material, especially regarding the long term salt stability and the corrosion effects of materials at high temperatures.

Keydata (*based on companies annual reports 2008-2012*)

Year	Employees (overall)	Employees (CSP)	Sales (overall) million €	Sales (South America related division) million €
2012	110’782	n.A.	72’129	4’549
2011	111’141	n.A.	73’497	4’418
2010	109’140	n.A.	63’873	3’829
2009	104’779	n.A.	50’693	3’001
2008	96’924	n.A.	62’304	4’359

BASF is a joint stock company.

BASF is present in Brasil with several plants. The regional headquarter for South America is placed in Sao Paulo, important research center is placed in Guaratinguetá.

Track record in CSP

BASF has a detailed R&D-track record concerning the assessment of the corrosion behavior of molten salt and regarding the salt characterization.

4.1.3 China FOMA Group

The Chinese company FOMA, headquartered in Beijing, in one of the TOP 50 machinery manufacturers in China. The company is active in the sectors power equipment, forestry equipment and engineering & trade.

FOMA has exported their products in more than 130 countries and regions worldwide, including the US, Germany and Japan. Since 20 years the company is delivering potassium nitrate and sodium (the key elements for the solar salt) for industrial heat processes and industrial storage applications.

Keydata (*based on company interview*)

Year	Employees (overall)	Sales (overall) million €
2012	4’500	600
2011		680
2010		650

China FOMA is a subsidiary company of China National Machinery Industry Corporation and is owned by the government. The company German-Tech is the exclusive distributer for export outside China.

Track record in CSP

China FOMA is well experienced in supplying industrial processes. Their assumed delivery capacity of solar salt is around 80’000 tons per year.

4.1.4 Saint-Gobain NorPro

Short company presentation

Saint-Gobain was founded more than 300 years ago and has developed to an international industry corporation based in France. They provide solutions in five major business sectors: Flat Glass, Packaging, Construction Products, Building Distribution and High-Performance Material (in the Sector Saint-Gobain NorPro is represented).

Saint-Gobain NorPro, based in the United States and Germany, provides extensive expertise and experience in engineering high-performance ceramic shapes and materials to optimize the heat transfer properties and the system pressure drop. The company is providing ceramic-based solution for industrial applications and is offering a wide range of different structures and materials.

Keydata (*based on companies annual reports 2008-2012*)

Year	Employees (overall)	Sales (overall) million US$	Employees (High Performance Material Sector)	Sales (High Performance Material Sector) Million US$
2012	192’781	43’198	~27’000	4’376
2011	194’658	42’116	~27’000	4’163
2010	189’193	40’119	~27’600	-
2009	191’442	37’786	-	-
2008	209’175	43’800	-	-

Saint-Gobain is a joint stock company, with International (42 %) and French (18 %) institutional investors as main shareholders.

Track record in CSP

Saint-Gobain NorPro is well experienced company supplying ceramic for regenerative thermal oxidizers (RTO). They offer their products also to the CSP market, providing solutions for fixed and moving bed applications.

4.2 HEAT EXCHANGERS

4.2.1 Alfa Laval

Short company description

Alfa Laval was founded in 1883 in Stockholm, Sweden. The company produces heat exchangers, separators, pumps and valves for the chemical and petrochemical industry, power plants and the food industry. Heat transfer products account for more than 54 % of sales and Alfa Laval has an estimated market share in this field of more than 30 %

For CSP-plant and thermal storage systems, Alfa Laval is providing heat exchangers for the heat transfer between the thermal-oil from the solar field and the molten salt system. The company also provides other heat-exchangers, condensers and dry coolers for CSP-plants. The CSP-sector is one part of the process technology division.

Keydata (*based on companies annual reports 2008-2012, exchange rate: 1 €/0.11 SEK*)

Year	Employees (overall)	Sales (overall) million US$	Sales (Process technology division, CSP related sector) million €
2012	16’419	3’337	1’409
2011	16’064	3’153	1’337
2010	12’618	2’625	1’168
2009	11’390	2’369	1’279
2008	12’119	3’021	1’371

Alfa Laval is a joint stock company; the main single shareholder is Tetra Laval (26.1 %).

Track Record in CSP

In 2013 Alfa Laval delivered Molten Salt / HTF Heat exchangers to CSP-plant built by Abengoa Solar in South Africa (Kaxu-Upington) and the US (Solana).

4.2.2 Babcock Power

Short company description

Babcock Power Inc. is a global, multiproduct and privately owned energy and environmental services company. Babcock is one of the world’s leading suppliers of technology, equipment and services to the power generation industry. Through its subsidiaries, the company designs, and manufactures heat exchangers, heat recovery steam generators, steam surface condensers, and feedwater heaters for fossil-fired and nuclear plants.

For CSP-plants the subsidiary Struthers Wells (part of the Thermal Engineering division) designs and fabricates high pressure steam generating systems, central receivers and feedwater heaters. Concerning the solar thermal storage system, Struthers Well manufactures the molten salt heat exchanger for the heat transfer from the direct molten salt storage system to the power block. They also offer heat exchanger from thermal-oil to molten salt.

Keydata

There is no company data public available.

Track Record in CSP

In 1982 Struthers Wells designed and fabricated a complete solar steam generator in Bakersfield, California. In 1994 they delivered the molten salt heat exchanger for the Solar Two power tower, the first CSP-system with direct molten salt storage system.

Since 2011 Struthers Well equipped several plants in Spain and the Middle East with solar steam generators and HTF heaters.

4.2.3 SPX

Short company description

SPX based in Charlotte, United States, is a multi-industry manufacturer serving the power and energy, food and beverage and industrial sector. SPX Thermal Equipment & Service is one of the world's leading manufacturers of thermal power plant components. On a worldwide level SPX is developing and producing solutions for all kinds of thermal power plant. With several subsidiaries like "Balcke-Dürr" the company is offering power plant components in the water-steam, heat-transfer fluid or molten salt cycle.

For CSP-plants and the thermal storage systems, SPX is providing heat exchangers for direct heat transfer from the molten salt system to the water steam cycle of the power block. The company also produces solutions for the heat transfer from the thermal-oil cycle to the molten salt storage system. Cooling solutions and components for the steam generator and the power block are also provided by SPX for CSP-plants.

Keydata (*based on companies annual reports 2009-2012*)

Year	Employees (SPX, overall)	Sales (SPX, overall) million US$	Sales (SPX, power and energy sector) Share of overall sales	Employees (Balcke-Dürr)	Sales (Balcke-Dürr) million €
2012	15'000	5'100	43 %	-	-
2011	18'000	4'536	35 %	689	109
2010	15'500	4'098	36 %	768	139
2009	-	4'161	-	770	144
2008	-	4'864	-	734	186

Track Record in CSP

SPX provided the steam generator for several CSP-plants (e.g. Nevada Solar One, US, 2007) using the thermal-oil from the solar field to produce steam.

The heat exchangers necessary for the heat transfer from the solar field to the molten salt storage system was provided by SPX for several plants in Spain (e.g. Andasol 1 and 2, 2009).

4.2.4 GEA HEAT EXCHANGERS

Short company description

GEA Heat Exchangers is one sector of the GEA group, offering plate heat exchangers, shell and tube heat exchangers, air cooled heat exchangers, finned tube heat exchangers, air filter systems, synthetic fillings for numerous areas of application, wet cooling towers and dry cooling systems as well as air-conditioning technology.

GEA is offering all services related to the design, engineering (basic and detailed), procurement, manufacturing, testing, delivery and commissioning of heat exchangers for the power plant business. GEA is also offering air-cooled condensers (ACC) for power station, that could be used in CSP-plants.

Keydata (*based on companies annual reports 2009-2012*)

Year	Employees (GEA Group, overall)	Sales (GEA Group, overall) million US$	Sales (GEA Group, Heat Exchanger sector) million €	Employees (GEA Group, Heat Exchangers)
2012	24’498	5’720	1’608	7’329
2011	23’834	5’416	1’616	7’679
2010	20’386	4’418	1’483	7’340
2009	20’693	4’411	--	--
2008	21’327	5’179	--	--

GEA Heat Exchangers is present in Brasil with”GEA do Brasil Intercambiadores Ltda”, based in Sao Paulo.

4.2.5 Bertams Heatec

Besides molten salt heat exchangers, Bertams Heatec is also delivering turnkey storage solutions. The detailed company presentation is given in chapter 4.3.4

4.3 EPC-COMPANIES

4.3.1 ACS Cobra (Grupo Cobra)

Short company description

Since its inception in 1944, Grupo COBRA has evolved to become a world leader, thanks to its ability and determination to develop, build and operate industrial infrastructures and power plants requiring a high level of service.

In the field of CSP-plants and thermal storage, ACS Cobra is delivering: turnkey construction and operation and maintenance of solar thermal power plants, both with parabolic trough technology and concentration tower technology. Most of the plants are the first in the world with a Management Certification for using molten salt thermal energy storage.

Keydata (*based on companies annual reports 2008-2012*)

Year	Employees (overall)	Employees (CSP)	Sales (overall) million €	Sales (CSP related sector) million €
2012	18’400	~150	4’059	
2011	17’525	n.A.	3’856	
2010		n.A.	3’793	
2009		n.A.	3’484	
2008		n.A.	3’171	

The main shareholders are:

- Cobra Instalaciones y Servicios, S.A.: 80 %
- Recursos Ambientales, S.A.: 7.5 %
- Urbaenergía, S.L.: 10 %

Track Record in CSP

ACS Cobra was EPC for several solar thermal power plants with parabolic trough technology and indirect molten salt storage. Since 2008 they build plants in Europe (e.g. Andasol 1 and 2; Valle 1 and 2).With Gemasolar in Spain and Crescent Dunes in the USA they also acted as EPC in large solar tower plants with a direct molten salt system, totaling over 500 MWel in both technologies worldwide.

4.3.2 Abengoa (Abengoa Solar)

Abengoa, S.A is a multinational corporation based in Seville, Spain, which includes companies in the domains of energy, telecommunications, transportation, and the environment. It is a global biotechnology company specializing in the development of new technologies in producing biofuels and biochemicals and promoting sustainability of raw materials.

Abengoa invests in research in sustainable technology, and implements these technologies in Spain as well as exporting them globally. These technologies include concentrated solar power, second generation biofuels, and desalination.

Abengoa started solar energy research with construction of components such as heliostats and facets for the Cesa Power Tower at the Almería Solar Complex. They collaborated with Israel's Weizmann Institute on the design and construction of its solar power tower project. Abengoa geographic strategy on solar systems is based on the use of specialized teams in different locations for the promotion and sale of energy on the local level, manufacturing components at the regional level, and the development of new technologies on a global scale.

Keydata (based on companies annual reports 2008-2012)

Keydata (*based on companies annual reports 2008-2012*)

Year	Employees (overall)	Employees (Abengoa Solar)	Sales (overall) million €	Sales (Abengoa Solar) million €
2012	26.402	1.247	7.783	688
2011	22.261	771	7.089	345
2010	20.445	480	5.566	168
2009	23.323	388	4.147	116
2008	23.234	241	3.114	65

Track record in CSP

Abengoa build worldwide several plants with molten salt storage systems. In Spain Abenoga has installed CSP-plants with more than 650 MWel (e.g. Solonova, El Carpio). In South Africa the Khi Solar One Solar Tower plant is under construction, including 2 h of storage capacity.

From 2011-2013 Abengoa constructed the largest CSP-plant (Solana, US) with an electrical output of 280 MWel and 6 h storage capacity (6 parallel 2-Tank molten salt systems).

4.3.3 Sener Ingenería y sistemas S.A.

Short company description

Sener Ingenería y Sistemas S.A. is an Engineering and Construction company backed by more than 50 years' experience. The company was founded in Spain and is active in the fields of civil engineering and architecture, aerospace engineering, power and process technology and marine engineering. Sener is acting worldwide and has 17 offices located around the world.

In the field of CSP-plants Sener is present with its subsidiary "Torresol Energy", which was founded to promote technological development and the construction, operation and maintenance of large CSP-plants. Torresol was founded in 2008 through an alliance between Sener (owner of 60 %) and MASDAR, an alternative power company in Abu Dhabi (owner of 40 %). The company activities focus on plants in the south of Europe, North Africa, the Middle East and the United States.

Sener is also very active in the development of new storage concepts. The first pilot plant of a single tank molten salt storage was constructed by Sener at the "Valle CSP-plant".

Keydata (*based on companies annual reports 2008-2012*)

Year	Employees (overall)	Sales (overall) million €	Sales (Engineering and construction division) share of overall sales
2012	5'458	1'174	~50 %
2011	5'165	1'159	~51 %
2010	5'005	1'066	~51 %
2009	4'916	937	~46 %
2008	4'573	845	--

With more than 98 % the main shareholder of Sener is the founder family.

Sener is present in Brasil with an office in Sao Paulo.

Track Record in CSP

With the Gemasolar-tower (Spain, 2012) Sener/Torresol constructed and operates the first molten salt tower system with a 16 h molten salt storage system and 19.9 MWel electrical power output.

Sener/Torresol also constructed and operates two parabolic trough plants (Valle 1 and 2, Spain).

4.3.4 Bertams Heatec (The Linde Group)

Short company description

Bertrams Heatec, headquartered in Switzerland, is providing solutions for process heat transfer, particularly in chemical and petrochemical industries. The company offers all components and services, including the design and development phase, the plant construction and commissioning of the finished system.

In the field of CSP and molten salt system Betrams Heatec is offering engineering and design services of molten salt melting units, molten salt HTF-oil heat exchangers and complete storage systems for CSP-plants, based on over 50 years experience of handling molten salts in heat transfer plants. Together with Linde Engineering they also act as turnkey EPC for complete molten salt storage systems.

Keydata (*based on company interview and annual reports 2008-2012*)

Bertrams Heatec belongs to "The Linde Group", for big commercial projects Bertrams Heatec is supported by its partner Linde Engineering.

Year	Employees (Linde Group, overall company)	Employees (Bertrams Heatec)	Sales (Linde Group, Engineering division) million €	Sales (Linde Group, overall company) million €
2012	61'965	~45	2'561	15'280
2011	50'417	--	2'531	13'787
2010	48'430	--	2'461	12'866
2009	--	--	--	11'211
2008	--	--	--	12'663

The Linde Group is present in Brasil with the "Linde Engenharia Do Brasil Ltda." based in Rio de Janeiro.

Track Record in CSP

Betrams Heatec delivered three initial salt melting units to Spanish plants and the nitrate backup heating system for a solar tower project in Spain. They also acted as FEED (Front End Engineering Design) for the solar thermal storage system for Andasol 3(Almeria, Spain).

At the moment they are acting as EP (Engineering and Procurement) for two pilot plants with high temperature molten salt (up to 550 °C).

4.3.5 KAM

Short company description

Kraftanlagen München (KAM), headquartered in Munich, Germany, has a 55 years experience as a piping system and plant construction company. KAM is active in the fields of conventional power plant technology, renewable energies, plant maintenance and service and the chemical and petrochemical industries.

In the field of CSP technology, KAM is active since 2002 with own research projects in Spain and Germany. Besides their R&D activities concerning open volumetric receiver for solar tower systems and the honeycomb storage system, they act as EPC for solar tower projects.

Keydata (*based on company interview and annual reports 2010-2012, exchange rate for Alpiq Holding: 1€ / 0.833 CHF*)

Year	Employees (KAM)	Employees (KAM-CSP divison)	Sales (KAM) million €	Sales (Alpiq Holding) million €
2012	2’586	~20	451	10’578
2011	2’683	--	397	11’630
2010	2’294	--	366	11’748

KAM belongs to the Alpiq Holding AG, a Swiss company active in the electrical sector.

Track record in CSP

Kraftanlagen München (KAM) was responsible for the engineering and production of a high-temperature receiver for a demonstration tower plant at the Plataforma Solar (Spain).

For the solar tower 1.5 MWel demonstration plant in Jülich (Germany, 2006) they acted as turnkey contractor for engineering, supply, construction and commissioning.

At the moment KAM is developing a hybridized solar tower project in Algeria.

5 TECHNOLOGY DEVELOPMENT

5.1 FURTHER TECHNICAL DEVELOPMENT OF COMMERCIAL TECHNOLOGIES

The existing thermal storage technologies commercially available for CSP-plants are under further development. The main objective of these developments is to reduce the system costs. Therefore higher temperature values are investigated in order to increase the efficiency of the system and solutions to reduce the overall system cost are developed.

5.1.1 Molten Salt storage

Storage material

Efforts to apply an extended operational temperature range for molten salts, in order to decrease the lower temperature limits is one of the biggest challenges. An increased temperature range grants higher energy densities for the storage which results in smaller footprints and cost savings for the storage material. Cost savings caused by the increasing energy densities have to compete with additional costs due to increasing material cost for new technically sophisticated salt mixtures. To extend the temperature range to lower operation conditions further makes the complete handling and the anti freeze protection of the system easier and improves heat losses and own consumption behavior of the system. Also the plant operation is improved, including the daily start-up and shut-down procedures. The challenge is to change the characteristic of the storage medium without losing its chemical stability at high temperatures. The focus for new salts covers the whole range of Nitrates and Nitrites and all kinds of their mixtures. Additional to main parameters like specific heat capacity, thermal long term stability, solidification temperatures, viscosity also market availability and costs of potential additives and new mixtures have to be considered.

There are several studies and experimental works ongoing, trying to find suitable nitrates, mixtures and additives. It is expected, that within the next years, new and innovative salt mixtures will enter the market, offering higher temperature ranges than current solar salt mixtures.

System layout (1-Tank system)

In order to achieve a more efficient technical-economical layout of the molten salt system, the use of a 1-Tank system is under investigation. As distinct from the 2-Tank solution, the single tank storage consists of a single thermocline tank, including the whole storage fluid at cold and hot temperature. The two fluids are separated by a barrier floating between, physically separating and insulating them. In Figure 19 a schematic layout of a first prototype, constructed by Sener is shown.

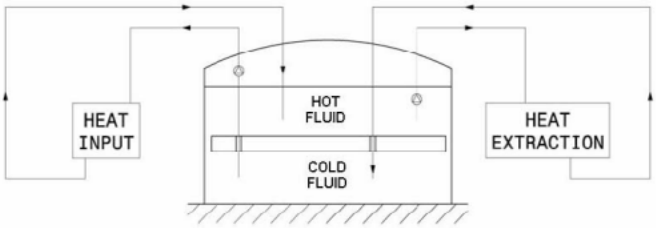

Figure 19: Schematic design of the single tank storage system with floating insulation barrier [19]

In charging mode, the cold fluid from the bottom of the tank is heated up and returns at the top of the tank. In order to discharge the system, the hot fluid is extracted and the cold fluid returns at the bottom. With this approach the tank is always operating at its full load.

One challenge for this kind of storage system is the barrier, separating and insulating the hot and the cold fluid. On one hand, the barrier must be moveable and the fluid must be able to move the barrier itself. On the other hand the barrier must be stiff enough to withstand the pressure load of the stored fluid. According to [20] the barrier must include compression resistant materials which eliminate any problems related to thermal deformations, resulting in an outer shell manufactured in the same material as the tank shell and some filling materials placed inside the shell.

Even at the small prototype with a thermal storage capacity of 24 MWhth, the barrier is traveling a distance of 8.3 m [19].

For a commercial realization of the single tank system, reduction of thermal losses of 50 % (resulting in an increase of the efficiency) and of the investment costs is expected compared to the 2-Tank solution. As the single tank solution is always filled, it is possible to use conventional pumps. Compared to the 2-Tank solution were special and more expensive vertical shaft pumps have to be used this results in an additional cost decrease.

5.1.2 Ruth's storage

Based on the system design, no further developments of the Ruth's storage system are expected. Due to the fact, that the system is only able to deliver saturated steam, the main challenge of this storage system is the combination with a superheating stage.

Combination with other storage systems

Based on the system design, Ruth' storage is only able to deliver saturated steam. To increase the efficiency of the steam cycle higher temperatures are necessary resulting in the use of superheated steam. To provide this steam, a second "superheating storage" is added behind the Ruth's storage, shown in Figure 20.

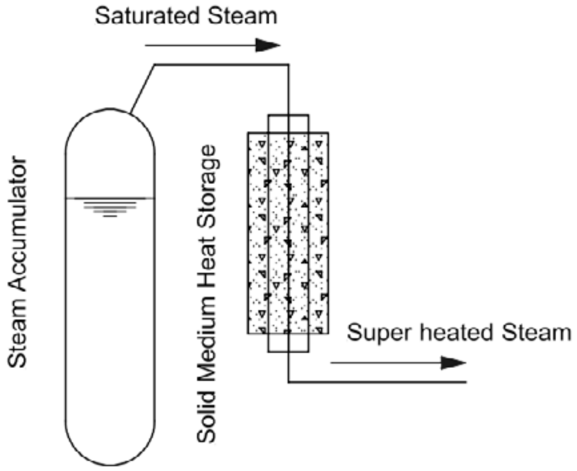

Figure 20: Combination of a steam accumulator with an additional superheating storage [9]

Possible storage systems could be sensible heat systems like solid-medium heat storage systems (e.g. rocks or sand storage systems) or molten salt storage systems. In most CSP-plants only a small amount (about 15 %) of energy is necessary for superheating, resulting in a significantly smaller storage system for the superheating than necessary for the steam accumulator.

5.2 NEW STORAGE MATERIALS

Among the already existing and commercially available thermal storage systems for CSP-plants, there are several other thermal storage concepts that are already used in industrial applications on a lower temperature levels or in a small scale.

These new storage technologies over a great potential in terms of reducing the storage systems cost, providing a higher storage capacity or allowing an easier application within the CSP-plant.

Thermo-chemical storage systems

Thermo-chemical storage systems offer a very high potential in terms of volumetric heat capacity, temperature range and storage possibilities.

The thermal energy is stored by using reversible chemical reactions. The storage is charge by providing energy to a chemical reaction. In this reaction a chemical compound is divided in its basis elements. With the reverse reaction, the basic elements are reacting, thermal energy is released and the storage is discharged.

Although there are several potential chemical compounds available and under investigation, it is a huge challenge to realize such a storage system in large scale. Even if there are first developments (e.g. considering a moving bed reactor), it is not expected to be realized as a commercial application within the next few years.

Phase Change Material

PCM-storage system are latent heat storage systems, using the phase change of the material (from solid to liquid) to store the heat. As materials, chemical compounds with a fixed melting point are used. Due to the fixed melting point of each material, different materials for different applications are necessary. Considering a DSG-plant with sliding pressure would also require different materials for different pressure set points.

A big advantage of PCM-systems is the high volumetric storage capacity of the material, resulting in a relative small storage vessel.

One challenge of the system is the relatively low heat transfer coefficient between the PCM and the heat-transfer fluid. In order to achieve fast charging and discharging rates, the available surface for the heat transfer must be as big as possible. In demonstration plants, this is realized by finned tubes. Other challenges are the costs of the material itself and the long-term thermal stability in high temperature environments.

A possible integration of a PCM-storage system in combination with two sensible heat systems for a DSG-pant is shown in Figure 21. The sensible heat systems (A and D) are used for the preheating (A) of the feed water and the superheating (D) of the steam.

The PCM storage (as latent-heat storage) is used to realize the evaporation of the feed water. In this demonstration plant, the feed water is heated up to the evaporation point at about 295 °C. As PCM sodium nitrate (NaNO3) is used with a melting temperature of 306 °C is used. The preheated water is enters the PCM module and the energy stored in the PCM is used to evaporate the water. After leaving the steam drum, the saturated steam is used to superheat the steam. For discharging, steam with a temperature slightly above the saturation point enters the PCM-storage, where it condenses [21].

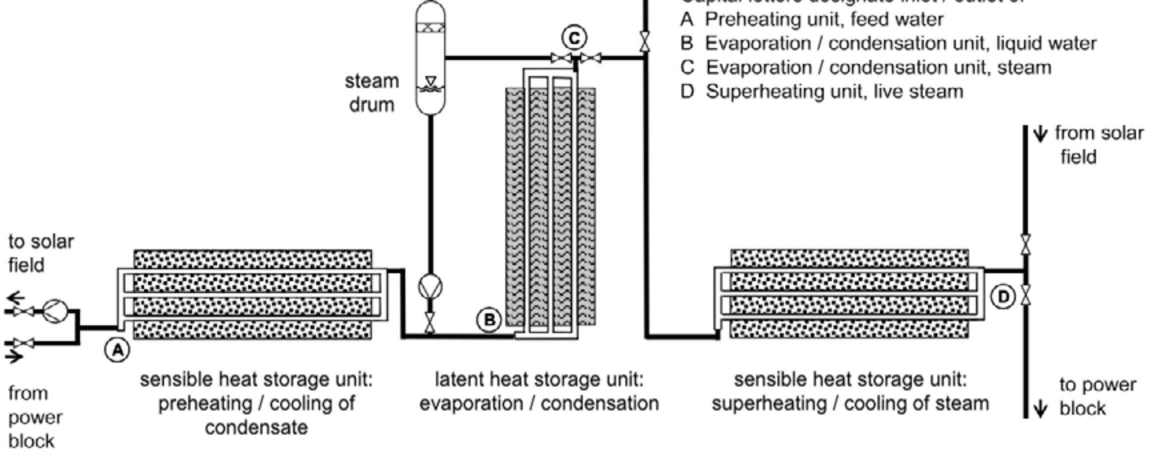

Figure 21: Overview of a three-stage thermal storage concept combining sensible and latent heat storage [21]

As PCM offers a high potential for the CSP technology, several research institutes are investigating many materials for different temperature ranges (e.g. University of Stellenbosch (South Africa) is working on a PCM based on AlSi12 with a melting point at 577 °C in combination with a high temperature HTF [22])

Nevertheless there are still some challenges to overcome, especially concerning the material costs. Regarding a time horizon of five years, it seems to be possible that PCM storage systems are available in combination with other storage systems.

Packed-Bed storage systems

Storage concepts using solid material to store sensible heat are considered as one key element to reduce the costs of the thermal energy storage system, resulting in lower costs for the whole CSP-system. A lot of research institutes (like DLR in Germany, NREL in the United States or Stellenbosch University in South Africa) and companies (like Airlight in Switzerland or Storasol in Germany) are developing different storage concepts based on cheap and local available storage material.

The storage material is usually placed in a packed bed system and air is used to transfer the heat. A packed bed system consists of loosely packed solid material through which the air is circulated. Similar to the honeycomb storage system described in chapter 2.3.3 the surface for the heat exchange must be very huge to achieve a good heat transfer. With a packed bed system, the hot air is entering at one end of the bed, flowing through the bed where the heat is transferred to the storage material and is leaving the bed with a low temperature. The temperature barrier within the packed bed separating the hot and the cold side of the bed is called thermocline. In order to achieve good storage efficiency, this thermocline must be as small as possible.

The packed bed could be arranged in two different ways: the hot air could either flow vertically or horizontally trough the layer, resulting in different approaches in the design of the storage vessel. To visualize the principal processes, the schematic layout shown in Figure 22 is used, showing the main characteristic of a packed bed storage system with a horizontal flow.

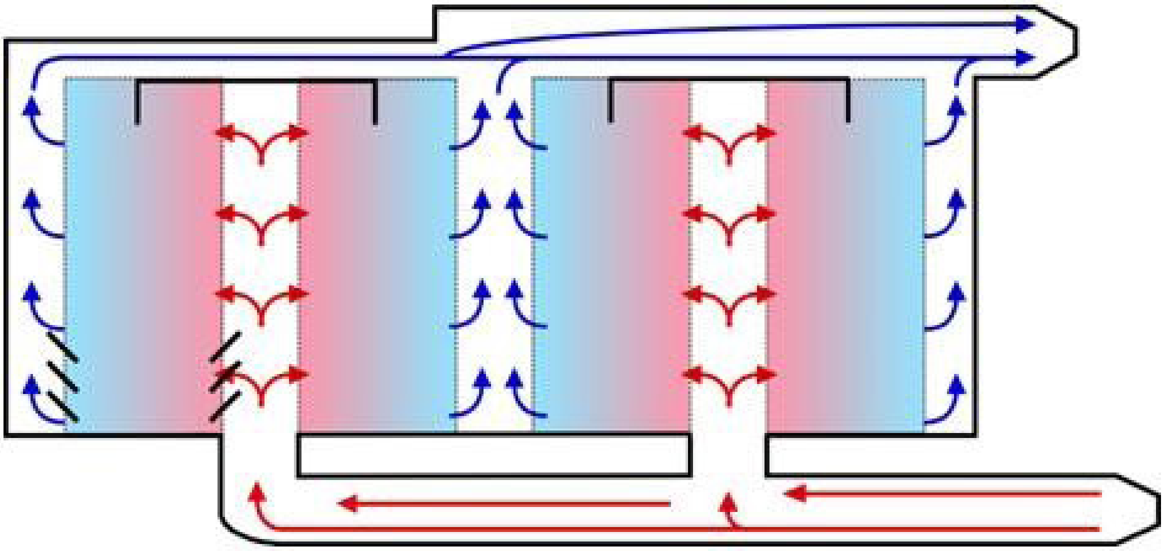

Figure 22: Schematic flow through a horizontal flow storage system, based on [23]

To charge the system the hot air enters the storage system and is directed to the storage material, the hot air flow horizontally through the storage material. With this arrangement of the packed bed, a huge surface is created. The main challenge of this system is an equal distribution of the hot air on each bed.

Another key parameter for the design of a packed bed storage system is the pressure loss trough the bed. A high pressure loss is resulting in high energy consumption and is therefore reducing the overall storage efficiency.

Summarized, the key parameters for a solid media storage system are:

- Cheap and local available storage material with a high heat capacity and a good heat transfer coefficient;
- Material size and free cross section between the storage material, influencing the heat transfer as well as the pressure loss, resulting in a higher own consumption;
- Longtime thermal stability of the storage material;
- An adapted design of the packed bed, allowing a small thermocline zone and a low pressure loss over the system.

As storage material sand and rocks are considered, applicable in a wide temperature range, with limiting temperatures given only by the rock's melting point. A list of various materials along with their thermodynamical properties is given with the following table, based on [24]. There are several experimental works ongoing investigating and assessing the stability of the rocks at high temperatures and in the storage cycle operation, summarized in [24].

Medium	Density (kg/m^3)	Specific heat (J/kgK)	Heat capctity 106(J/m^3K)	Volumetric heat capacity (kWh/m^3)
Brick	1698	840	1.4263	178
Concrete	3000	1130	2.5310	316
Stone, granite	2640	820	2.1648	270
Stone, sandstone	2200	710	1.5620	195
Aluminum	2707	896	2.4255	303

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[2] Calculated for a temperature range of 450 K, assuming a temperature drop over the heat storage system from 570 °C to 120 °C, no free cross section is taking into account.

5.3 INFLUENCE ON THE OVERALL CSP-SYSTEM

Summarizing the influences of the expected developments on some key points are analyzed. The assessment is related to the current state of the art, therefore all given improvements (e.g. reductions of specific costs) are marked with a "+" sign. If a harming impact is expected (e.g. the specific storage capacity will decrease), the component is marked with a "-" sign.

Technology / Development	State of development	Upper temperature	Reduction of specific costs of the CSP-system	Specific storage capacity (related to state of the art)	Flexible adjustment of storage size and capacity	Increase of efficiency of the CSP-system
New molten salt material	Detailed analysis	560-580 °C	+	+	o	++
1-Tank system for molten salt	Pilot plant	560 °C	++	o	-	+
Combination of Ruth's storage with superheating stage		550 °C	-	-	+	+
Thermo-chemical storage	Basic research	unknown, theoretically above 900 °C	No estimation possible	+++	No estimation possible	++
PCM storage	Pilot plant	380 °C (up to 580 °C)	-	++	+	o
Packed-Bed storage	Pilot plant	up to 800 °C	++	+	+++	+

Especially regarding the influences on the specific costs, several partly antagonistic parameters are included. Considering for example the "new molten salt material", on the one hand the new salt components are expected to be more expensive; on the other hand less material is necessary due to the higher specific heat capacity. In sum, a cost reduction effect is expected.

All new technology development offers a positive impact on the overall CSP-plant. Especially regarding the new storage concepts and materials, a significant improvement of the storage technology is expected. As the thermal storage must be included into the CSP-plant, all further developments must always be related to the development of the CSP technology itself.

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[3] Assessment of the influence:

-- harming ;- slightly harming; o neutral; + slightly positive ; ++ positive; +++ significant positive

6 SUMMARY AND CONCLUSION FOR BRAZIL

The CSP technology offers a great possibility to produce environmental friendly and dispatchable electrical energy. Independent of the used CSP-technology (parabolic trough, Linear-Fresnel or solar tower), the direct solar insulation is concentrated on an absorber and a heat transfer fluid is heated up. The generated heat could either be delivered to a steam generating power block or stored in a thermal storage system. If additional electrical energy is needed, the storage releases its stored energy and electrical energy is produced.

With this "integrated" storage principle, CSP-plants offer a big advantage compared to other new renewable technologies like wind or to hydro plants without reservoir. The ability to store energy over a certain amount of time allows a very flexible generation profile. Therefore thermal storage systems play a key role in the design and development of CSP-plants.

More than half of the CSP-plants in operation and nearly all CSP-plant under construction are equipped with a thermal storage. Within special markets (like South Africa) it is even not possible to enter the market without a thermal storage due to restrictions in the political framework, special feed in tariffs during peak times or other restrictions. Summarized, there are two key drivers for the use of thermal: On the one hand, the additional thermal storage supports the grid stability and on the other hand the additional storage increases the amount of produced energy and lowers the specific generation costs of the electrical output.

Thermal storage systems are not for single use in CSP-plants. All "state-of-the-art"-technologies and even some of the upcoming storage principles, are used in smaller size within industrial applications, resulting in a good operation experience of the principal systems.

Every mentioned technology has its own field of operation. The steam accumulator, the so called Ruth's storage, is implemented in CSP-plants with direct steam generation and is used as a short-term buffer tank. The ceramic honeycomb storage is representing an upcoming class of thermal storage system using solid storage material. It is implemented in an ambient air solar tower. The 2-Tank molten salt storage system is the most mature technology. It is widely implemented in parabolic trough systems with thermal-oil HTF as indirect storage system, or in solar towers with molten salt HTF as direct storage system. Storage sizes up to 16 h are possible. This huge storage sizes enables the CSP-plant to produce electricity from the sun even at night.

Thermal storage systems offer a huge potential for Brazil, not only regarding the local production capabilities, but also regarding the further development of this technologies. With the further development of the CSP-technology towards higher temperature ranges, the importance of new storage concepts and storage materials rises.

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APPENDIX A

	Electrical storage	Mechanical storage	Chemical storage	Thermo-chemical storage	Thermal storage
Exemplary systems	• condenser • superconducting magnetic storage	• pumped storage hydro systems • flywheel systems • pressurised gas (air) systems	• lead-zinc accumulator • metal-hybrid accumulator. • Li-Ion-accumulators • redox flow accumulators. • power-to-gas	• zeolite-systems • metal-hybrid (fuel cell) • silica gel	• hot water storage • steam storage • salt storage • sand/stone/concrete • ceramic storage
Time range	short term storage	short and long term storage	short to medium term storage long term storage	short to medium term storage	short to medium term storage
Typical performance category	very small capacity	small to large capacity	(power-to-gas)	medium to large capacity	Small to large capacity
Stage of development	commercial	commercial (pumped hydro and flywheel) R&D (compressed air)	small to medium capacity large capacity (power-to-gas)	R&D basics	commercial (salt, water, steam) R&D (remaining)
Area of application	• stability of voltage at the transition to the battery • power quality applications	• longer-term storage of electricity • provision of standard benefit in electric grid systems • power conditioning devices (flywheel) in sensitive industry sectors e.g. semiconductor industry	R&D demonstration scale	• energy storage with high storage density • theoretical application as long-term storage is conceivable	• district heating system (hot water) • solar thermal power plants (salt & steam storage) • as integrated storage solution in thermal power plants • large industrial concerns (steel, chemistry, etc.)

Table 1: Overview of the main energy storage systems and their main applications

APPENDIX B – SPECIFICATION OF MAIN COMPONENTS

This appendix gives a short functional specification of the main components necessary for a molten salt storage system. All information and data given here are based on public available information and internal estimations based on experiences of enolcon. Of course, these data may vary from plant to plant.

Boundary conditions

All relevant components are designed for a 2-Tank molten salt system with a thermal capacity of about 1200 MWhth. This kind of storage system is typically used in a 50 MWel plant with a storage capacity of approx. 7 h. Due to limitations of the tank size the scale up for bigger plant sizes is done by using several of these 2-Tank systems in parallel.

As storage material the typical mixture of 60 % (sodium nitrate) and 40 % (potassium nitrate) by weight ratio is assumed. This molten salt could be used within a temperature range of 260 °C and approximately 620 °C.

Additional heating systems driven either by fuel (gas) or electricity are integrated in the system. The tanks and the balance of plant as well as the salt piping and valves should be equipped with additional heating loops, traced or steam jacketed in order to prevent freezing, especially for intermittent operation. All components carrying molten salt should be drainable by gravity.

Storage vessel

In principal, the mechanical design of the storage vessels should follow common design standards like the API 650/620. There are 2 Tanks necessary, one hot and one cold tank. The tank consists of the vertical vessel itself with a dome as roof. The salt enters the vessel via inlets at the top of the storage.

The storage vessel itself consists of carbon steel usable for temperatures below 450 °C (e.g. ASTM 516 Gr70) or alloyed steels or stainless steels for CSP-plants using higher temperatures (direct molten salt systems like tower plants) [25]. The used material must be able to withstand the strong oxidizing environment (salt) and the high temperature with a low corrosion rate.

The storage vessel itself must be isolated against the environment with an adequate insulation to reduce heat losses.

The filling rates could be higher than the emptying rates due to the fact, that the charging process could be faster than the discharging.

Condition	Unit	Molten Salt Hot Tank	Molten Salt Cold Tank
Dimensions			
Design capacity	m^3	18’000	18’000
Diameter (outer)	mm	40’500	40’500
Height (outer)	mm	14’000	14’000
Operational conditions			
Pressure		atmospheric	
Operational temperature	°C	390	290
Minimal / Maximal temperature	°C	280/400	280/400
Filling / Emptying rates	m^3/h	~2’400	~2’400

Due to the lower density, the cold tank could be designed slightly smaller. If both tanks are manufactured with different materials (e.g. for high temperature application like solar tower plants with molten salt as HTF) this could be also economical feasible.

Pump groups

The molten-salt pump groups are necessary for the transport of the molten salt from the cold tank through the heat exchanger to the hot tank. The pumps are typically electrical driven shaft pumps located on top of the storage tanks. During the operation of the plant, around 20.000 cycles must be considered in a 20 years life-cycle of the plant. This value must be considered in the design phase of all relevant components.

Comparable to the storage vessel, the pumps could be divided in a cold and a hot molten salt pump group. Typically, the pump group is equipped with three independent pumps, with each pump delivering 50 % of the necessary operational flow. This arrangement guarantees a redundant operation of the pumping system and allows easy maintenance. With the following data one pumping group is described. Like the filling rates of the storage vessel, an increased charging speed is resulting in a higher flow rate of the cold molten salt pump.

Condition	Unit	Molten Salt Hot Tank	Molten Salt Cold Tank
Operational conditions			
Operational head	m fluid	~55-65	~55-65
Minimal / Maximal temperature	°C	260/400	260/400
Operational flow	m^3/h	~1’200	~1’200 (could be higher, if the charging is faster than the discharging process, up to 1’400)
Viscosity of the medium at operational conditions	Ns/m^2	0.0018	0.0035

Heat Exchangers

The heat exchangers for charging and discharging of the system are typically realized as a tube and shell heat exchanger with the solar salt on the shell-side and the thermal-oil on the tube side.

The heat exchangers are arranged along a heat exchanger train, with several (e.g. six) heat exchangers in series. To increase the redundancy of the system two heat exchanger trains could be arranged in parallel (see Figure 23). With the arrangement of the heat exchangers, an easy access for maintenance reasons has to be considered.

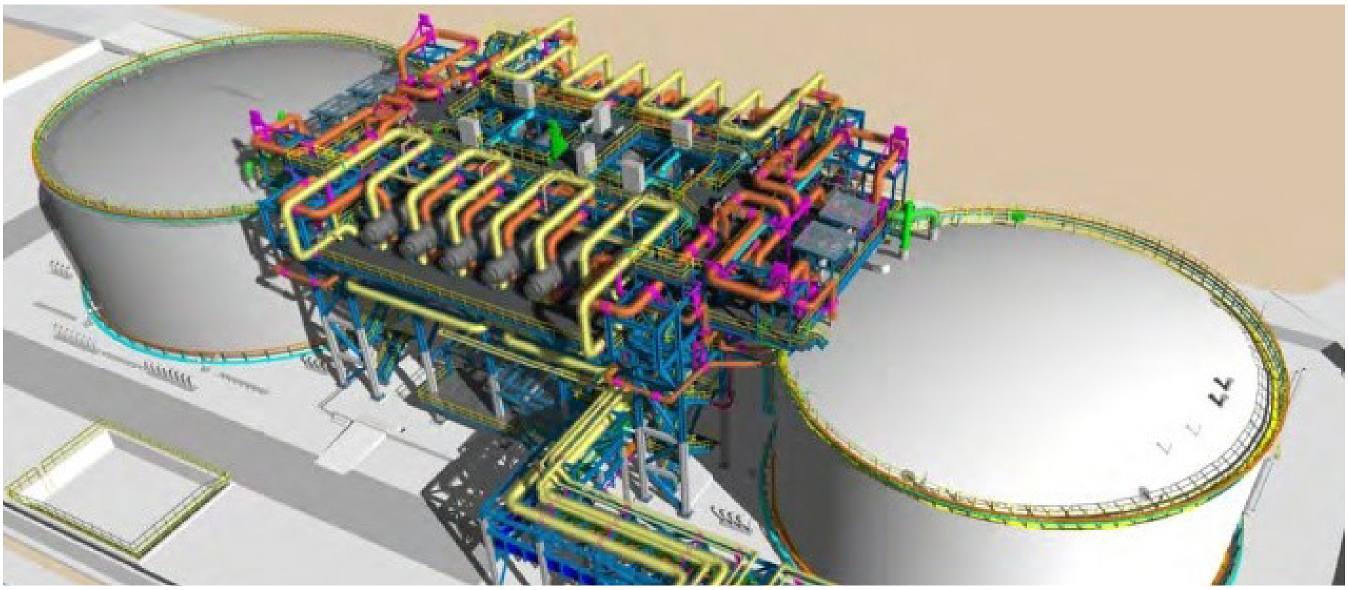

Figure 23: Exemplary design of a 2-Tank molten salt storage with parallel heat-exchanger trains [26]

For the design of the heat exchangers, the total values of the different fluids are given. Based on the experience and the design of the manufacturer, a single train or parallel trains could be chosen. Similar to the previous components, the maximum transferred heat is defined by the charging process, as this could be faster.

Condition	Unit	Molten Salt Side	Thermal oil side
Operational conditions			
Temperature in / out	°C	290 / 390	395 / 295
Necessary heat transferred (discharging)	MW	~140-145	
Necessary heat transferred (charging)	MW	Could be higher than discharging, if the charging process should be faster, resulting in values of around 200 MW or higher	

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