ELECTRIC POWER RESEARCH INSTITUTE

Program on Technology Innovation: Evaluation of Concentrating Solar Thermal Energy Storage Systems

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PRODUCT DESCRIPTION

Adding solar thermal energy storage to concentrating solar thermal power plants expands both the amount of power and the timing of production. With thermal energy storage, plant power output can be firmed and shaped to better match consumer demand for electricity. Thermal storage associated with these plants is typically much more efficient and cost-effective than electrical or mechanical forms of storage. In many cases, the addition of thermal energy storage can lower the levelized electricity production cost and increase the solar plant capacity factor, enabling the sale of electricity during peak demand periods and boosting plant revenues. This report describes and compares the most common types of thermal energy storage systems, evaluates the commercial maturity of various storage technologies, and identifies further development needs for several of the more advanced technologies. Where possible, the report provides relevant technical data for each of these systems, focusing on storage system attributes.

Results and Findings

Commercial operations with thermal energy storage systems have been limited to date. Even so, cost-effective thermal energy storage is considered a key element for future solar thermal power plants. Currently, only the two-tank (hot and cold) sensible heat storage designs have been proven at large scale, albeit with limited operating experience. Other technologies, such as single-tank thermoclines, concrete and graphite blocks, and phase change materials are yet to be proven at commercial scale. Because of this limited operational data, comparisons in this report are largely qualitative. Quantitative results are presented where available. Many of the thermal energy storage systems reviewed in this report are believed to be poised to achieve commercial maturity with further development and validation at utility-scale solar thermal plants.

Challenges and Objective(s)

Generation potential from solar thermal electric energy is very large, however, experience is limited and costs remain relatively high. Variability adds to the cost of integrating solar energy. The main objective of this study is to provide an overview of the state-of-the-art and commercial readiness of solar thermal energy storage. The work is aimed at providing a roadmap from the current development status of pilot scale and unproven to future applications with large-scale solar thermal plants. This report summarizes critical research and development for achieving cost-effective storage systems for the various concentrating solar thermal power plant technology options.

Applications, Values, and Use

Although the cost of solar energy is still high compared to traditional generation options, this cost is expected to decrease as technologies mature and deployment increases. Thermal energy storage presents a unique opportunity to reduce the levelized cost of electricity, while providing increased plant operating flexibility and energy value. This report provides a relative comparison of utility-scale thermal energy storage technologies and describes the challenges to achieving commercial status. Preliminary cost data and design configurations are provided for select technologies. The results of this project will be beneficial to any energy company or project developer considering a solar thermal project. This report will also help electricity providers determine which thermal energy storage option best serves the needs and fits the operating characteristics of a particular electric grid.

EPRI Perspective

The first utility-scale concentrating solar thermal power plants in the world were built in southern California in the 1980s, and several new large-scale plants are currently under development in the U.S. Southwest, Spain, and other locations throughout the world. More than eight gigawatts of concentrating solar power capacity is planned worldwide over the next five years. This trend is expected to continue as energy companies broaden their generation mix to include solar energy and prepare to meet state Renewable Portfolio Standards. EPRI is interested in accelerating near-term development and deployment of renewable energy technologies, such as solar energy technologies, which can serve the growing electricity demand and offer energy companies a low-emission generation option. Thermal energy storage can increase plant capacity factors and enable operation during periods of peak demand. Continued research and the operation of the first utility-scale thermal energy storage units in the next few years will provide more concrete data by which to compare thermal energy storage systems. This work supports a long-term vision for a broad generation portfolio that includes renewable energy as a cost-competitive option.

Approach

The project team's approach was to define the general types of thermal energy storage, including sensible, latent heat, and thermochemical technologies. They compared existing available technical data from both laboratory-scale prototypes and pilot production units on a common basis. Where possible, the report provides relevant evaluation results for each of these systems, focusing on storage system attributes, such as energy density of the storage material, heat transfer capacity, mechanical and chemical stability of the storage medium, system lifetime, material compatibility, thermal efficiency, and ease of operation. The report includes an evaluation of the maturity of the various storage technologies and identifies further development needs. Finally, a design overview includes estimates of the sizes and costs for the most advanced systems.

Keywords

Thermal energy storage
Solar electric
Solar thermal energy
Parabolic trough
Power tower
Linear Fresnel
Renewable energy

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1
INTRODUCTION

Solar thermal energy offers the promise of an abundant, clean and safe source of energy. The generation potential from solar energy has the capability to become a valuable addition to the range of renewable generation technologies available to utilities and consumers. Solar output naturally results in a good correlation with daytime electric loads, generally following morning load ramping up and dropping off a few hours before the evening load ramping down, as seen in Figure 1-1.

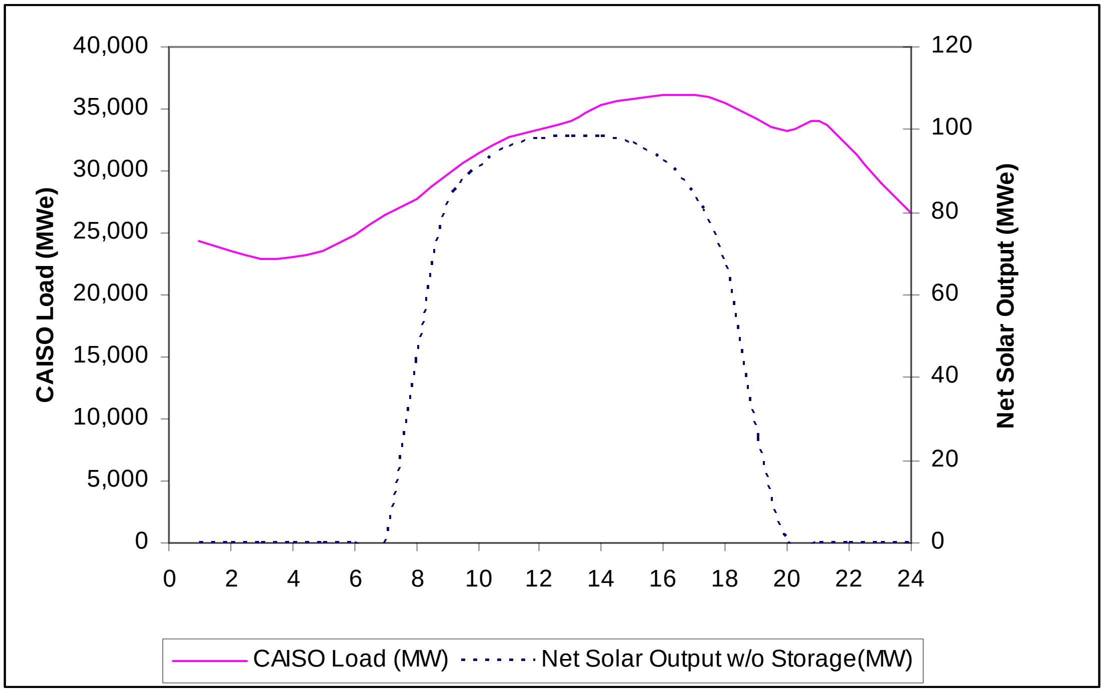

Figure 1-1
Hourly CAISO Load and Net Output from a Solar Thermal Plant Without Storage

Despite this general correlation between solar output and electrical load, like most renewable technologies solar energy is considered to be a variable resource that is inherently not dispatchable. While the annual and diurnal cycles associated with solar energy are predictable, and both correlate well with the load in most locations, the hourly and minute-to-minute variations in solar insolation remain unpredictable due to cloud cover and other inconsistencies and are not ideal for providing firm electricity to the grid. As a result, as long as solar energy remains a variable, non-dispatchable resource its penetration into the energy supply market will be limited.

The Value of Thermal Energy Storage

Proven storage concepts such as pumped hydro or battery storage are already used in electricity generation and other applications, and could likewise be used in conjunction with solar thermal generation. However, the thermal energy collected from the sun is a natural choice for storing energy from a solar thermal facility. Thermal storage can be added to a thermal plant at relatively small incremental cost. Thermal storage is usually more efficient than electrical or mechanical forms of storage. Although commercial operation of thermal energy storage systems has been limited to-date, existing projects have demonstrated round trip efficiencies greater than 90%[1]. As a result, cost-effective thermal energy storage (TES) has come to be considered a key element for the increased market penetration of solar thermal power plants. Several concepts for storing thermal energy have been proposed and studied in past years, although until very recently, thermal energy storage has primarily been limited to demonstration projects or prototypes. Renewed interest in solar thermal energy has also led to increased funding and research for thermal energy storage systems, and significant advances can be expected in the coming years. The first utility scale storage units since the 1990's are now operational, and several new research and development endeavors are planned across a range of thermal storage concepts.

Transforming solar energy from a variable resource to a firm dispatchable source of energy with high availability of the energy even during periods of low or no direct solar insolation would require a significant amount of storage. In most practical applications there is a diminishing added value for increasingly large amounts of storage. However a few hours for firming the output of a concentrating solar thermal (CST) plant provides the benefit of extended utilization and increased efficiency of the power block, offering a greater return on the turbine-generator investment, as well as an increased annual capacity factor for the CST plant.

In addition to firming the output of a solar thermal facility, an energy storage system can also be used to shape the output to better match consumer demand for electricity. Energy can be collected and stored during the operating day in order to shift its delivery to a later time, potentially reducing the time of use (TOU) rate mismatch between the energy supply from the sun and energy demand. The following figure shows how a percentage of the solar resource can be diverted to storage while the rest is used to generate electricity during the day; once the solar resource begins to drop off at the end of the day, the stored energy is discharged and used to continue production into the evening hours.

[1] Pilkington Solar International GmbH, "Survey of Thermal Storage for Parabolic Trough Power Plants", NREL/SR-550-27925. 2000.

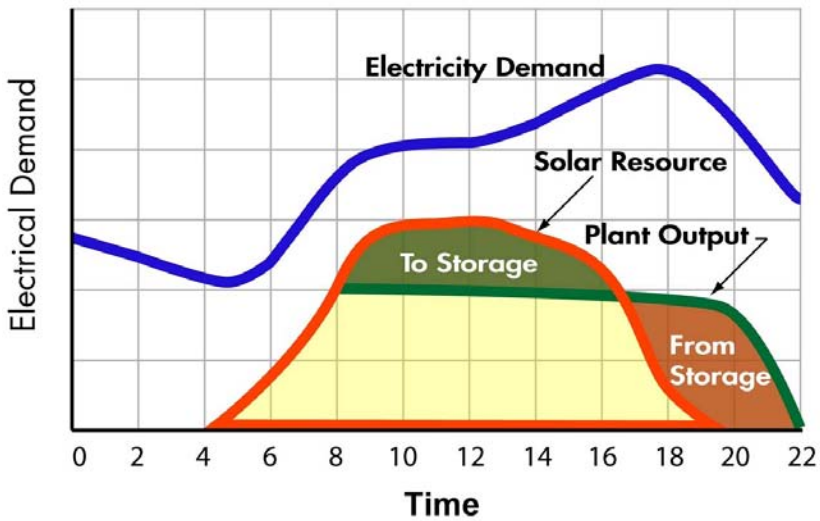

Figure 1-2
Comparison of Electrical Demand to Availability of Solar Energy and Output from a Solar Thermal Plant

CST plants without storage are limited both in the amount of power they can produce, and in the timing of their production. Although a storage system will increase the plant capital costs, the increased utilization of the plant equipment, particularly the power block, combined with the value of a firm, dispatchable power source is expected to outweigh the added costs and result in an overall lower levelized cost of energy. A feasibility study of CST development in New Mexico investigated the effect of thermal storage on the levelized cost of electricity (LCOE) for both a parabolic trough and central receiver CST plant, with the results shown in Figure 1-3. In this particular study, the addition of six hours of storage reduced the LCOE of a 125 MW_e parabolic trough plant by nearly four percent, while for a central receiver plant with molten salt as the heat transfer fluid (HTF), thermal storage from three hours to six hours reduced the LCOE by eight percent (Note - the central receiver plant with molten salt as HTF requires some storage even in a base case scenario, per the modeling program).

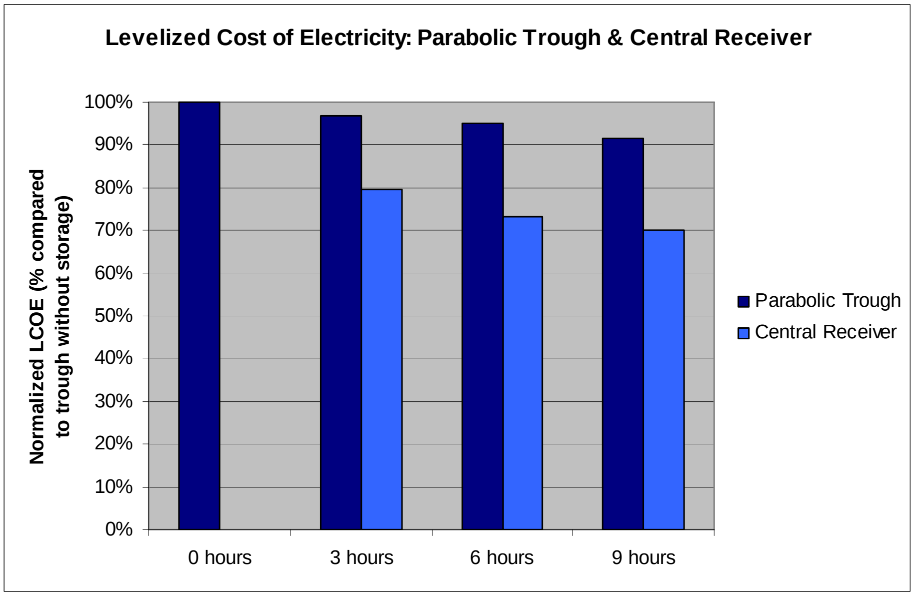

Figure 1-3
The Effect of Thermal Energy Storage on LCOE[2]

Thermal Energy Storage Systems

The selection of an appropriate storage system for a CST project depends on a combination of design requirements, as well as an assessment of the potential benefit to be gained from the incremental cost associated with the addition of a storage system. In comparing possible storage systems, the requirements for the system must first be established, primarily the nominal HTF operating temperature in the collector field, the maximum electrical output required by the plant, the desired mode of operation for the storage system, the manner in which the storage system will integrate with the collector field and power block, and the solar multiple to be selected, which determines the field size. Chief among the technical attributes to consider is the thermal capacity of the system, or the maximum amount of energy that the storage system can provide. Many other factors must be considered though in comparing thermal storage systems, including, but not limited to:

- Energy density of the storage material
- Heat transfer capacity between the storage material and the collector field heat transfer fluid
- Stability of the storage medium, both mechanically and chemically, through daily thermal cycling
- Lifetime of the storage system components

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[2] EPRI, *New Mexico Central Station Solar Power: Feasibility Study*, EPRI, Palo Alto, CA; PNM Resources, Inc., Albuquerque, NM; El Paso Electric Co., El Paso, TX, SDG&E, San Diego, CA; SCE, Rosemead, CA; Tri-State Generation & Transmission Association, Inc., Westminster, CO; Xcel Energy Services, Inc., Denver, CO. 2008. 1016344.

- Compatibility between the HTF, storage medium, and heat exchanger materials and design
- Roundtrip thermal efficiency of the storage system
- Ease of operation

In the following chapters, the most common types of thermal energy storage systems are described and compared. The report evaluates the commercial maturity of the various storage technologies and identifies further development needs for several of the more advanced technologies. Where possible the report provides relevant technical data for each of these systems, focusing on the storage system attributes listed above. However, experience with commercial-scale thermal storage systems is extremely limited, and much of the existing technical data for TES systems is derived from laboratory-scale prototypes or pilot modules. A summary of historical experience with TES systems is provided as an appendix courtesy of the National Renewable Energy Laboratory. Continued research and the planned operation of the first commercial storage units in the next few years will provide more concrete data on which to base comparisons of thermal storage systems.

The report concludes with an overview of the design process for a thermal energy storage system, including the compatibility of the available storage systems with the current solar thermal generation technologies and the selection of appropriate storage media for a particular CST plant. Estimates of the sizes and costs for the most advanced TES systems are included in the design overview.

2
SOLAR THERMAL GENERATION TECHNOLOGIES

Solar thermal electric technologies, or concentrating solar thermal (CST) plants, produce electricity by collecting solar radiation using various mirror or lens configurations. The concentrated energy from the sun is focused on a receiver that contains a heat transfer fluid, which is used to transfer heat energy to a power block with a turbine or engine that converts the heat to electricity. Four main types of CST plants are currently in use or in development. This study includes discussions of the following solar thermal technologies:

- Parabolic trough
- Central receiver (power tower)
- Compact linear Fresnel reflector (CLFR)
- Dish/engine

Parabolic trough, central receiver, and CLFR technologies use a centralized power block to generate electricity; this configuration makes large scale power plants of 50 MW or greater the most economically viable option for these systems. Dish/engine installations are modular, consisting of individual units in the 3 to 35 kW range, and are perhaps best suited for distributed generation applications, although any number of individual units can be combined to create a single larger plant.

In a CST system only the Direct Normal Insolation (DNI) component of solar radiation contributes to the thermal energy absorbed by the plant. As a result, a single-axis or two-axis sun tracking system can be an important component of a CST plant, allowing the mirrors to maximize the amount of DNI that is reflected onto the receiver and achieve high working temperatures for the heat transfer fluid.

Parabolic Trough

Parabolic trough plants use a field of linear parabolic collectors to redirect and concentrate sunlight onto a tube receiver located at the focal line of the mirrors. Each collector tracks the sun by rotation about a horizontal axis. The heat transfer fluid is typically a synthetic oil mixture with a maximum operating temperature of 390 °C (735 °F). With a synthetic oil HTF, the steam generator produces live steam at nominal conditions of 377 °C (711 °F) and 100 bar (1465 lbf/in2), and reheat steam also at a temperature of 377 °C (711 °F). An important aspect of parabolic trough technology is that the electrical energy production is separated from the solar energy collection, creating a natural insertion point between these two elements for a thermal energy storage system. Most of the thermal storage technologies that are described in the following chapters are compatible with parabolic trough CST plants. For a parabolic trough system storage capacities up to 16 hours of full load turbine operation are feasible. Thermal storage is also inherent in a parabolic trough system, in that the high fluid volume in the collector field provides over 15 minutes of thermal storage, or thermal inertia, which can be used to provide a form of buffer storage.

Figure 2-1
Parabolic Trough Collector Field

Parabolic trough is a mature commercial technology that has generated electricity reliably for over two decades. The most recent CST plant installations have utilized trough technology, and the financing for trough plants without TES is comparable to other mature, commercial generation technologies. There is ample design and performance data available for trough plants.

Central Receiver

Central receiver plants use a collector field array of several thousand sun-tracking heliostats to redirect and concentrate solar radiation onto a tower mounted single receiver. The heat transfer fluid is typically water/steam for small systems, and a sodium/potassium nitrate salt mixture for large plants. For either fluid, receiver outlet temperatures up to 650°C (1200°F) are feasible. If molten salt is used, a conventional steam generator can produce live steam at nominal conditions of 125 bar (1800 lbf/in^2) and 540°C (1005°F), and reheat steam at a temperature of 540°C. As in a parabolic trough system, the collector array and electrical generation equipment are separate, offering a natural point for including a thermal storage system, and either molten salt or steam can serve as a storage medium if used in the receiver. A molten salt storage system was used at the Solar Two demonstration facility, and other storage systems discussed in this report could prove successful for a central receiver system. The higher temperatures that are possible with a central receiver must be considered when selecting an appropriate storage system, however. Figure 2-2 shows the heliostats and towers at one of Abengoa's central receiver CST plants in Spain.

Figure 2-2
Central Towers and Heliostats at Abengoa's CST Plants in Spain (2008)

The ultimate performance and cost estimates for mature, molten salt central receiver technology are very attractive, but the main challenges for the technology at this time lie in scaling up the receiver assembly for larger plant sizes and in operating the molten salt system in a consistent and reliable manner. The cost to finance a plant of commercial scale is expected to be a significant hurdle as well. Commercial operation of central receiver technology is currently being demonstrated at the 11 MW PS-10 plant in Spain; PS-10 uses direct steam in its operations, rather than molten salt. The 20 MW PS-20 system is scheduled to come online in mid-2008 and will use similar technology. The Solar Tres Power Tower currently under development in Spain will be a molten salt system with 15 MW capacity.

Compact Linear Fresnel Reflector

Compact Linear Fresnel Reflector (CLFR) technology consists of rows of solar collectors that reflect solar radiation onto a tower mounted linear receiver consisting of a series of steel tubes surrounded by a trapezoidal reflective surface. Within the receiver, pressurized water is converted to saturated conditions at approximately 270°C. The "Fresnel" in CLFR refers to the optical arrangement of reflectors in rows. While a conventional parabolic trough system has one curved reflector for each receiver line, the CLFR system typically has ten. The reflectors are largely flat, but the orientation of each row is controlled independently so that together the rows act as a segmented, curved reflector. While storage systems have not yet been tested for CLFR systems, the configuration of the CLFR technology is similar to a parabolic trough collector field, and storage should be relatively easy to incorporate into future designs, albeit at a lower temperature.

Until just recently, CLFR had not yet generated standalone electricity, only saturated steam for feedwater heating. However, in December 2008 a 5 MW plant became operational in Bakersfield, CA. Currently, there is no third party independent data available for CLFR systems to validate the cost and performance. A provider of CLFR technology has announced agreements with two major utilities to provide the first operational units beginning in 2010 and totaling close to 500 MW. Ultimately this technology may prove to be less expensive than trough systems, but it will be several years until that is known.

Figure 2-3
CLFR Collector Field at Ausra's 5 MW Kimberlina Facility Near Bakersfield, CA (2008)

Dish/Engine

A solar parabolic dish/engine system comprises a solar concentrator (or "parabolic" dish) and a power conversion unit containing a solar receiver and engine-generator. The concentrator consists of mirror facets, which combine to form a parabolic dish. The dish redirects solar radiation to a receiver mounted on a boom at the dish's focal point. The system uses a two-axis tracker such that it points at the sun continuously. In the solar receiver, radiant solar energy is converted to heat in a closed hydrogen loop, which typically drives a Stirling engine-generator.

Figure 2-4
Parabolic Dish with a Stirling Engine

Dish/engine technology has been demonstrated on a small scale, with the leading technology provider having built and tested about 150 kW. No commercial dish/engine plants are currently in operation; the first phase of commercial units is scheduled to go online in 2009, and the first plant is to be completed in 2012. Utility agreements total as much as 1750 MW. Although dish/engine technology is very efficient, capital costs are still quite high. The standard dish/engine technology may eventually prove to be more economical than either parabolic trough or central receiver systems, but it may not have the dispatchability or operating flexibility of those systems. In a standard dish/engine system the solar energy collection element and power generation equipment are co-located on the dish, eliminating most of the storage options available to the other CST technologies. Without storage its ability to follow load or generate constant output is limited. However, in 2009 the Department of Energy plans to begin funding research that will focus on developing thermal energy storage for dish/engine systems.

Infinia Corporation developed a solar dish/engine system using a free-piston Stirling generator that was originally developed for critical power applications in the aerospace, medical devices, and combined heat and power industries. The company was recently awarded Department of Energy (DOE) funding to develop and demonstrate a thermal storage solution for their solar dish-Stirling product, the 3-kW Infinia Solar System. A thermal energy storage module will be integrated with the Stirling engine, providing the energy needed to ride through weather transients and the ability to generate power at full capacity for four to six hours after sunset. The system will utilize phase change materials to store energy in the receiver.

An Australian company is also developing a commercial dish system based on research at the Australian National University. The system is dubbed the Big Dish, and a prototype has been in operation at ANU since 1994, with a second generation prototype scheduled to begin operation in October 2008 and a pilot plant planned for 2009. In addition to utilizing individual parabolic dishes that are five times larger than those used in the current Stirling engine systems, the Big Dish includes a thermochemical storage system that uses solar energy to drive the dissociation of ammonia, an endothermic reaction, which can then be synthesized when needed to provide the energy to produce steam for the power cycle.

3
THERMAL ENERGY STORAGE TECHNOLOGIES

The primary purpose of thermal energy storage is to compensate for the sometimes variable nature of solar energy, as well as permitting operation of a solar energy system later in the day when the sun is no longer available. The energy contained in the storage system can be dispatched in any number of ways according to the desired output profile, but the strategies for using energy from storage fall into three main categories:

- Buffering power delivery
- Extending delivery period
- Displacing delivery period

Storage that is used for buffering power delivery is intended to smooth the output of the solar thermal plant, which can otherwise become subject to the intermittent insolation caused by passing cloud cover. The turbine-generator can only operate at full load when sufficient solar energy is available without interruption. When insolation fluctuates, the turbine-generator is forced to shut down or operate under part-load conditions, effectively degrading the electrical production of the solar plant and interfering with the capability for integrating a solar thermal power plant into the utility electrical grid. Multiple startups and shutdowns can shorten the lifetime of the turbine-generator, and at part load, turbine efficiency can decrease considerably. The life expectancy of components within the power block also decreases due to an increase in thermal transients. Using energy storage can help to minimize shutdowns and part-load turbine operation in addition to firming the solar resource into a dispatchable, dependable source of energy. The following figures were prepared for a feasibility study of solar thermal generation in New Mexico, and offer a picture of how energy storage improves the operation of a solar thermal electricity generation facility. Figure 3-1 shows each hour of net output of a solar thermal plant without storage, while Figure 3-2 shows the same plant after a storage system has been added, where many of the hours of part-load operation found in the plant without storage have been converted to full-load operation in the plant with storage. The TES system modeled for this plant provides buffer storage as well as extended power delivery.

A buffer storage system allows production to continue uninterrupted through brief periods of lost insolation. Because the storage system is only used to buffer the plant output rather than extend or displace delivery, it is only required to provide short-term storage, corresponding to no more than an hour of equivalent full-load operation. As mentioned in Chapter 2, the large volume of heat transfer fluid contained in the collector field of a parabolic trough plant can provide buffer storage in the form of thermal inertia without the need for a separate storage system. Other types of solar generation would require a separate system for buffer storage. Another option for buffer storage is to oversize the HTF piping, or for a trough, to add a small oil tank at the exit of the field piping before the inlet to the oil-heated steam generators. Nevada Solar One and the existing SEGS plants have some inherent buffer storage as a result of these design options.

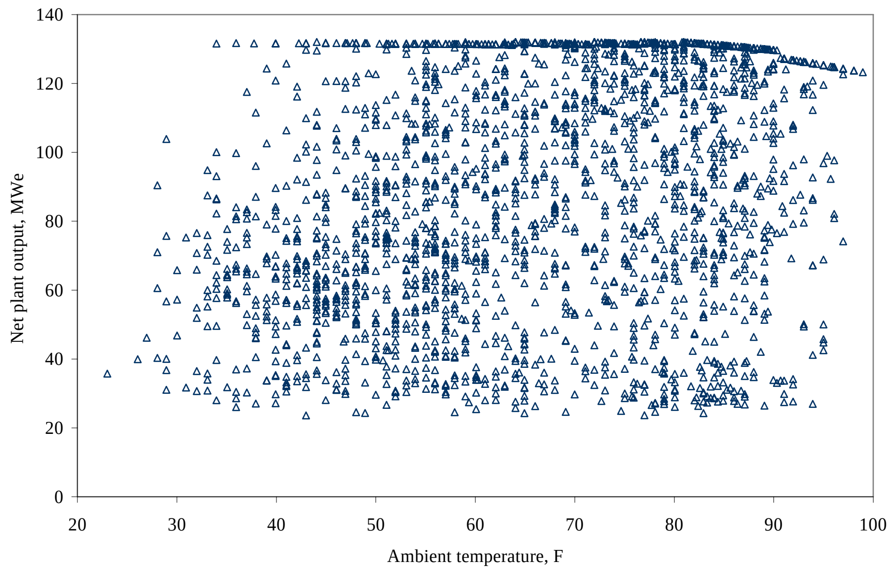

Figure 3-1
Net Output of a 125 MW_e Parabolic Trough Plant Without Storage

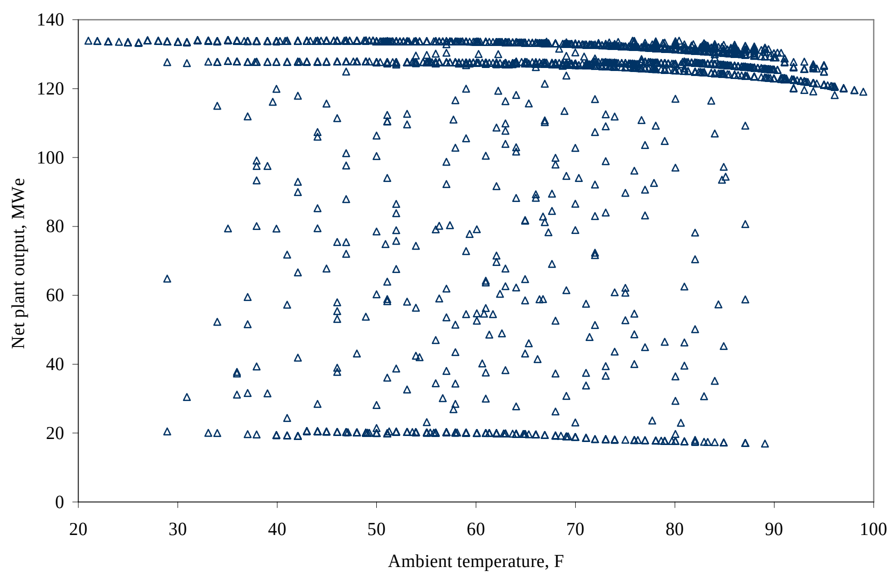

Figure 3-2
Net Output of a 125 MW_e Parabolic Trough Plant With 9 Hours of Storage

Thermal energy storage can also be used to shift or extend the delivery period of the energy from the solar facility. Electrical utilities designate Time-of-Use (TOU) periods for electricity demand from customers; during periods of high demand, or on-peak times, the market price of electricity is higher than during off-peak, or low demand periods. While solar thermal power plants appear capable of providing energy for a large part of the on-peak TOU period, in some regions of the country the on-peak period can extend well into the evening hours when solar facilities without storage are no longer capable of delivering energy. Two main options exist for altering the output of a solar thermal power plant to better match the load profile in locations that require electricity into the evening hours. The first operations strategy requires diverting a portion of the output from the collector field over the course of daily operation to charge the storage system, which is then discharged once the sun has set to extend the delivery period. Alternatively, all of the energy output from the collector field can be used to charge the storage system at the beginning of daily operation, delaying plant startup until the storage system has been fully charged. The plant will then again have sufficient energy in storage to continue operating through the peak and into the evening use period. This strategy simply shifts the delivery period a couple hours later into the day. Both of these storage options are depicted in the following figure.

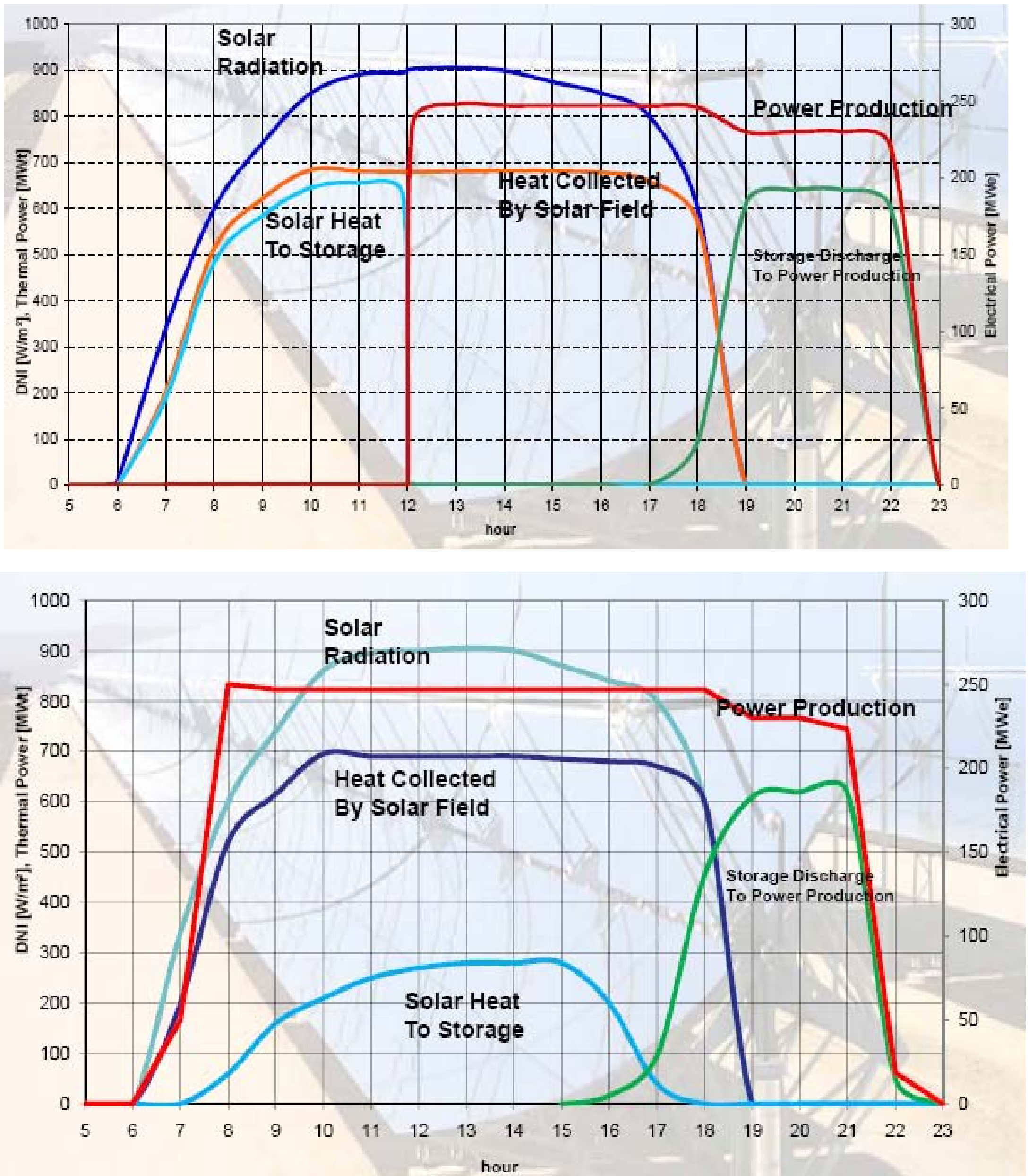

Figure 3-3
Displacement and Extension of Power Production Using Thermal Energy Storage[3]

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[3] Solar Millenium.

The length of full-load turbine operation to be provided by the TES must be selected to offer the best trade-off between the cost of the TES and the benefits provided by the storage system. Increasing the number of hours of storage capacity will increase the annual plant output up to a certain point, but eventually the performance of the plant as a function of increasing TES system size will level off. Figure 3-4 demonstrates this trend for a central receiver plant with a solar multiple of either 1.2 or 1.8 with increasing amounts of storage. A larger collector field (larger solar multiple) produces a greater amount of excess thermal energy that can be diverted into storage, and will continue to see increases in power output through longer storage times beyond the point where the smaller field has reached equilibrium.

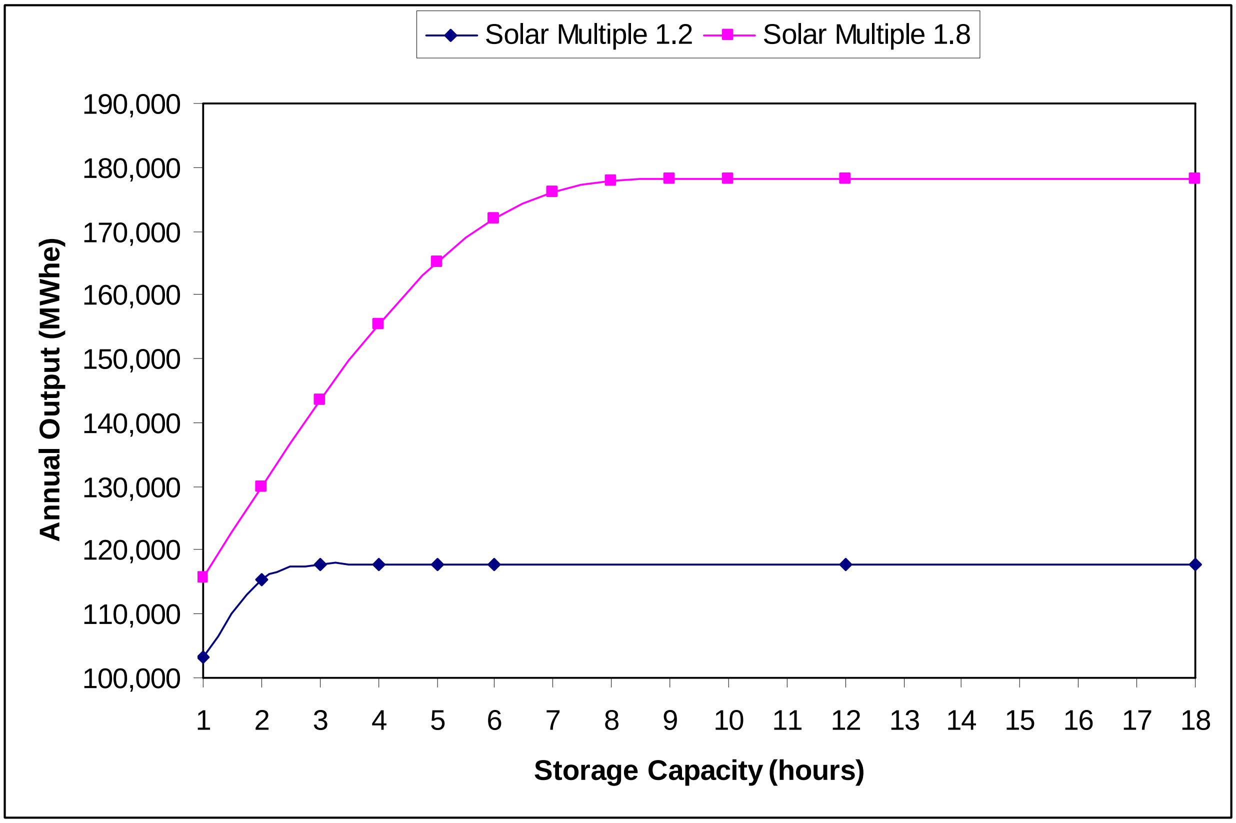

Figure 3-4
Annual Net Output From a Central Receiver Plant With Up to 18 Hours of Storage

Furthermore, as the storage system increases in size, the added cost of the storage system and collector field will eventually outweigh the added benefit to the levelized cost of electricity. In the Southwestern U.S., six to nine hours of full load capacity has been identified as an appropriate system size for load displacement or extension, although this is highly dependent both on regional variations in electricity demand, and on the requirements of a particular project.

The cost of a TES system for a given storage capacity depends on the operating temperature of the CST technology. The size of the storage system is directly proportional to the temperature difference. CST technologies with a greater differential in the hot storage charging temperature and the cold return temperature will require a smaller volume to store the same amount of energy. It follows that tower storage operating at a charging temperature of 540°C is potentially half the cost of parabolic trough storage operating at 377°C with a nominal cold return temperature of 290°C for both systems. To reduce trough storage costs the operating temperature needs to increase. A direct storage system also should be used to further reduce cost and efficiency losses. Developing cost effective trough storage is a significant R&D challenge that will likely require development of a new lower cost HTF.

Sandia National Laboratories estimates that with existing central receiver technology the most cost-effective storage system would have a capacity factor between 65 to 70 percent, as shown in Figure 3-5. The 65 percent capacity factor is achievable with 13 hours storage and a solar multiple of 2.7, assuming 91 percent plant availability (based on simulations at Sandia National Laboratories with the SOLERGY computer code). To achieve a 70 percent capacity factor, the storage capacity increases to 15 hours with a solar multiple of 3.0. This design assumes the turbine runs at full power near the summer solstice for 24 hours per day. In the winter months the turbine would run at part load during the night. Such a plant would operate similar to a baseload coal plant, which has important implications to the current climate change challenge.

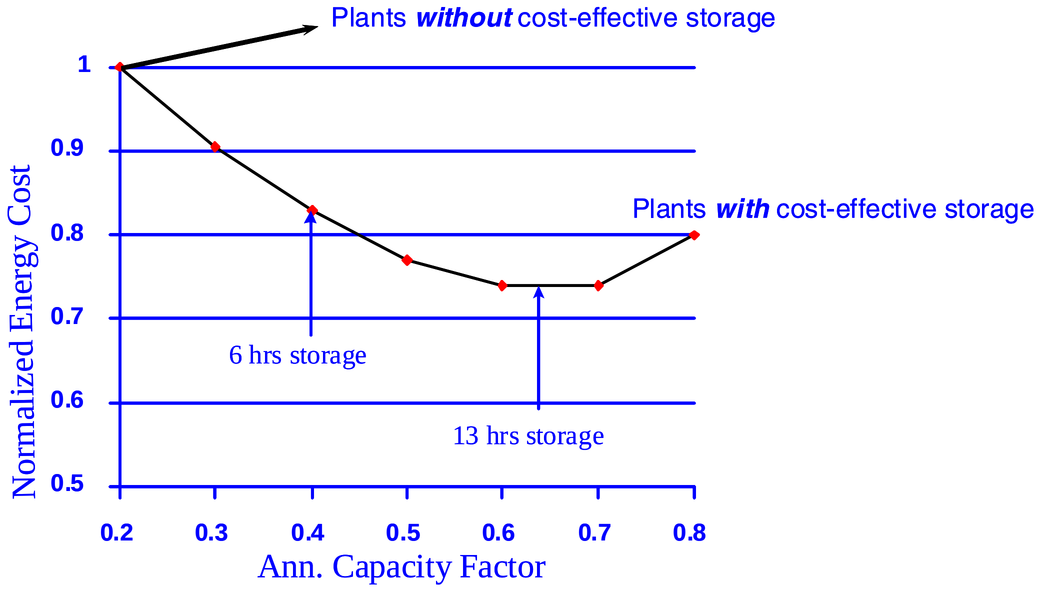

Figure 3-5
Levelized Cost of Electricity for Central Receiver Technology With Two-Tank Molten Salt Storage for a Plant Located in Barstow, CA (Source: Sandia National Laboratories)

By comparison, the maximum practical capacity factor for troughs is about 55 percent. This is achieved with 16 hours of storage and a solar multiple of 3.0. The field efficiency (or thermal output) of central receiver plants is more uniform throughout the year because the heliostats track on two axes; whereas the trough field, which tracks on one axis, has a significantly lower efficiency during the winter.

Methods of Thermal Energy Storage

The three basic methods for thermal energy storage include sensible heat storage, latent heat storage and thermochemical storage. Thermal energy storage can also be classified as passive or active, depending on the role of the storage medium in the TES system. Active storage is characterized by a storage medium that circulates through the storage system, and relies on forced convective heat transfer to move energy into and out of the storage medium. In a passive storage system, the storage medium does not circulate through the system; rather, the heat transfer medium is passed through the storage medium to transfer energy to and from storage.

Sensible Heat Storage

Sensible heat storage is achieved by raising the temperature of a liquid or a solid material without the material changing phase. The stored energy is calculated by the product of its mass, the average specific heat, and the temperature change of the material. Important physical properties for sensible heat storage materials include: density, the specific heat of the storage material, operational temperatures, thermal conductivity and diffusivity, vapor pressure, heat loss coefficient and cost.

Liquid Media

Synthetic organic oils and nitrate salts are the most common liquid storage media used in solar thermal energy systems. Average thermodynamic properties for candidate liquid sensible heat storage media are shown in Table 3-1. The upper temperature limit refers to the maximum temperature the medium can withstand before it begins to physically break down, while the low and high temperature limits refer to typical storage system operating temperature limits. When combined with the average fluid density and heat capacity, these temperature limits lead to the volumetric heat capacity. The heat capacity listed in the table is temperature-specific, and is provided for a typical hot temperature at which the storage system would operate for each fluid. Although water actually has a higher volumetric heat capacity per degree Celsius than any of the oils or nitrate salts, it is limited to a much lower temperature and can therefore store much less energy per unit volume at the typical operating temperature of each fluid. Heat capacity is an important measure of the amount of energy the medium can store per unit volume; high volumetric heat capacity corresponds to smaller storage system sizes, which is both less expensive, and in turn leads to smaller auxiliary equipment and piping requirements. The heat capacity in Table 3-1 is intended to show the heat capacity of each storage medium at a reasonable operating temperature.

Table 3-1
Thermodynamic Properties of Liquid Storage Media

Fluid	Freezing Point (°C)	Upper Temperature Limit (°C)	Cold Operating Temperature (°C)	Hot Operating Temperature (°C)	Average Density (kg/m^3)	Average Thermal Conductivity (W/m-C)	Average Heat Capacity (J/kg-C)	Volume-Specific Energy Density* (kWh$_t$/m^3)
Hitec®	142	530	290	500	1790	0.332	1560	306
Hitec XL®	120	500	290	500	1913	0.519	1415	297
Binary nitrate salt	210	650	290	565	1818	0.524	1517	327
Therminol VP-1	12	400	290	390	768	0.089	2449	178
Caloria HT-43	-12	315	200	290	715	0.090	2557	124
Xceltherm® 600	-20	316	200	290	715	0.118	2762	134
Water	0	100	50	100	975	0.663	4193	85

* Calculated at the hot operating temperature for each storage medium.

Liquid storage media systems typically rely on either a two-tank or single-tank system to contain the storage medium, which can be combined with the collector field either directly or indirectly. The following sections describe some of the most common storage system configurations for liquid media.

Two-tank Indirect

The distinguishing feature of the two-tank indirect system is that the HTF that circulates through the collector field remains separate from the storage medium kept in the tanks. The HTF is typically a synthetic oil such as Therminol VP-1 (currently in use at the California SEGS plants[4]) or Dowtherm, and the storage medium is likely to be molten salt. The system consists of a cold tank, normally operating at 290°C (554°F) or less, a hot tank, operating at temperatures up to 390°C (703°F), the storage medium, the heat exchangers for transferring energy from the heat transfer fluid to the storage medium (and back), the storage medium pumps, and the associated balance of system equipment, such as an ullage gas system and electric heat tracing for all molten salt components. Electric heat tracing is required to maintain inventory temperature in the event of an extended plant outage, while the ullage gas system prevents oxidation of the storage medium. A schematic diagram of a two-tank indirect system is shown in Figure 3-6.

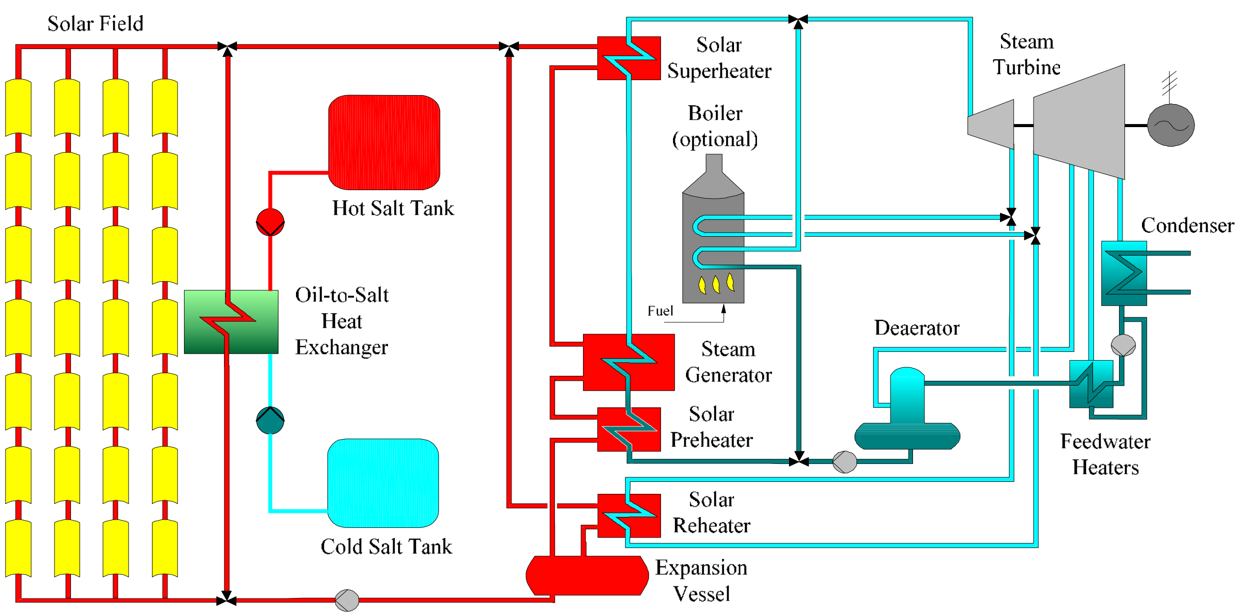

Figure 3-6
Two-Tank Indirect Thermal Storage System[5]

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[4] S.D. Odeh, G.L. Morrison, and M. Behnia, "Thermal Analysis of Parabolic Trough Solar Collectors for Electric Power Generation", Darwin: ANZES Annual Conference, 1996.

[5] Nexant, Inc., "Thermal Energy Storage Models Inputs to User's Manual", San Francisco. 2007.

The thermal energy storage system is charged by taking hot HTF from the solar field and running it through the oil-to-salt heat exchangers. Simultaneously, cold molten salt is pumped from the cold storage tank, and delivered to the heat exchangers. In the heat exchangers, the salt and the heat transfer fluid flow in a countercurrent arrangement. Heat is transferred from the HTF to the cold salt flowing through the heat exchanger, which leaves as hot salt that is then stored in the hot salt tank. When the energy in storage is needed, the flows of both the HTF and the salt are reversed in the oil-to-salt heat exchangers in order to reheat the HTF. Countercurrent flows in the heat exchangers are necessary in order to maximize heat transfer between the two fluids. The reheated HTF is then used in the power block to generate steam to run the power plant.

The feasibility of the indirect system is proven and at present the concept is associated with the lowest technological risk. However, the transfer of energy from the heat transfer fluid to the salt during charging, and the transfer of heat from the salt to the heat transfer fluid during discharging, both require a temperature drop across the oil-to-salt heat exchanger. As such, the temperature of the heat transfer fluid delivered to the steam generator when operating from thermal storage is 10 to 20 °C lower than when operating directly from the collector field. Due to temperature and efficiency reductions associated with the heat exchangers, both the output and the efficiency of the Rankine cycle are unavoidably lower when operating from thermal storage. The round trip efficiency of a storage system is defined as the net electricity delivered from the storage system divided by the amount of electricity that would have been generated from the solar field thermal energy had it been directly converted to electricity. A typical efficiency for an indirect two-tank trough storage system is about 93 percent, whereas a future trough with a direct two-tank molten salt storage system might be 98 percent efficient. These results hold for other types of storage systems that require a temperature differential for charging and discharging, such as the solid media and phase change systems that are covered in the sections below.

Two-Tank Direct

In a two-tank direct system, the fluid which circulates through the collector field is also used as the storage medium. Like the indirect system, the direct system consists of a cold tank and a hot tank, the storage medium and the associated balance of system equipment, such as an ullage gas system and the electric heaters for inventory maintenance during plant outages. However, unlike the indirect system, this design uses the same fluid in both the storage system and the collector field, which eliminates the need for a second set of heat exchangers used to transfer thermal energy between the heat transfer fluid and the storage medium in the indirect system. When molten salt is used as the storage medium, the cold and hot tanks can operate at temperatures up to 290°C (550°F) and 565°C (1050°F), respectively. A schematic diagram of the system is shown in Figure 3-7.

To charge the system, fluid from the cold tank is circulated through the collector field, and returned to the hot tank. To discharge the system, fluid from the hot tank is circulated through the steam generator, and returned to the cold tank. All of the fluid from the collector field passes through the hot storage tank. Depending on the residence time in the tank, the temperature of the fluid leaving the tank is 0 to perhaps 1.5 °C lower than the temperature entering the tank. As a result, the performance of the Rankine cycle in a plant with a two-tank direct storage system is essentially the same as a plant without thermal storage.

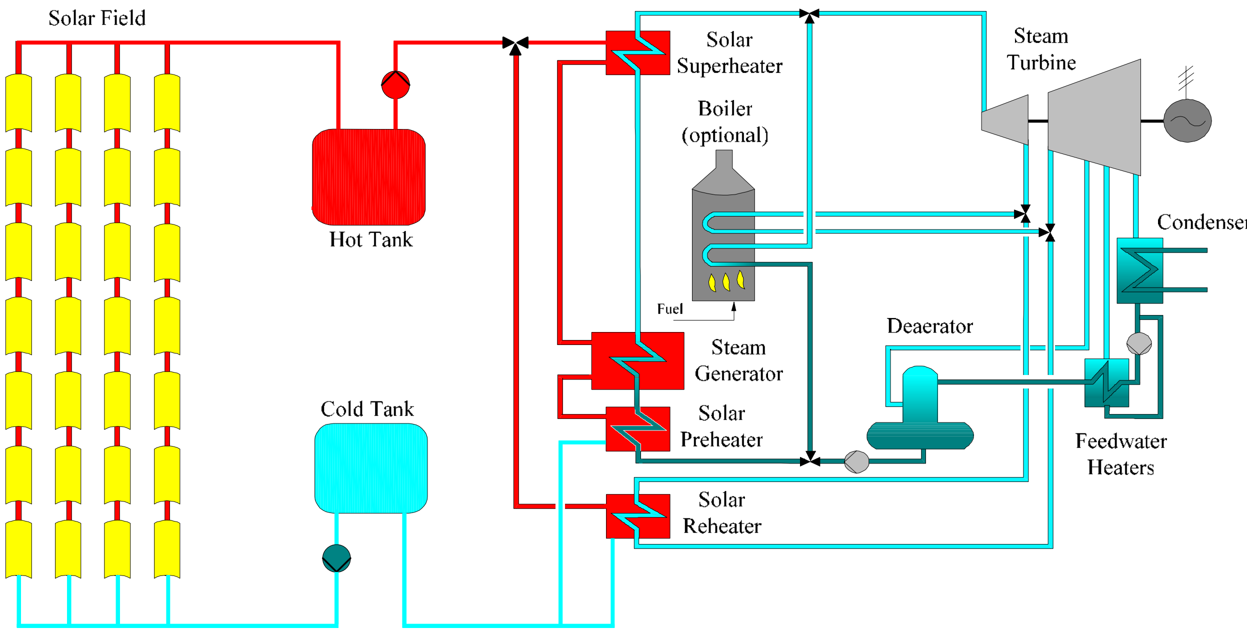

Figure 3-7
Two-Tank Direct Thermal Storage System[6]

It may seem that only a single tank would be needed for the charged storage medium, but a cold tank is required to contain the volume of storage material that has already discharged its energy to the steam generator. During storage system discharging, the collector field will likely not be receiving solar energy, although it is possible to charge and discharge simultaneously, as was demonstrated at Solar Two. If the cold storage medium were simply pumped back into the system it would eventually reach the hot storage tank and interfere with the operation of the hot storage tank by introducing lower-temperature storage media. While the purpose of the two tank system is to keep the hot and cold storage media separate in order to preserve the maximum hot tank temperature, the mixing of the hot and cold storage media would effectively create a thermocline within the hot storage tank.

Two-tank direct TES systems will likely use a molten salt as the storage medium. Nitrate salts are inexpensive and can provide tank storage capacity ranging between 3 and 16 hours of full load turbine operation. The primary disadvantage to a molten salt storage system is the relatively high freeze point of typical nitrate salts. As such, considerable care must be taken to ensure that the salt does not freeze in the solar field or elsewhere in the TES. This includes installing an electric heat trace system on all equipment that comes in contact with the salt. The higher outlet temperature has other negative impacts as well, including higher heat losses from the solar field, lower durability of the selective coating on trough receivers, and the need for more expensive equipment, such as piping and valve packings, in order to withstand the increased operating temperatures. Research on lower temperature salts is underway at government laboratories and universities throughout the world.

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[6] Ibid.

Single-Tank Thermocline (Indirect or Direct)

Like the two-tank systems, a thermocline can operate either directly, with the storage medium also serving as the HTF in the collector field, or indirectly, with a separate storage media and HTF. A thermocline system involves a single tank that is used to store both the hot and cold fluid, further reducing the cost of the TES system. This single-tank configuration features the hot fluid on top and the cold fluid at the bottom of the tank. The zone between the hot and cold fluids is called the thermocline. While a thermocline can simply combine the hot and cold storage fluids into a single tank, the primary advantage of the thermocline storage system is that most of the storage fluid can be replaced with a low-cost filler material. This filler displaces the majority of the molten salt that would be used in a comparable two-tank system, and provides a robust and inexpensive storage medium. A thermocline with a packed bed would actually be considered a dual-media storage system, as it utilizes both a liquid and solid medium for storing energy.

To charge the system, hot fluid is introduced at the top of the tank, flows down through the porous bed, and leaves from the bottom of the tank; in the process, heat is transferred from the hot fluid to the porous filler material. To discharge the system, the flow is reversed; cold fluid enters at the bottom of the tank, and is heated as the fluid flows up through the porous bed. A schematic diagram of a direct thermocline system is shown in Figure 3-8. On the cold fluid side of the tank, the system includes a bypass line to return cold fluid to the suction side of the pump during storage charging.

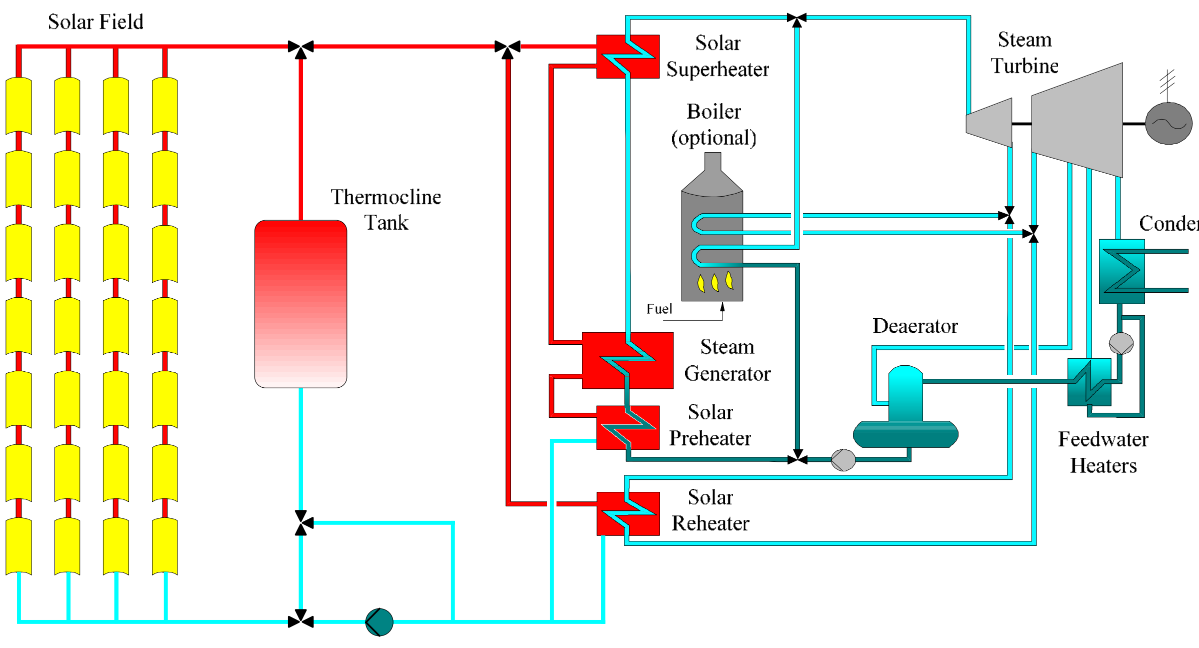

Figure 3-8
Single Tank Direct Thermocline System[7]

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[7] Ibid.

The principal liability for a thermocline is a fluid-to-solid media heat transfer coefficient which is necessarily less than infinite. As a result, a thermal gradient is established in the storage media, and the gradient can grow to occupy the entire height of the tank. To prevent the gradient from increasing to the full tank height, the temperature of the fluid leaving the tank at the end of a discharge cycle must be allowed to fall below the design collector field outlet temperature, and the temperature of the fluid leaving the tank at the end of a charge cycle must be allowed to rise above the design collector field inlet temperature. Figure 3-9 shows the performance of both a direct and indirect thermocline system at the end of a 3-hour charge cycle and at the end of a discharge cycle. As predicted, the temperature at the tank outlet decays below the collector field outlet temperature throughout the discharge cycle, while the tank inlet temperature gradually rises above the collector field inlet throughout the charge cycle.

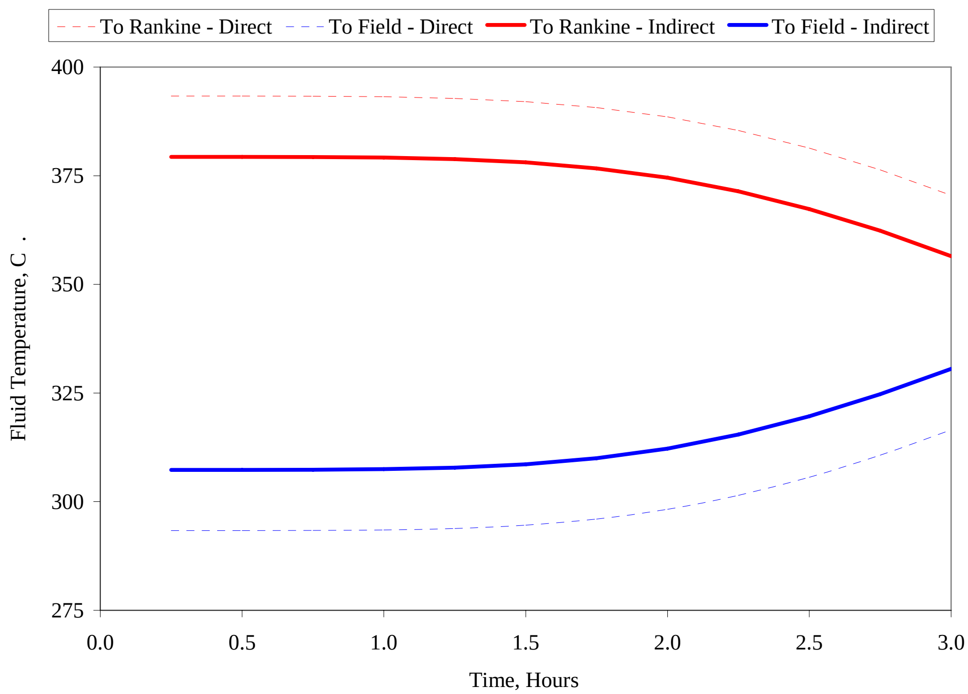

Figure 3-9
Indirect and Direct Thermocline Fluid Temperatures During Storage System Charging and Discharging

Thus, as the temperatures entering and leaving the thermocline tank diverge from the design temperatures, the operation of the thermocline tank will influence the performance of both the Rankine cycle and the collector field. Further, the magnitude of the effect will depend on the coincident output of the Rankine cycle, and the coincident thermal output of the collector field. In addition, the degree to which the thermocline is subjected to a full or partial charge cycle during the day, and a full or partial discharge cycle at the end of a day, will influence the shape and the size of the thermal gradient the following day.

Hot Water Storage

A hot water storage system could provide a variation on either the two-tank system or a thermocline in which water replaces molten salt as the storage medium. Using water in place of molten salt could greatly reduce the complexity and cost of the storage system, eliminating the need for both electric heating and an ullage gas system. Water for the system could be obtained from a municipal supply, further reducing the cost of the storage system.

The major drawback associated with using water as a storage medium is the low maximum operating temperature. At atmospheric pressure, water can only be used at temperatures up to around 100°C, which could have a significant impact on the efficiency of the power cycle. The low operating temperature leads to much larger storage volume requirements than for media operating at higher temperatures. Further, if hot water is used with a higher temperature HTF such as an organic oil, the transfer of thermal energy from the HTF to the water will incur a large thermal penalty in that much of the energy in the HTF will necessarily be lost to avoid overheating the water. Hot water would therefore be most suitable in a direct storage system, or in an indirect storage system operating at low temperatures.

Steam Accumulators

Another option for hot water storage is the variable-pressure steam accumulator, or Ruths accumulator, which is currently used for thermal storage in process heat applications. Steam accumulators use sensible heat storage in pressurized saturated liquid water, profiting from the high volumetric storage capacity of liquid water for sensible heat, and are capable of providing saturated steam in the 100-300°C temperature range at pressures up to 100 bar.[8] Hot pressurized water comprises 50-90% of the volume of a variable-pressure accumulator, which relies on changes in pressure within the storage vessel to flash the water to steam. The large volume of water allows for greater storage capacities than could be achieved with a direct steam accumulator. High discharge rates and rapid deployment of the storage system are possible since water is used both as a storage medium and working medium, making the steam accumulator an ideal candidate for buffer or short-term storage systems. Figure 3-10 shows the scheme of a variable-pressure steam accumulator.

[8] Tamme, R., Bauer, T., Buschle, J., and Steinmann, W-D., "Constant Temperature and Pressure Process Steam Storage and Generation with PCM Storage – Results of the German PROSPER Project", German Aerospace Center (DLR): Institute of Technical Thermodynamics, Stuttgart, Germany, 2008.

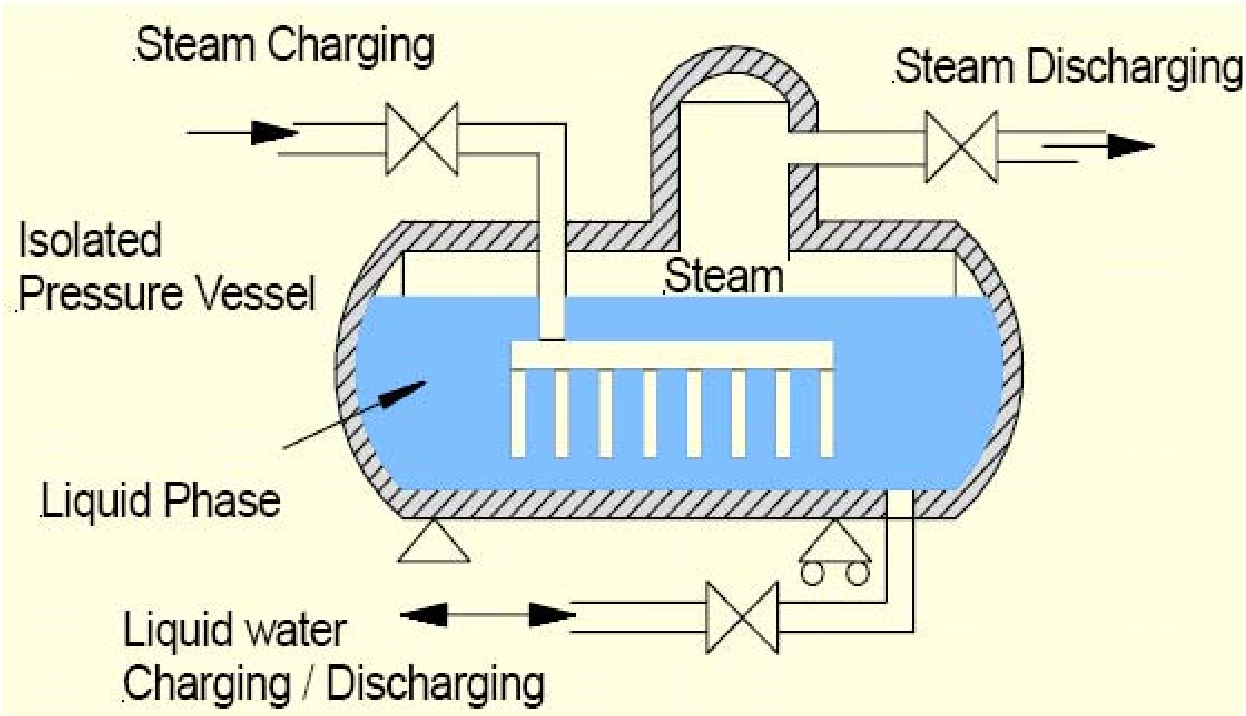

Figure 3-10
Variable-Pressure (Ruths) Steam Accumulator (Source: German Aerospace Center [DLR]),

To charge the steam accumulator, steam is injected into the hot water in the vessel. Depending on the thermodynamic equilibrium in the vessel, the steam condenses and increases the temperature of the water, or it passes through the water and increases the steam volume. If the steam volume increases, the pressure in the vessel increases with little variation in the liquid storage mass. The increased pressure in the gas volume results in a higher saturation temperature. During discharge, steam is drawn from the storage vessel, causing the pressure inside the vessel to drop and the water in the vessel to flash to steam. As the vessel empties, the pressure and temperature inside the vessel decrease, and the pressure of the steam leaving the accumulator drops off.

Solid Media

Solid media storage represents a second group of technologies relying on sensible heat transfer for storage charging and discharging. Unlike liquid media storage, solid media is primarily a passive form of thermal energy storage in which the heat transfer fluid is passed through the solid media after heating in the collector field. Many different types of solid materials could potentially serve as a storage medium and properties of some of the options for solid storage media are shown in Table 3-2 below. It should be noted that due to the temperature differential to charge the solid media and another temperature differential to discharge the solid media, turbine operation is degraded compared to operation without the storage system.

Table 3-2
Properties of Materials for Use in Solid Media TES Systems

Storage Medium	Temperature (°C)		Average Density (kg/m^3)	Average Heat Conductivity (W/m-K)	Average Heat Capacity (kJ/kg-K)	Volume-Specific Energy Density (kWh_t/m^3)*
	Cold	Hot				
Sand-rock-mineral oil	200	300	1,700	1.0	1.30	60
Reinforced concrete	200	400	2,200	1.5	0.85	100
Castable ceramic	n.a	n.a	3,500	1.35@350°C	n.a	n.a
NaCl (solid)	200	500	2,160	7.0	0.85	150
Cast iron	200	400	7,200	37.0	0.56	160
Cast steel	200	700	7,800	40.0	0.60	450
Silica fire bricks	200	700	1,820	1.5	1.00	150
Magnesia fire bricks	200	1200	3,000	5.0	1.15	600

* Calculated at the hot operating temperature for each storage medium

High Temperature Concrete Block Storage

The German Aerospace Center (DLR) constructed a facility at the University of Stuttgart for testing a concrete thermal energy storage system. It examined the performance, durability and cost of using a thermal storage system for parabolic trough power plants that utilizes a solid media as the storage medium (high temperature concrete or castable ceramic materials)[9]. The system can operate with any of the standard HTFs in the collector field. After heating in the collector field, the fluid passes through an array of pipes embedded in the solid media to transfer the thermal energy to and from the media during plant operation. A schematic of this setup is shown in Figure 3-11 below.

[9] D. Laing, W. Steinmann, R. Tamme, and C. Richter, "Solid Media Thermal Storage for Parabolic Trough Power Plants", Oaxaca, 2004.

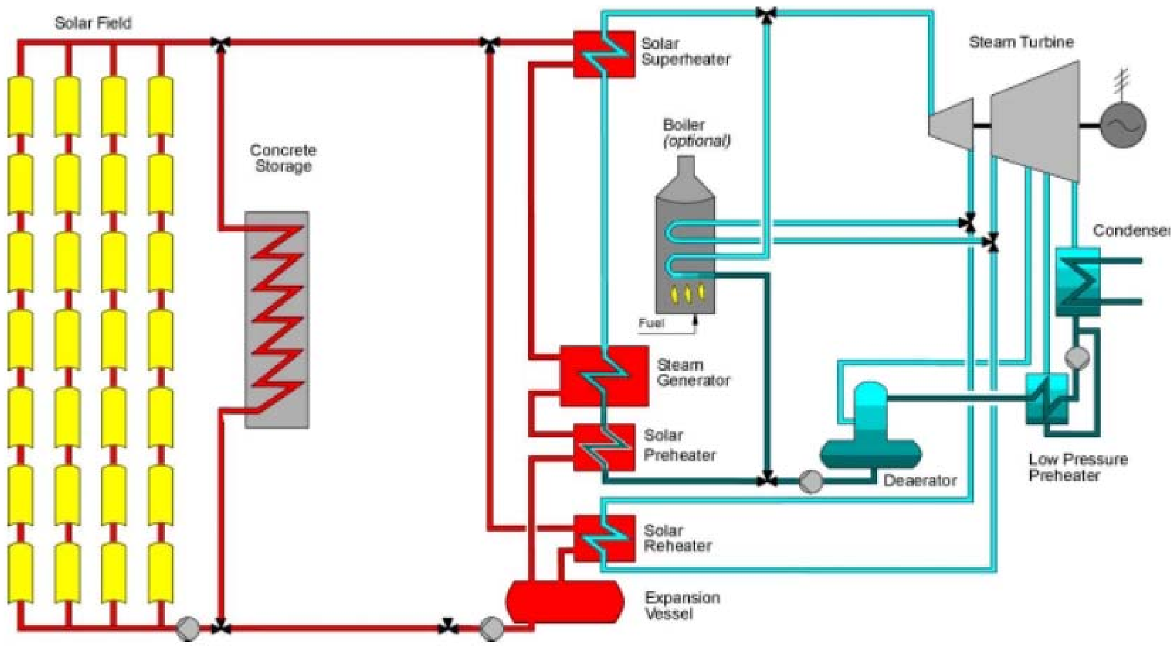

Figure 3-11
High Temperature Cement Block Storage System[10]

DLR's initial tests found both the castable ceramic and high temperature concrete suitable for solid media sensible heat storage systems. High temperature concrete is favored however, due to lower costs, higher material strength and easier handling. The primary advantage of this approach is the low cost of the concrete. Test results have also shown good heat transfer between heat exchanger and storage material, acceptably high power levels during cooling, and no problems in handling high temperature gradients between storage and the oil HTF. Due to the modular nature of concrete TES, there are various approaches that could be taken to allow the storage system to better integrate with the solar field and power cycle, allowing for improved overall utilization of the system. Primary issues with this system include maintaining good contact between the storage media and the internal piping after repeated thermal cycling, and the heat transfer rates into and out of the solid medium, in addition to the inefficiencies related to charging and discharging the system.

High-Purity Graphite Storage

Graphite is another option for sensible heat storage utilizing a solid media. Graphite is an allotrope of the element carbon, and the prevalence of carbon in nature makes graphite an attractive option as a storage media. The thermal properties of graphite also offer advantages for thermal energy storage: the heat storage capacity of graphite actually increases as the temperature of the graphite increases, from 300 kWh_t per ton at 750 °C up to 1000 kWh_t per ton at 1800 °C[11]. Graphite also possesses a low coefficient of thermal expansion, and will experience

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[10] M. Herrman and D. Kearney, "Overview on Thermal Storage Systems", 2002.

[11] Lloyd Energy Storage, http://www.lloydenergy.com/heatstorage.htm

minimal stresses from the thermal cycling associated with a thermal energy storage system. However, due to the performance improvement at higher temperatures, graphite may not be ideally suited for the relatively low temperatures found in solar thermal installations, unless the heat transfer fluid is eliminated and the concentrated sunlight is focused directly onto the graphite. This circumstance would allow the graphite to reach the very high temperatures that will maximize its storage capabilities. Additionally, while graphite is an extremely common material and is generally inexpensive and easy to obtain, the high-purity graphite that would be ideal for thermal storage may be both harder to acquire and more costly.

Engineered Ceramic Solid Media

With heat capacities in excess of 1.0 kJ/kg-K and densities at or greater than 3,200 kg/m^3, ceramics have the capability to store a large amount of energy in a small volume. Since the manufacturing process of ceramics typically requires sintering at temperatures in excess of 1000°C, they also possess a wide operating temperature range. The material properties of engineered ceramics can be tailored to provide corrosion resistance and high mechanical integrity, and the materials can be formed into a variety of shapes and sizes to reduce pressure drop and maximize heat transfer. These advantages could be applied to solar thermal storage applications. The shape and size of the ceramics could be customized to provide enhanced thermal conductivity and thermal capacitance for a given storage vessel, while ceramic compositions could be tailored to provide the desired storage properties for a range of heat transfer fluids. Ceramics provide excellent thermal and chemical stability, and can be designed to maintain their performance over the life of the solar facility. Like concrete, ceramics can also directly contact the heat transfer fluid, eliminating the heat exchangers found in indirect storage systems. In addition, engineered ceramics can be manufactured economically in large quantities.

Two examples of the successful use of engineered ceramics for thermal storage in other industries are Regenerative Thermal Oxidizers (RTO) and glass furnace regenerator checkers. RTOs are environmental emission abatement devices where volatile organic compounds (VOCs) are combusted before being released to the atmosphere, while glass furnace regenerator checkers are ceramic refractories used to recover heat in glass furnaces over extended time periods. Engineered ceramics are utilized as heat sink media in both of these applications and can significantly increase thermal efficiencies, resulting in substantial energy savings while maintaining low resistance to flow. Significant improvements in the thermal efficiency and resistance to flow have been achieved by optimizing the shape, size, and composition of the materials.

Latent Heat Storage

Thermal energy can be stored nearly isothermally in some substances as the latent heat of phase change. In latent heat storage systems the thermal energy from the collector field is transferred to the storage medium through a set of heat exchangers, much like a sensible heat storage system, but rather than changing temperature, the storage medium is induced to change phase, and so the discharging or charging of the thermal storage system requires a much smaller temperature change than a sensible heat system. Sandia reports that the typical temperature differential for charging and discharging a phase change system is 100 °F or more. Any phase change is theoretically possible, including the heat of fusion (solid-liquid transition), heat of vaporization (liquid-vapor) and heat of solid-solid crystalline phase transformation. However, the latent heat of transformation from one solid phase into another is usually small, and while solid-vapor and liquid-vapor transitions have large heats of transformation, they are also associated with large changes in volume that make the systems complex and impractical. Solid-liquid transformations, on the other hand, involve relatively small changes in volume compared to the magnitude of the heats of transformation. For a solid-liquid phase change system, the storage medium stores heat as the latent heat of fusion by changing from a solid to a liquid and back. When the stored heat is extracted by the load, the material will again change its phase from liquid to solid.

TES systems utilizing phase change materials (PCMs) tend to be smaller than single-phase sensible heating systems because the latent heat of fusion between the liquid and solid states of materials are rather high compared to a sensible heat change. This could result in some of the lowest theoretical storage media costs of any of the proposed thermal energy storage concepts. However, the selection of storage media and heat transfer design is more complicated and difficult than for the sensible heat storage systems. This complexity can reduce the benefit.

Salt or salt mixtures have been identified as potential candidate PCMs for latent heat storage systems. Nitrate salts tend to have high heat capacities, which make them ideal for storing and releasing thermal energy, and are both readily available and fairly low-cost. Such materials are also available in a range of transition temperatures, and can thus be adapted to suit storage systems requiring widely varying temperatures. Among the drawbacks of using nitrate salts is that they also tend to have low thermal conductivity. The rate of heat transfer is thus limited by the thermal conductivity of these PCM salts, which are typically in the range of 0.5-1.0 W/m-K. Recent evaluations of PCM systems have found that the cost of the system is driven not only by the cost of phase change storage material, but also by the rate at which energy can be stored or delivered by the system. Relevant thermophysical properties for potential salts that have been identified as suitable PCMs are listed in Table 3-3. The final column of this table provides an estimate of the volume change that will occur during the phase change, presented as a percentage of the total salt volume.

Table 3-3
Physical Properties of Pure Nitrate and Nitrite Salts

Salt System (composition in weight)	Melting Point (°C)	Latent Heat of Fusion (kJ/kg)	Thermal Conductivity (W/m-K)		Specific Heat Capacity (kJ/kg-K)		Average Liquid Density (kg/m^3)	$\Delta V/V_s$ (%)
			Solid	Liquid	Solid	Liquid		
KNO_3-$LiNO_3$ (67-33)	133	170	n.a	n.a	n.a	n.a	n.a	13.5
KNO_3-$NaNO_2$-$NaNO_3$ (53-40-7)	142	80	0.51	0.48-0.50	1.30	1.57	1,980	n.a
$LiNO_3$-$NaNO_3$ (49-51)	194	265	n.a	0.54	n.a	n.a	n.a	13.0
KNO_3-$NaNO_3$ (54-46)	222	100	n.a	0.46-0.51	1.42	1.46-1.53	1,950	4.6
$LiNO_3$	254	360	1.37	0.58-0.61	1.78	1.62-2.03	1,780	21.5
$NaNO_2$	270	180	0.67-1.25	0.53-0.67	n.a	1.65-1.77	1.81	16.5
$NaNO_3$	306	175	0.59	0.51-0.57	1.78	1.61-1.82	1.89-1.93	10.7
KNO_3	337	100	n.a	0.42-0.50	1.43	1.34-1.40	1.87-1.89	3.3

The design of storage systems using PCMs is inherently more difficult than for those that rely on sensible heat transfer. In addition to the limitations associated with the low thermal conductivity of the nitrate and nitrite salts that have been identified as potential PCMs, storage concepts must also consider the volume change that occurs during a material phase change. In order to become competitive with the current state-of-the-art storage systems, both of these design constraints must be resolved, while also producing cost-effective storage units.

A variety of concepts have been proposed for improving the heat transfer performance of PCM storage systems. In order to compensate for low thermal conductivity, PCM design concepts can focus on increasing the area available for heat transfer into and out of the PCM, or on increasing the effective thermal conductivity of the PCM. The macro-encapsulation of the phase change material is one concept that has been studied as a means to increase the heat transfer area. Capsules filled with PCM are stored in a pressure vessel filled with water and steam. The tubes are not filled completely with PCM in order to accommodate volume expansion of up to 10% during phase change. A gas volume fraction of about 20% is required inside the rigid capsules to limit the increase of pressure when the PCM melts. A minimum wall thickness is necessary due to the corrosive behavior of nitrate salts, and thus flexible encapsulation is not permitted. Figure 3-12 shows a diagram of a macro-encapsulated PCM in a pressure vessel.

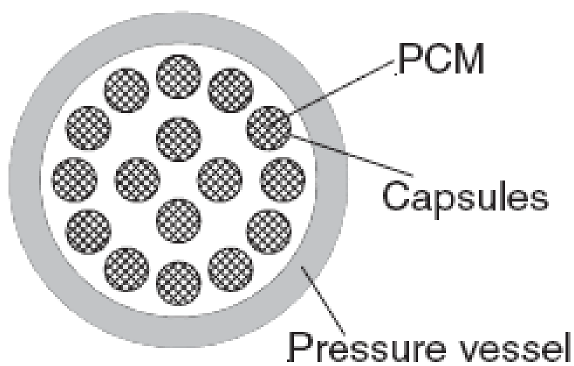

Figure 3-12
Macro-Encapsulated Phase Change Material (Source: DLR)

Another option for improving the performance of PCM storage systems is to improve the effective thermal conductivity of the material. One such method uses composite materials, such as compressed PCM and expanded graphite powder that is manufactured in blocks and subsequently assembled together with a tube bank heat exchanger, as shown in Figure 3-13.

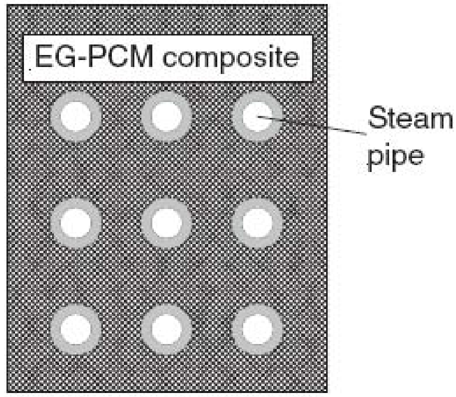

Figure 3-13
Composite of Expanded Graphite and PCM (Source: DLR)

A second method to increase the effective thermal conductivity of the PCM is to integrate layers of highly conductive materials between layers of PCM in a sandwich configuration, which act as fins to augment conduction from the heat exchanger into the PCM. Figure 3-14 shows a graphite-PCM sandwich. Expanded graphite is a promising material for such layers due to its high thermal conductivity and corrosion resistance. However, studies have shown that graphite becomes unstable in the presence of nitrate salts at temperatures above 275 °C[12]. Although for similar sized fins, graphite displays better heat transfer properties and is cheaper than metals such as steel[13], for higher temperature applications involving nitrate salts, metallic fins must be used. Carbon and stainless steels have been used in molten salt applications up to 650°C, but the corrosive behavior of molten nitrate salts precludes the use of aluminum in these systems.[14]

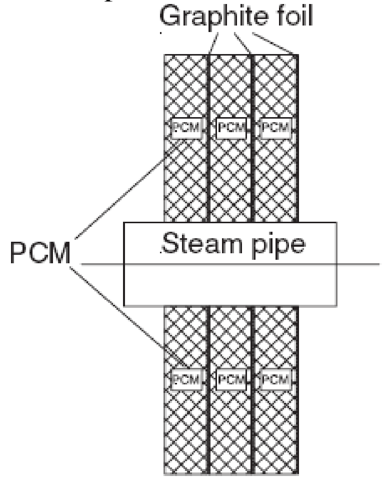

Figure 3-14
Graphite Foil Layers Inserted Between PCM to Increase Heat Transfer (Source: DLR)

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[12] Steinmann, W-D., Laing, D., Tamme, R., "Latent Heat Storage Systems for Solar Thermal Power Plants and Process Heat Applications", German Aerospace Center (DLR): Institute of Technical Thermodynamics, Presented at SolarPACES 2008, Las Vegas, 2008.
[13] Ibid.
[14] Steinmann, W-D., Tamme, R., "Latent Heat Storage for Solar Steam Systems", Journal of Solar Energy Engineering 130 (2008) 011004-1.

Cascading PCM Thermal Storage System

A cascading set of phase change materials is one system that has been proposed as a PCM storage system for CST plants. In this approach, the system is charged by circulating HTF through the collector field and then through a series of heat exchangers containing PCMs that melt at different temperatures. Thermal energy is transferred from the HTF to the PCMs, causing the latter to melt and store heat as latent heat of fusion. To discharge the storage, the HTF flow is reversed. The PCM solidifies, releasing its latent heat of fusion and reheating the HTF. The HTF is then used in the power block to generate steam to run the power plant. A diagram of a cascading PCM system is shown in Figure 3-15.

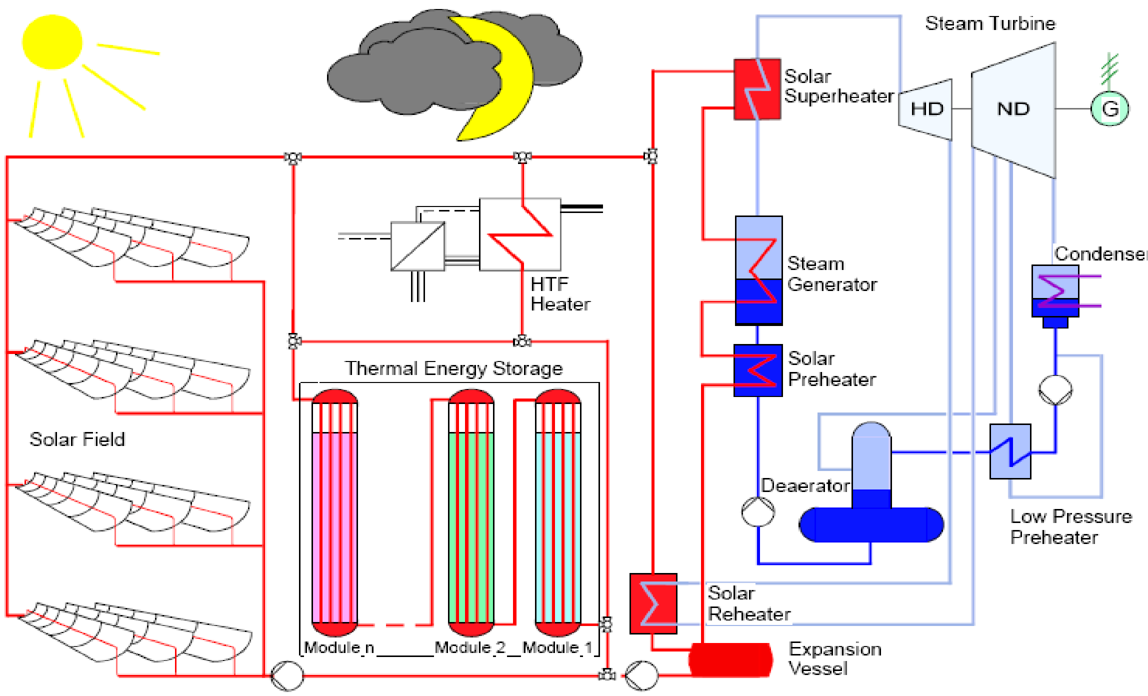

Figure 3-15
Cascading Phase Change Material TES System

Thermochemical Storage

In a thermochemical storage system, thermal energy from the solar collector field is used to initiate an endothermic chemical reaction in the storage medium and the constituents of the storage medium are then stored for later use. The chemical reactions selected for the storage system would necessarily be completely reversible. Like latent heat storage, this method operates essentially isothermally during the reactions. The heat collected in the field is used to induce an endothermic chemical reaction, whereby thermal energy is stored. This energy is recovered by the reverse exothermic reaction; catalysts are usually necessary in order to release the heat. The advantages to this system include high storage energy densities and the indefinitely long duration of storage at near ambient temperatures. However, these systems have tended to be very complex due to the uncertainties in the thermodynamic properties and reaction kinetics under a wide range of operating conditions.

Among the chemical reactions proposed for use in a thermochemical storage system are the dissociation of ammonia, or hydrogen production from the CO_2/CH_4 reforming reaction, thermolysis of water, H_2S, or a number of other reactions.[15] Ammonia is attractive as a thermochemical storage medium for a number of reasons, including a high energy density by mass or volume - 4.31 kWh/kg, or 4.33 kWh/liter (approximately half the energy density of gasoline) - environmentally benign constituents, and a reaction that is easy to control and reverse with no side reactions. Ammonia can operate at temperatures between 400-500 °C, which is an ideal temperature range for many CST applications, and the dissociation reaction has been studied at temperatures up to 720 °C. Another important feature of ammonia storage is that the ammonia component of reactant mixtures is a liquid at ambient temperatures, while the nitrogen and hydrogen components are gases, permitting the use of a single storage vessel for both the ammonia and the dissociation products. The ammonia production industry is also one of the largest chemical process industries in the world, with over 100 years of operational experience, so both experience with ammonia dissociation and synthesis reactions and the system components are readily available.[16]

Thermal Storage Technology Summary

This chapter provides characterizations of the various methods and options for thermal energy storage for CST facilities, including active vs. passive heat storage, sensible, latent, or thermochemical heat storage, liquid and solid storage media, and different configurations for each of these types of storage. Figure 3-16 shows the categories of TES systems discussed in this chapter.

[15] Komulainen, K., "Thermochemical Energy Storages for Solar Power Plants", University of Jyväskylä, Jyväskylä, Finland, 2004.
[16] Australia National University, http://solar-thermal.anu.edu.au/high_temp/thermochem/index.php, Canberra, Australia

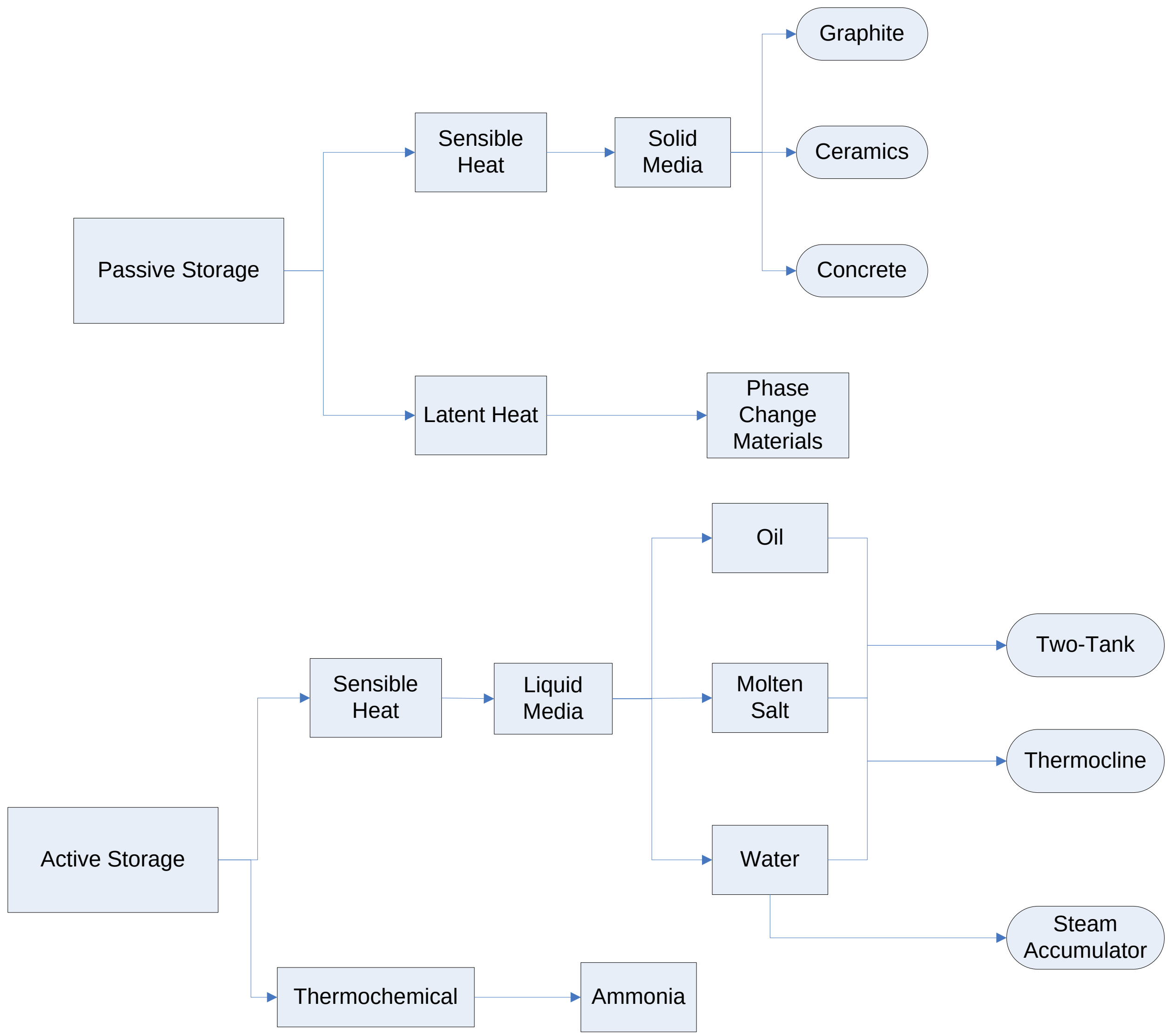

Figure 3-16
Organization of Thermal Energy Storage Systems

Table 3-4 provides a summary of the current characteristics and operations capabilities of the most advanced thermal energy storage systems. Values that have not been included in the table are unknown or are not well-established at this time.

Table 3-4
Thermal Energy Storage System Characterization

Storage Technology	Two-Tank Indirect[1]	Two-Tank Direct[1]	Two-Tank Hot Water	Steam Accumulators	Single-Tank Thermocline	Concrete Block	Graphite Block
Energy Storage Capacity	Up to 11,000 MWh_t	Up to 11,000 MWh_t	Up to 400 MWh_t	Up to 50 MWh_t			
Duration of Discharge	Up to 16 hours	Up to 16 hours	Up to 3 hours	Up to 1 hour			
Power Level	Up to 250 MW	Up to 250 MW	50 kW-20 MW	50 kW – 20 MW	50 kW – 20 MW	50 kW - 50 MW	50kW-20MW
Response Time	<30 min.	<30 min.	< 30 min.	<5 min.			Continuous
Round-trip Thermal Efficiency	>90%	>90%				>95 %	
Lifetime	30 years	30 years	30 years	30 years			

[1] Multiple tanks can be added to meet the capacity and discharge duration.

4

THERMAL ENERGY STORAGE DEVELOPMENT STATUS

This chapter compares the state of the thermal energy storage systems that are most likely to see continuing near-term investment and development, including:

- Two-tank direct and indirect systems
- Single-tank thermocline
- Steam Accumulators
- High-temperature concrete block
- Graphite
- Phase Change Materials (PCM)
- Thermochemical (Ammonia Dissociation/Synthesis)

The commercial readiness of each of these systems is the primary subject of this chapter, with an emphasis on which systems are ready for commercial operation and what types of research are currently in progress for the non-commercial systems. This chapter will describe the ongoing research for each of these systems, as well as identifying future research needs and development opportunities that could help bring emerging technologies to market.

Technology Maturity

The thermal energy storage systems described in the previous chapter range from systems such as the two-tank indirect system, which is ready for commercial deployment, to systems involving phase change materials that will require extensive research and development before they can be demonstrated at full scale and in time considered mature. Most of the proposed storage technologies lie somewhere in between these two ends of the spectrum. Table 4-1 provides a summary of the commercial readiness of the most common types of thermal energy storage systems. The definitions of the categories for maturity are as follows:

- Commercial: At least 5 units installed, with more than 10 years of experience per plant, with demonstrable economic return on investment
- Pre-commercial Prototype: One or more plants installed as commercial ventures, but lacking sufficient cumulative time in service to be regarded as commercial
- Demonstration Stage: Some in-grid and/or in-field experience, but not commercial or pre-commercial as defined above
- Developmental: Laboratory units, sub-scale plants, or technologies that are used in non-utility applications

Table 4-1
Commercial Status of Thermal Energy Storage Systems

Commercial	Pre-commercial Prototype	Demonstration Stage	Developmental
Steam Accumulators	Two-Tank Indirect Two-Tank Direct*	Two-Tank Direct** Graphite Block Single-Tank Thermocline Concrete Block Phase Change Materials[+] Thermochemical[†]	Phase Change Materials

* Two-tank direct system using Caloria oil
**Two-tank direct systems using molten salt
+PCM systems for direct steam generation only
†Ammonia dissociation reaction used with parabolic dish collector technology

Although both latent heat and thermochemical storage mechanisms show promise for decreasing the cost and size of thermal energy storage systems, it is important to note that most of the mature storage technologies involve sensible heat transfer. The two-tank direct and indirect storage systems are the only thermal energy storage systems to have seen commercial operation at a grid-connected CST plant; the SEGS I facility used a two-tank direct storage system from 1985-1999. In 1999, the SEGS I storage tanks were destroyed due to the use of flammable mineral oil which led to fires at this plant. Like the rest of the thermal energy storage systems that are either in the pre-commercial prototype or demonstration stages, the SEGS I TES was a one-of-a-kind storage system, and was not included in any of the later SEGS facilities. The two-tank indirect system is the closest to achieving commercial status, with one unit now operational at the Andasol 1 plant in Spain, and more either under construction or planned for operation in the next few years. The rest of the storage system concepts have undergone testing as prototypes and are poised to become commercial ventures with further research and development. For most of these systems in the demonstration stage, a pilot plant presents the logical next step required for achieving technological maturity.

National energy departments, particularly in Europe and the U.S., are investing heavily in thermal energy storage research. The U.S. Department of Energy has awarded 15 grants totaling up to $67.6 million dollars for FY 2009. The projects cover a broad range of TES technologies, including the construction of the prototype thermocline system at the Arizona Public Service CST plant in Red Rock, AZ, solid media storage, thermochemical storage and phase change materials. Through these grants and other renewable research, the DOE intends to spur the commercialization and deployment of solar technologies and to reduce the levelized cost of electricity generated at CST facilities. The DOE goals include reducing the LCOE from 13-16 cents/kWh today with no storage to 8-11 cents/kWh with 6 hours of thermal storage capacity by 2015, and to less than 7 cents/kWh with 12-17 hours of thermal storage by 2020.[17]

[17] Department of Energy, " DOE Funds 15 New Projects to Develop Solar Power Storage and Heat Transfer Projects For Up to $67.6 Million", http://www.energy.gov/news/6562.htm, 2008.

Sensible Heat Storage

Two-Tank Indirect

The two-tank indirect system has been proven at small scale, and the first large scale commercial system was recently commissioned at the Andasol 1 plant in Spain. The technology is expected to be commercially viable and is considered the current state-of-the-art in thermal energy storage systems. The two-tank indirect TES system using molten salt is operational as of March 2009. The Andasol 1 storage system represents an important step towards incorporating thermal energy storage into CST plants – the performance data from the Andasol 1 plant will provide a valuable source of information for future thermal storage systems, and the knowledge and experience gained at Andasol 1 will help pave the way for future two-tank TES systems. Andasol 2 is currently under construction with an identical TES system, and other plants with the same design are in development. Figure 4-1 shows the Andasol 1 storage tanks during construction.

Figure 4-1
Thermal Storage Tanks Under Construction at Andasol 1 (2007)

In addition to the Andasol storage system, Arizona Public Service has contracted Abengoa to design and build a plant that will include a two-tank indirect thermal storage system using molten salt as the storage medium. As of this publication, difficulty financing the plant had delayed the progress of developing the project. The Solana plant will be located near Gila Bend, Arizona and will provide 280 MW of electricity to APS customers; it is expected to be in operation by 2011. The design uses a molten salt storage system consisting of six storage tanks (three pairs of hot and cold tanks) with the capability for six hours of full load operation. Figure 4-2 shows the proposed layout for the Solana plant; the molten salt storage tanks are labeled “5” in Figure 4-2.

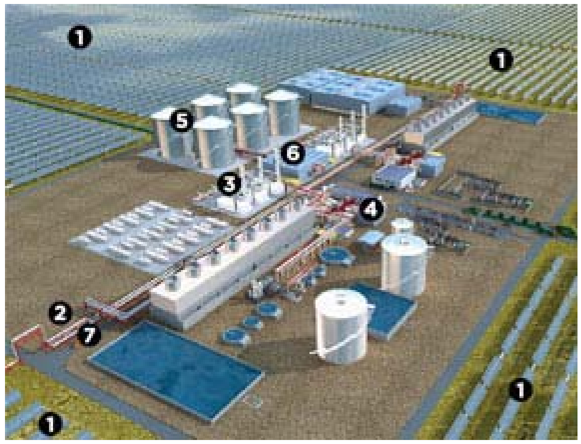

Figure 4-2
Artist's Rendering of the APS Solana Power Plant; Molten Salt Storage Tanks are Labeled "5"[18]

With Andasol I about to come online, and Andasol 2 and 3 and the APS Solana plant under development, the two-tank indirect storage system will likely be the first TES technology to achieve full commercial status, and can be considered the state of the art for thermal energy storage systems. Although outdated, thermal storage cost estimates prepared by Nexant in 2006 indicated that an 880 MWh_t two-tank indirect storage system would cost around $30/$kWh_t$. Commodity prices have increased in the last couple years, however.

Two-Tank Direct

The SEGS I system included a two-tank direct thermal energy storage system that was used in plant operation from 1985-1999. SEGS 1 used Caloria as both the HTF in the collector field and the storage medium. In SEGS II-IX Caloria was replaced by the higher-temperature Therminol oil in the collector field, but since Therminol is difficult to store due to its higher vapor pressure at the operating temperatures in the plant, the later SEGS system did not include a thermal energy storage system.

A two-tank molten salt storage system was first used at Solar Two, and has provided the foundation for current two-tank molten salt thermal storage systems. Unlike the parabolic trough plants that are most common in today's CST market, Solar Two was a central receiver plant. Circulating molten salt through a parabolic trough field presents distinct challenges in contrast to a central receiver plant, and research is still in progress to determine the capabilities for using molten salt in the collector field. Salt freeze recovery and heat loss in the collector field loops is a concern, as are the capabilities of the collector field process components, such as the piping, valves, and pumps, when molten salt is used as the HTF. Two-tank direct systems are a major subject of research around the globe – Spain, Germany, Italy, and the U.S. are all dedicating resources to such topics as the development of low-melting point salts and process equipment for molten salt systems. The Department of Energy's research grants for 2009 include projects that seek to improve the heat transfer fluids used in two-tank direct systems. Figure 4-3 shows the two-tank direct molten salt TES system at Solar Two, which has since been dismantled.

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[18] Arizona Power Service, "About Solana Generating Station", http://www.aps.com/main/green/Solana/Technology.html, © 1999-2009.

Figure 4-3
Thermal Energy Storage System at Solar Two, Barstow, CA

The Italian National Agency for New Technologies, Energy and the Environment (ENEA) has been testing molten salt in a Solar Collector Test Loop facility since 2004 to study the effects of molten salt on the valves and other process components of a parabolic trough installation. After more than 2000 hours of operation and approximately 200 fill and drain cycles, ENEA reported that no major obstacles to molten salt operation in the test collector loop were encountered. According to ENEA, further research is needed to fully characterize such items as the sealing and gasket materials and any rotating joints that come into contact with the molten salt.

While conducting the collector loop tests, ENEA simultaneously developed a design for a pilot project, dubbed Archimede, which will integrate a parabolic trough and a direct two-tank TES system with a combined-cycle plant, using molten salt as the HTF. The project stalled due to a delay in receiving national subsidies for solar thermal power plants, but is expected to come online in 2010. Like Andasol for indirect systems, Archimede will be an important source of operating and performance data for a direct storage system.

Significant cost savings are anticipated for direct trough storage systems. The cost of the oil-to-salt heat exchanger is high due to the large surface area needed for the low approach temperature of the oil. A two-tank direct molten salt storage system was proven in operation at Solar Two, and the success of this system for parabolic trough plants will depend heavily on the ability to operate the collector field using molten salt as the HTF. Salts with lower melting points would increase the likelihood that molten salt could be successful in a parabolic trough facility, as freezing in the collector field and other plant components would become much less of a concern. Operation of the Archimede facility in Italy will help to determine the feasibility of using molten salt in a parabolic trough field. However, if molten salt proves untenable as a HTF in a parabolic trough collector field, it will certainly remain an option for central receiver plants in the future.

The high freezing point of molten salt remains an issue for both direct and indirect systems, in troughs especially, and is the subject of current R&D efforts. Both the DLR and the DOE are developing salts with much lower melting temperatures than those associated with the common binary nitrate salts, having achieved melting points as low as 100°C[19], and they are performing experiments with these salts to study freeze recovery. The Department of Energy has also awarded grants for near-term development of advanced heat transfer fluids, including funding for projects that will attempt to develop low melting point eutectic salt mixtures.

Thermocline

A single-tank thermocline using thermal oil rather than molten salt has been successfully tested at the Plataforma Solar de Almería, one of Europe's most prominent CST research facilities. The PSA thermocline is a component of the Small Solar Power Systems – Distributed Control System (SSPS – DCS), which includes a parabolic trough collector field and a Multi-Effect Distillation (MED) desalination plant in addition to the thermal energy storage system. The system is a direct thermocline that uses Therminol 55 from the collector field as the storage medium, and can provide up to 5 MWh_t of thermal storage capacity. Although the thermocline testbed has been operating successfully since the early 1980's, no plans for further commercial development of this system have been proposed at this time. As discussed earlier in this chapter, storing synthetic organic oils such as Therminol at high temperatures requires a pressurized storage tank due to the volatility of the heated oils, which would require a more expensive tank, limiting the storage capacities the system is capable of providing.

Sandia National Laboratories successfully demonstrated a 2.3-MWh, packed-bed thermocline storage system with binary molten salt fluid and quartzite rock and sand for the filler material.[20] In developing the design of the thermocline testbed, Sandia evaluated various filler materials and found that a quartzite and sand mixture was both an economical and practical choice, and that both materials were able to withstand immersion in an isothermal molten salt bath as well as repeated thermal cycling tests with molten salt. Relatively simple cost analyses were conducted to evaluate the costs of materials, molten salt and filler materials for a larger commercial-scale thermocline TES system. The analyses showed that thermocline-based energy storage configurations may offer the least-cost energy storage option, being about 35 percent cheaper than a similar-sized two-tank TES system. The system studied by Sandia sought to improve on the indirect two-tank storage system concept, but a thermocline concept could also be applied to a direct system, and, like the two-tank system, will benefit from molten salt HTF research.

A single-tank indirect molten salt thermocline storage system was proposed and designed for the 1 MW Saguaro parabolic trough power plant owned by Arizona Power Service. The plant began operation in December 2005 without a TES system, but APS and the national labs began studying options for retrofitting the plant to include six hours of thermal storage in order to provide electricity during the evening peak period. A design and cost estimate for the system was developed by Nexant, Inc. and Sandia National Laboratories provided a performance analysis of the proposed systems. Both studies indicated that the thermocline was a viable option for the Saguaro plant, and a recent grant from the DOE will be used to build and test the thermocline

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[19] Brosseau, D. and Kolb, G., "Sandia Thermal Storage Activities", Presented at Trough Workshop, Golden, CO. 2007.

[20] D.A. Brosseau, P.F. Hlava, and M.J. Kelly, "Testing Thermocline Filler Materials and Molten Salt Heat Transfer Fluids for Thermal Energy Storage Systems Used in Parabolic Trough Solar Power Plants", Albuquerque, NM 2004.

storage system. The project is one of three thermal storage systems that will be incorporated into an operational power plant as part of this research phase.

A direct oil thermocline may prove to be a viable storage option for small-scale CST plants in the range of 1-10 MW, like the 1 MW Saguaro plant, because the low temperature (~300 °C) allows the use of a low cost atmospheric pressure storage tank. Studies have suggested that it may not be feasible to scale a thermocline up to provide storage for larger plants, with a plant such as Nevada Solar One (64 MW) requiring an indirect molten salt thermocline tank per hour of thermal storage desired. At this time, further studies will be necessary to better characterize the thermocline system. The development of the thermocline TES would benefit greatly from improved modeling and tank design techniques, which would offer a more complete picture of design and performance. Testing and operation of a larger scale pilot thermocline will also demonstrate the capabilities of the system - the results of the Saguaro project will provide much-needed performance data and operations experience for a thermocline system.

Steam Accumulators

Steam accumulators are a commercially mature technology and are used to supply process steam for a range of applications in modern industry, including power generation. However, steam accumulators tend to be inefficient, and the need for a costly pressurized tank limits the capacity a steam accumulator storage system can provide. Also, steam accumulators use water as both the heat transfer fluid and storage medium. Due to both of these constraints, steam accumulators are only suitable for buffer or short-term storage for facilities with direct steam generation (DSG). The PS10 central receiver plant in Spain uses steam accumulators that provide 20 MWh_t of storage capacity, enough to power the turbine at part load for up to one hour. The system consists of four tanks that are discharged in sequence. Figure 4-4 shows the steam accumulator at PS10.

Figure 4-4
Steam Accumulator Storage System at PS10 (2008)

Steam accumulators could potentially be used as a complement to a larger capacity storage system, providing buffering during short periods of intermittent insolation, when a large system is not required, or until the larger system can come online during longer periods of lost insolation. For DSG systems, the steam accumulator could be combined with the DLR's PCM storage modules described in the following section or with a concrete or other solid media storage system. The DLR is also studying PCM-enhancements for improving the performance of steam accumulators.

Concrete Storage

The German DLR has dedicated extensive research to developing solid media storage, focusing primarily on concrete and ceramic blocks with an embedded pipe manifold. In 2006, DLR partnered with Ed. Züblin AG and FlagSol GmbH to work on the next phase of concrete storage development. The project looked for ways to achieve further cost reduction of solar media sensible heat storage and developed a final storage material definition, and attempted to optimize both the storage design and the operation concept. The project also looked at ways to enhance heat transfer by adding structures with high heat transfer to the tube register. These included axial fins, radial fins, and orthogonal reinforcement grids. The addition of heat transfer structures allowed the distance between tubes to be increased, but the project ultimately determined that the additional cost of implementing these structures outweighed the benefits. A tube register design with straight parallel tubes was selected as the best option for a concrete or ceramic block.

The DLR has successfully tested both ceramic and concrete in separate 350 kWh pilot storage modules, as well as a 400 kWh concrete module. Based on the success of the pilot modules after two years of operation, DLR has determined that the concrete storage system is ready for scale-up and deployment and has developed a basic storage module with dimensions 18 m x 4 m x 2.6 m that requires 400 tons of concrete and can store up to 4 MWh_t[21] each. Figure 4-5 shows the size and piping arrangement of the basic module.

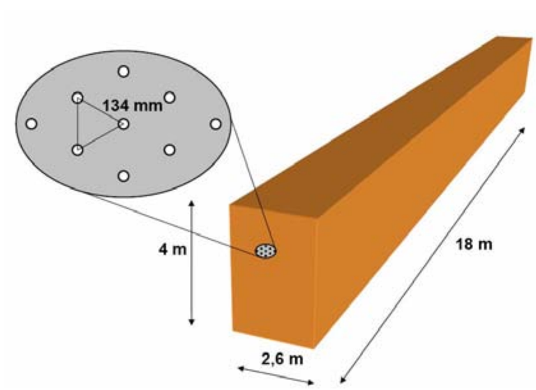

Figure 4-5
Basic 4 MWht Concrete Block Storage Module[22]

The basic module shown above can be combined into a unit consisting of multiple modules; any number of modules or units can be assembled into a TES system to meet the storage requirements of the plant. Scale-up to a 6 hour, 1100 MWh_t storage system that could be used at

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[21] DLR and Ed. Zublin AG, "Concrete Storage Technology", Presented at the Thermal Storage in Concrete Workshop, 2008.
[22] Ibid.

an Andasol-sized plant would require four storage units consisting of 63 individual storage modules. In Figure 4-6, a diagram of an 1100 MWht concrete storage system is shown. It is intended to be the equivalent storage capacity of the existing two-tank molten salt system currently operating at Andasol 1.

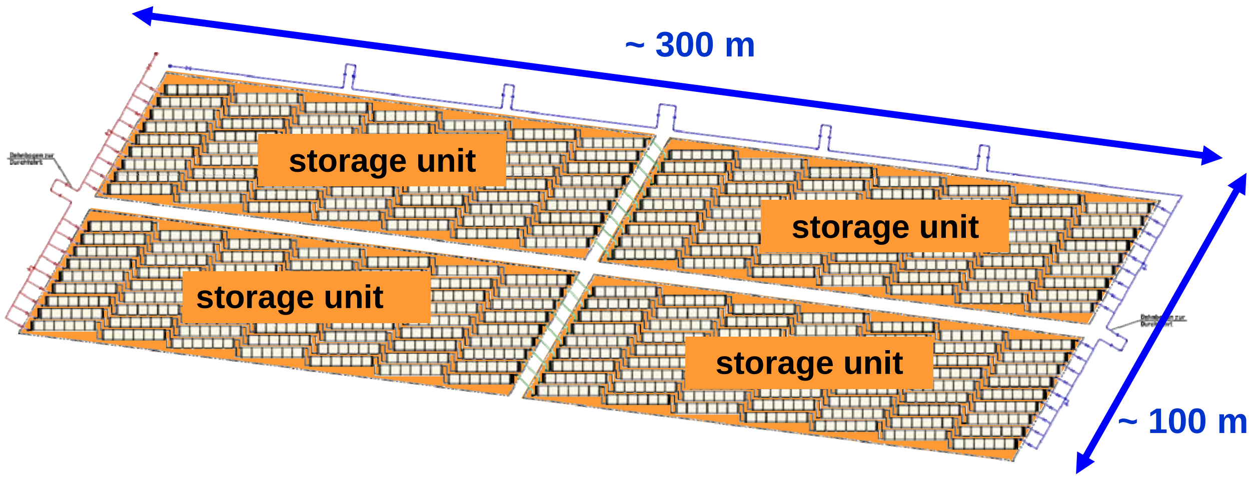

Figure 4-6
Artist's Rendering of an 1100 MWht Concrete Block Thermal Energy Storage System That Has the Equivalent Storage Capacity of Andasol's 7 Hour-50 MW Salt Storage System[23]

For the 1100 MWht concrete block storage system the DLR projects a total cost of 37.9 million Euro ($50.4 million), or 30-40 Euro/kWh$_t$ ($40-53/kWh$_t$), with the following storage system component cost breakdown shown in Figure 4-7. The cost of the concrete thermal energy storage makes it highly competitive with other TES options.

The DLR has also identified a use for concrete storage in parabolic trough power plants with direct steam generation. The proposed system, shown in Figure 4-8, is a hybrid storage approach in which concrete modules are combined with a phase change material storage module to create a steam generator. The PCM module acts as the equivalent of the evaporator, while the concrete modules bracket the PCM to serve preheating and superheating functions. The addition of a PCM storage module allows for smaller system sizes due to the compact nature of PCM storage, while also taking advantage of the low cost of concrete storage. A PCM module has been developed by the DISTOR consortium, which includes the DLR, for use in direct steam generation and is described later in this chapter.

[23] Laing, D., "Concrete Storage for Solar Thermal Power Plants and Industrial Process Heat", Presented at the International Renewable Energy Conference (IRES III), Berlin, 2008.

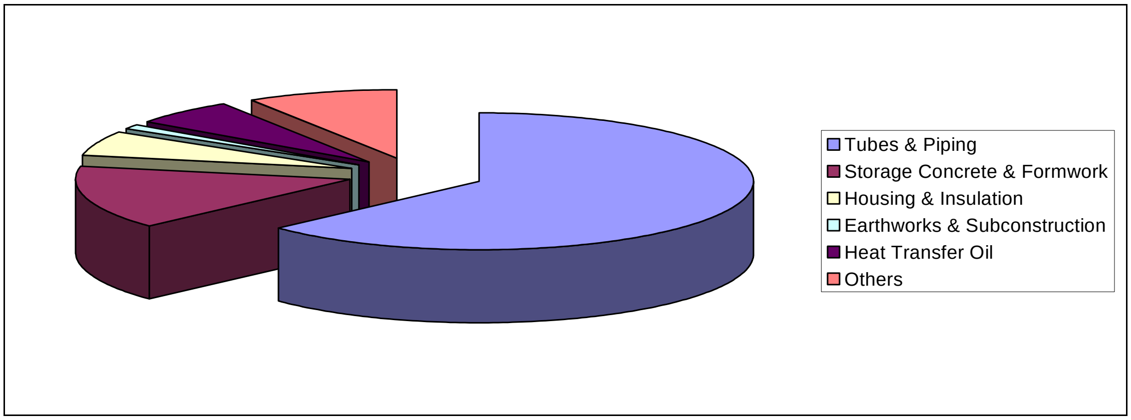

Figure 4-7
Cost Breakdown for a Concrete Solid Media TES System[24]

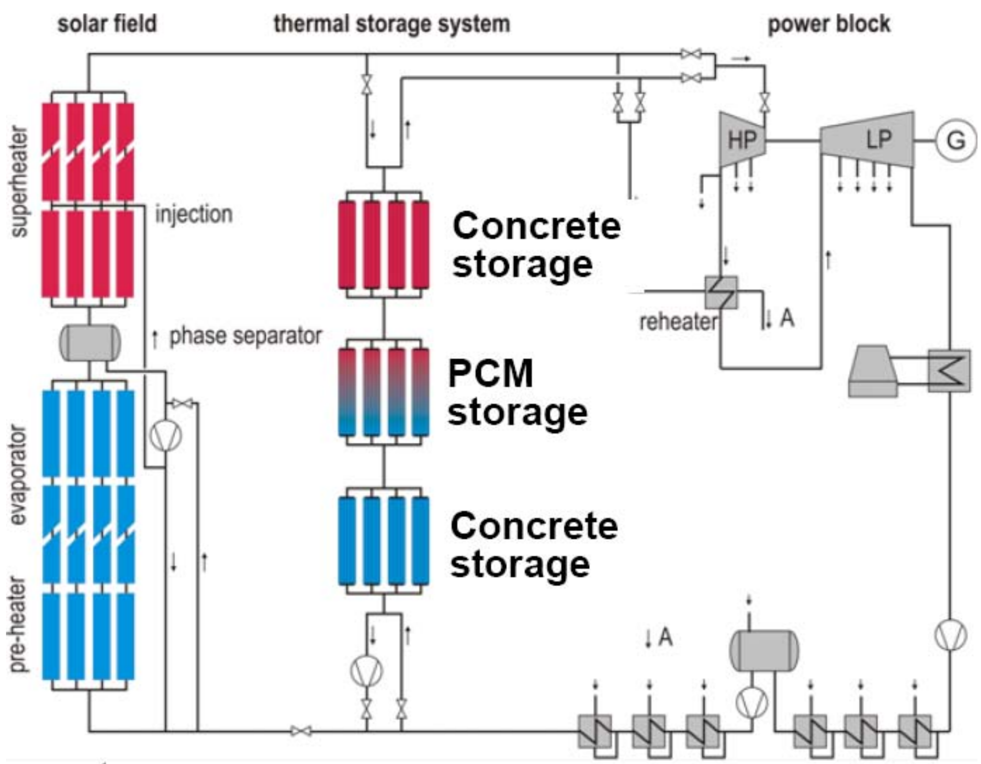

Figure 4-8
Combined Concrete and PCM Storage System for Direct Steam Generation[25]

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[24] DLR and Ed. Zublin AG, "Concrete Storage Technology", Presented at the Thermal Storage in Concrete Workshop, 2008.
[25] Laing, D., "Concrete Storage for Solar Thermal Power Plants and Industrial Process Heat", Presented at the International Renewable Energy Conference (IRES III), Berlin, 2008.

Graphite

Research into graphite TES systems has been limited to date, although the Australian company Lloyd Energy Systems has already developed and tested a central tower CST concept that utilizes high-purity graphite blocks. The graphite blocks have a threefold function, acting simultaneously as receiver, steam generator, and thermal storage system. The blocks are mounted on 15 meter towers surrounded by a field of heliostats; the focal point of the heliostat field is a receiver cavity at the base of the graphite block, allowing the concentrated solar energy to heat the graphite to temperatures of up to 1800 °C. Water is then passed through tubes embedded in the graphite block to produce steam for electricity generation. Figure 4-9 shows the graphite block utilized by Lloyd Energy Systems.

Figure 4-9
Graphite Block Thermal Storage and Receiver Concept Developed by Lloyd Energy Systems[26]

Australian press articles confirm that the company has contracts to install systems capable of producing up to 10 MW_e for power generation at rural communities in Australia, although little information is otherwise available at this time. LES systems appear to be primarily targeted for distributed generation markets, such as remote rural communities, islands and isolated mining operations that would benefit from an inexpensive modular solar generation and storage system.

Latent Heat Storage

Phase Change Materials

In the early 1980's researchers at Sandia National Laboratories investigated a wide variety of phase change material storage concepts, with the goal of developing a cost-effective latent heat TES system. The concepts included mechanisms for improving conduction into the PCM, such as macro-encapsulation and heat transfer fins, as well as mechanical devices for scraping the solid PCM from the heat transfer surface. After narrowing down the field and developing rough size and cost estimates for the most promising concepts, Sandia selected a passive tube heat

[26] Lloyd Energy Storage, http://www.lloydenergy.com/heatstorage.htm

exchanger concept for further testing. The final design included a passive serpentine tube bundle augmented with aluminum and steel fins for improved thermal conductivity, much like the sandwich design shown in Figure 3-14 in the previous chapter. The PCM thermal storage design was simulated using a proprietary modeling program written specifically for the project, and budgetary cost estimates were developed, although further development appears to have stalled.

Initially phase-change materials were considered for use in conjunction with parabolic trough plants that use Therminol VP-1 in the solar field. Luz, and later ZSW, proposed an approach that used a cascading set of phase-change materials to transfer heat from the HTF. Although testing proved that the system was technically feasible, the complexity of the system, thermodynamic penalty of going from sensible heat to latent heat and back to sensible heat, and uncertainty over the lifetime of phase change materials hindered the further development of this concept.

In 2007, the European DISTOR consortium successfully tested a 200 kWh_t PCM storage module using the DISS facility at the Plataforma Solar de Almería. The goal of the DISTOR project was to develop a thermal energy storage system that could store energy from a direct steam generation CST plant. DSG is an attractive option for lowering the cost of solar power plants, as it eliminates the need for the steam generator as well as the costly synthetic oils. Sensible heat storage systems based on temperature changes in the heat transfer fluid are not the most effective type of storage for maximizing the efficiency of a DSG plant, where the storage system is charged by isothermally condensing steam. The DISTOR consortium elected to focus on phase change materials for DSG storage. After testing lab-scale prototypes of different configurations, DISTOR concluded that the sandwich configuration offered the most potential for cost-effective, high power and high capacity PCM thermal storage. The team developed a pilot storage module for testing at the PSA. The module is non-pressurized and contains molten salt – the phase change material – a parallel tube bundle heat exchanger for passing the steam through the PCM, and layers of expanded graphite that improve conduction from the tube bundle into the salt circulating in the module. A diagram of the module is shown in Figure 4-10.

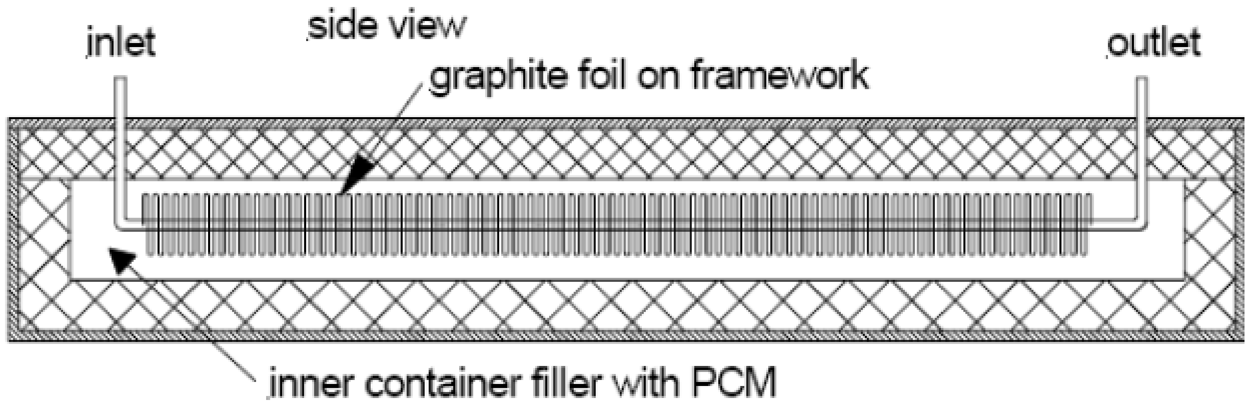

Figure 4-10
Phase Change Material and Expanded Graphite Sandwich Storage Concept for DSG Developed Through the DISTOR Project[27]

[27] Lupiana, F.J.G., "DISTOR Project: Thermal Storage in Solar Thermal Plants", Iberdrola Engineering and Construction.

The project proves the technical feasibility of the PCM storage concept for direct steam generation and offers a promising solution for DSG thermal storage. Ongoing research is currently focusing on optimizing the heat exchanger geometry and integrating the storage units into power plants, as well as developing a 1 MW storage unit.[28]

The DLR has also investigated a PCM-enhanced steam accumulator through Project PROSPER, with the goal of developing a steam accumulator that produces steam at constant pressure. As in the DISTOR project, PROSPER evaluated various options for improving the performance of phase change materials, such as encapsulated PCM materials and heat transfer fins. Figure 4-11 shows the three systems that were modeled in this project: 1) a simple variable-pressure (Ruths) accumulator, 2) a Ruths accumulator serving as the macro-encapsulation vessel for the PCM, and 3) an externally arranged PCM. The DLR developed simulation models for analyzing the performance of each of these systems. Simulation results show significant increases in steam accumulator performance using the external PCM enhancement, and laboratory-scale tests are planned to validate the modeling results. [29] Although the PROSPER project focused primarily on steam production for process heat applications, particularly in the concrete industry, the PCM-steam accumulator hybrid storage may be worth investigating as a storage option for medium-temperature CST applications if the lab-scale tests are positive.

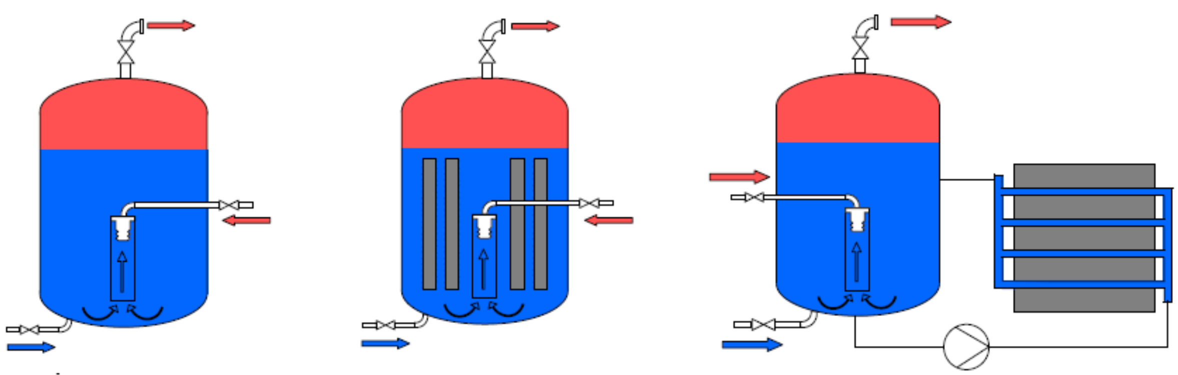

Figure 4-11
Three Options for Steam Accumulator Thermal Storage; Options 2 and 3 Include a PCM Storage Enhancement[30]

Recent research proposals in the U.S. have also returned to the concept of utilizing phase change materials as a thermal storage medium for CST plants. The U.S. Department of Energy has awarded grants for at least two new projects dedicated to studying phase change materials, including one project that will focus on eutectic salt mixtures. The results of these new studies should provide further insight into the capabilities of phase change materials for thermal storage. Storage systems involving PCMs are still in their infancy, and will require further study to determine the compatibility of these systems with CST plants using heat transfer fluids.

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[28] Steinmann, W-D., Laing, D., Tamme, R., "Latent Heat Storage Systems for Solar Thermal Power Plants and Process Heat Applications", German Aerospace Center (DLR): Institute of Technical Thermodynamics, Presented at SolarPACES 2008, Las Vegas, NV, 2008.

[29] Buschle, J., Steinmann, W-D., Tamme, R., "Latent Heat Storage for Process Heat Applications", DLR: Institute of Technical Thermodynamics, Presented at the Tenth International Conference on Thermal Energy Storage, Atlantic City, NJ, 2006.

[30] Ibid

Thermochemical Storage

A thermochemical storage system utilizing the ammonia dissociation/synthesis reaction has been developed by the Australian National University and is proposed for use in conjunction with the Big Dish parabolic dish concentrator technology. In the ANU design, the storage system is integrated into the solar energy collection technology by using ammonia as the heat transfer fluid in the dishes. Thermal energy collected by the dish is used to dissociate ammonia into H_2 and N_2, which are sent directly into a storage system. The storage system then releases energy by synthesizing ammonia from these constituents, an exothermic reaction that releases heat to produce superheated steam that is used to operate the power block. Figure 4-12 shows the process flow for ammonia dissociation and synthesis.

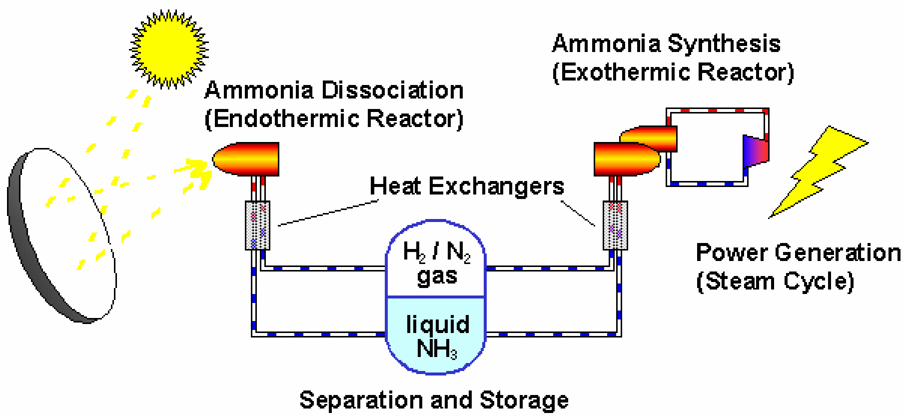

Figure 4-12
Thermochemical Energy Storage System Concept for Parabolic Dish Collector[31]

Ammonia reactors are a commercially mature technology, and the incorporation of the ammonia reaction into a CST facility has been studied at ANU for two decades. Since 1998, both a 1 kW and a 15 kW prototype solar ammonia dissociation system have been successfully demonstrated at ANU with a 20 m^2 parabolic dish, including operation of the 15 kW system for a full 24 hours. In 2007, Wizard Power Pty Ltd., which was founded in order to commercialize ANU's technology, received a $7.4 million Australian Greenhouse Office grant to build a commercial-scale demonstration.[32] The first 30 MW stage of the 6-dish Whyalla Solar Oasis will use direct steam generation and is scheduled for completion in late 2009. The ammonia thermochemical energy storage system is planned as a retrofit to the initial commercial plant, and is expected to come online in 2010. The success of the planned commercial operations could prove this technology to be a viable thermochemical storage option. Although developed for the Big Dish parabolic dish collector, ANU's research has shown that the ammonia storage system could also be compatible with parabolic trough collectors.

[31] Lovegrove, K., Luzzi, A., Soldiani, I., Kreetz, H., "Developing ammonia based thermochemical energy storage for big dish power plants", Solar Energy 76 (2004) 331-337, 2004.
[32] http://solar-thermal.anu.edu.au/pages/news.php

Thermal Storage Development Summary

A review of the commercial readiness of the various thermal energy storage systems shows that the majority of the concepts discussed in this report are poised to achieve commercial maturity with some further development and validation of their capability for operation at a commercial CST facility. Table 4-2 summarizes the current development needs for each of the thermal storage concepts based on the status of the technology as described in the previous sections. Only the two-tank technologies have been demonstrated in commercial operation, and although a two-tank direct system using Caloria oil was successfully operated for fourteen years at SEGS I, systems using molten salt as the storage medium have yet to see continuous long-term commercial operation. Both the compatibility of the raw materials and the long-term durability, reliability, and performance of critical components of thermal storage systems using molten salt remain uncertain. Extended operation of molten salt systems in addition to further testing and research will be required to complete commercial development and to fully characterize the technical constraints on molten salt TES.

The other technologies would benefit greatly from operation and testing at a non-commercial pilot plant, much like Solar Two, or by simply incorporating a storage system into an operational CST plant, as Arizona Public Service intends to do at the Saguaro plant. Although the oil thermocline at the PSA has performed well, the molten salt thermocline has yet to see any testing beyond the prototype studied at Sandia National Laboratories, and a full-scale pilot system integrated with a CST plant will permit further observation and validation of this concept.

Table 4-2
Current Development Needs for Thermal Storage Technology

Storage Technology	Development Needs
Two-Tank Indirect	• Operating experience from the planned commercial facilities (Andasol, Solana) • More units in commercial operation • An established supply-chain for system components • Evaluation of long-term durability and reliability of materials in use with molten salt
Two-Tank Direct	• Validation of molten salt operation in a full-sized collector field • Operation and evaluation of a commercially operated unit • Evaluation of long-term durability and reliability of materials in use with molten salt
Two-Tank (Hot Water)	• A pilot plant or commercially operated unit
Single-Tank Thermocline (Direct or Indirect)	• Improved modeling techniques, including an effective method for sizing the thermocline tank • A pilot plant or commercially operated unit
Concrete Block	• A modeling or system design tool • Operation and evaluation of a commercially operated unit
Graphite Block	• Operation and evaluation of a commercially operated unit
Phase Change Materials	• Further optimization of storage concepts using phase change materials • Development of prototype storage modules for testing and evaluation • A pilot DSG plant with a phase change storage module
Steam Accumulators	• Lab-scale tests for the hybrid PCM-steam accumulator system • Simple steam accumulators are commercially mature
Ammonia Dissociation/Synthesis Reactors	• Operation and evaluation of a commercially operated unit for parabolic dishes • Further investigation of the thermochemical system for parabolic troughs

5

THERMAL ENERGY STORAGE SYSTEM DESIGN

The process of designing a thermal energy storage system begins with the selection of a storage technology that is compatible with the associated generation technology. Compatibility depends on many factors, particularly the operating temperatures in the plant and the physical configuration of the solar energy collection and thermal storage systems. In addition to the temperature requirements and mechanical compatibility of the storage and collector technologies, the function and desired operating mode of the storage system must also be considered. This chapter details the compatibility of the storage systems described in Chapter 4 with each CST technology. For each of these storage systems, many combinations of storage medium and heat transfer fluid exist; the usual selections for each system are presented, as well as the maximum operating temperature possible with a particular storage medium. Once the appropriate storage configuration and medium have been selected, the design can proceed to sizing the various components of the storage system and estimating the capital costs. Due to the lack of reliable and standardized design information for most of the potential storage systems, size and cost comparisons are limited to the two-tank and concrete block systems.

Thermal Storage Technology Compatibility

It is important to note that each of the thermal energy storage systems may not be appropriate for all of the available solar thermal power plant technologies. Among the CST technologies, dish/engine technology is the most difficult to provide storage, as the heat collection and power generation components are co-located at the dish focal point. None of the storage technologies discussed here have been demonstrated with dish/engine technology, although recent research has begun to explore the possibility of storage for dish/engine systems, such as the Infinia technology discussed in Chapter 2. Incorporating storage systems into plants utilizing the other three technologies is a much simpler task, with an obvious insertion point for storage between the solar heat collection and steam generation components.

Parabolic trough plants are currently the only commercially operated solar thermal technology, and most of the storage technologies have been designed for operation with parabolic trough technology. Central receiver and compact linear Fresnel reflector technologies operate on similar principles to parabolic trough, albeit over different temperature ranges, and will be able to incorporate some of the same storage technologies with modifications. Central receiver plants are capable of operating at much higher temperatures than parabolic trough, while CLFR plants will operate at lower temperatures, which must be taken into consideration when selecting a storage system. Table 5-1 matches CST technologies with compatible options for storage systems.

Table 5-1
CST and TES Technology Compatibility

CST Technology	Storage System: Two-Tank Indirect	Two-Tank Direct	Hot Water Storage	Single-Tank Thermocline	Concrete Block	Graphite Block	Phase Change Materials	Ammonia Thermo-chemical
Parabolic Trough	+	+	/	+	+	T/D	+	U
Central Tower	/	+	/	+	/	+	+	U
Dish/Engine	D	D	D	D	D	D	+	+
Compact Linear Fresnel Reflector	+	+	+	+	+	T/D	+	U

+ Optimal technology match

/ Compatibility depends on collector field HTF design temperature

T Collector field and storage system temperatures not compatible

D Not compatible due to configuration of CST and storage technologies

U Unknown, but theoretically possible

Central tower CST plants are physically compatible with most of the storage technologies presented here. However, in practice the compatibility of the systems related to plant operations and efficiency will depend on the temperatures used in the plant. Central receiver plants have achieved maximum temperatures of 565 °C with molten salt HTFs, and at such temperatures certain types of storage would not be feasible, such as concrete and hot water storage. Receivers with a lower temperature output are possible, although one of the primary advantages of the central receiver technology is the capability for very high temperature steam generation and the corresponding increases in plant efficiency. For central receiver technology using molten salt as the HTF, the two-tank direct technology is a practical solution. To further reduce the cost of storage, a single-tank direct thermocline could be developed.

For parabolic trough there are several challenges to developing a low cost solution. Due to the high cost of the synthetic oil HTF, indirect storage systems are currently the only option. Moving toward a direct storage system would eliminate this inefficiency problem and eliminate a costly heat exchanger. Based on the operating temperature of the HTF storage system size is fairly large. In order to decrease the storage volume, the storage temperature would need to increase. It follows that the development of a low-cost, higher temperature HTF may be needed to achieve cost effective storage solutions.

Similarly, the CLFR technology is designed to operate at even lower temperatures than a parabolic trough plant typically uses, and while any of the storage systems described are feasible, it may not be cost-effective to use a molten salt storage system that is designed for much higher temperatures.

In its current design state, graphite storage is essentially a combined central receiver and storage technology, and so would not be compatible with any lower temperature trough or CLFR. If graphite were applied in a manner similar to concrete storage, it still may not be ideal for use with parabolic trough or CLFR plants, as it performs best at very high temperatures.

The ammonia thermochemical storage system was designed for integration into a parabolic dish collector, but initial theoretical studies indicated that the system may also be feasible for parabolic trough collectors as well. The system is based on using thermal energy to dissociate ammonia, and could likely be used with any of the collector technologies.

In addition to the various energy collection technologies, a solar thermal power plant can utilize different power cycles that operate over a wide range of temperatures. Certain TES systems will not be suitable for operation at some of these temperatures. The Rankine cycle is the most common power cycle used in solar thermal power plants, and can operate at very high temperatures with water/steam as the working fluid, or at lower temperatures using an organic fluid such as pentane. It should be noted that although organic Rankine cycles (ORCs) are feasible, turbine efficiencies are roughly half as efficient as steam Rankine cycles. Practically, this means that the solar field for an ORC would need to be twice as big to produce the same amount of power as a plant with a steam Rankine cycle. The Kalina cycle capitalizes on the temperature-dependent evaporation and condensation properties of an ammonia-water mixture to better utilize low-temperature resources; the Kalina cycle has been used extensively in geothermal applications and could be used for low-temperature solar thermal applications as well.

As an example, a hot water storage system would not be capable of providing the very high temperatures required to superheat steam for a Rankine cycle due to its low maximum operating temperature. On the other hand, molten salt and organic oils, with much higher maximum temperatures, are far more suitable for generating steam for use with a high temperature Rankine cycle. The hot water storage system, on the other hand, would likely be a much more cost-effective and efficient option for a low-temperature cycle such as the Kalina cycle, or an organic Rankine cycle with Isobutane as the working fluid. Table 5-2 correlates the power cycles that can be used in solar thermal power plants with the appropriate TES systems.

Table 5-2
TES Systems Matched to Solar Thermal Power Cycles Based on Cycle Temperature

Power Cycle			Storage System							
Power Cycle	**Working Fluid**	**Cycle Temperature (deg C)**	**Two-Tank Direct**	**Two-Tank Indirect**	**Single-Tank Thermocline**	**Hot Water Storage**	**High Temperature Cement**	**Graphite**	**Phase Change Materials**	**Ammonia Thermo-Chemical Storage**
Rankine	Water/ Steam	>500	X		X			X	X	X
		250-370	X	X	X	X*	X		X	X
Organic Rankine	Toluene	350-400	X	X	X		X		X	X
	Pentane	<350	X	X	X		X		X	
	Benzene	350-400	X	X	X		X		X	X
	Butane	150-200				X			X	
	Isobutane	150				X			X	
Kalina	Ammonia -Water	150-210				X			X	

*Steam accumulators for DSG

Storage System Operating Modes and Media Selection

In addition to the compatibility with the generation system, the intended use of the thermal storage system will also dictate which of the storage configurations and which storage medium will be best-suited for a particular project. As this report discussed, the TES systems are primarily used either to buffer the output of the CST plant or to extend or displace the output into the evening time of use periods. Certain TES systems are not suited for long-term storage or for the large storage systems that a power plant producing 50+ MW with six or more hours of storage would require. Similarly, some systems have longer response times, and would not be ideal for providing the rapid storage response that a buffer system will require.

The selection of the storage media is closely related to the manner in which the storage system will operate. While a range of heat transfer fluid-storage media combinations are theoretically possible, Table 5-3 lists the heat transfer fluid and storage media that are most likely to be selected for each of the TES systems, as well as the maximum operating temperature of a TES system using the selected medium.

Table 5-3
Heat Transfer Fluid and Storage Media for Each TES System

TES	Heat Transfer Fluid	Storage Media	Maximum Temperature (°C)
Two-Tank Direct	Binary Nitrate Salt	Binary Nitrate Salt	650
Two-Tank Indirect	Organic Oil	Binary Nitrate Salt	400
Single-Tank Thermocline	Binary Nitrate Salt	Salt/Quartzite Rock and Sand	650
Hot Water Storage	Water	Water	100
High Temperature Cement Block Storage	Any	High-Temperature Concrete	400
Graphite Block Storage	Water/Steam	High-Purity Graphite	1800
Phase Change Materials	Water/Steam	Nitrate Salt	650
Ammonia Thermochemical Storage	Ammonia	Ammonia	750

It is likely that any system incorporating a liquid storage media will use either molten salt or water. Therminol has replaced Caloria as the heat transfer fluid in parabolic trough systems, as it has a higher maximum temperature and can thus improve the efficiency of the power cycle. However, Therminol has a much higher vapor pressure than Caloria at the hot operating temperature of the system, and requires a pressurized vessel if used as the thermal storage medium. Pressurized tanks can significantly increase the cost of the TES system, and the large tank sizes required to store thermal energy for a larger system with Therminol could make the TES prohibitively expensive. Molten salt, on the other hand, can be stored at atmospheric pressure and is therefore more attractive as a storage medium.

For solar thermal systems operating at lower temperatures, water provides a low-cost, simple alternative to molten salt. Like molten salt, hot water can be stored at atmospheric pressure, and at very little cost. Hot water is also free of the complications that accompany a molten salt storage system. With a freezing point of approximately 200°C, a molten salt system must include provisions for freeze protection, such as electric heat tracing on all components that contain molten salt or through which the salt passes. Water could also be used indirectly with higher temperature collector fields, but the thermal losses incurred by transferring heat from a medium such as Therminol, which can achieve temperatures up to 400°C, to water, with a maximum operating temperature of 100°C, will negatively impact the overall conversion efficiency of the plant. Hot water storage is best suited for low temperature applications and would probably produce the best results in a direct storage system.

For solid media systems, the results of DLR research favor high-temperature concrete blocks with a pipe manifold embedded in the concrete. Concrete is inexpensive and represents a simple concept that could be used with any heat transfer fluid, as the HTF is simply passed through the pipe manifold in order to charge and discharge the concrete TES system.

Both the current graphite storage concept and the most advanced PCM storage concept operate through direct steam generation. Much like the concrete block concept, pipes are embedded in the storage material, and water is passed through the module to discharge the system and produce steam.

System Design

The following sections describe the components of a TES system and provide estimates of the size and cost of two-tank storage systems, which are the only commercial-ready technologies and have a fairly well-established design process. Concrete block solid media storage systems are likely to be the next TES systems to achieve commercial operation, and while currently still in the prototype stage, the DLR has provided sizing estimates for a commercial-size concrete block solid media storage system, and these estimates are included as well.

Storage System Components

An elevation drawing of a two-tank indirect system using molten salt is shown in Figure 5-1.

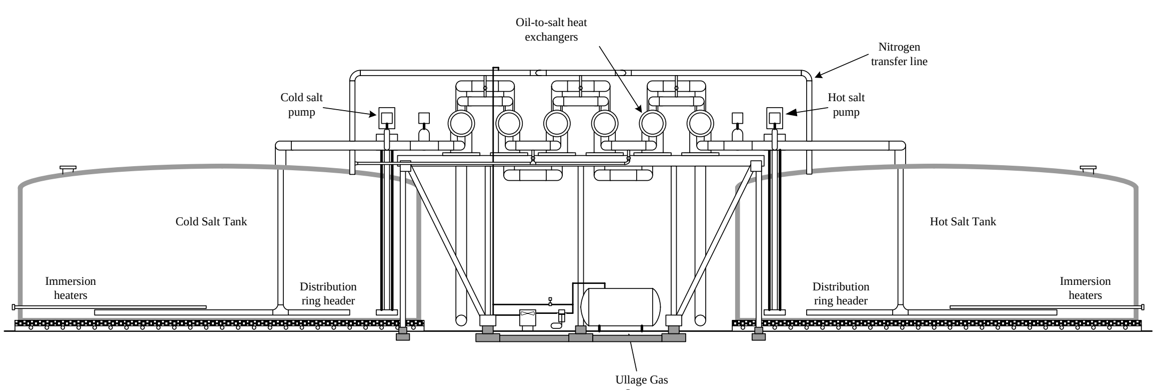

Figure 5-1
Two-Tank Indirect Molten Salt Elevation Drawing

This figure presents some of the major components of the TES system that are typically part of a storage system design, including:

- Storage tanks, tank foundations, and tank insulation
- Oil-to-salt heat exchangers (indirect systems only)
- Hot and cold storage medium pumps
- Piping and valves with associated insulation
- Ullage gas system (not used for hot water storage)

The design may also include auxiliary equipment such as the electrical heat tracing required for molten salt systems, immersion heaters to maintain storage inventory temperature, and any necessary instrumentation, and could also extend to such components as the steam generator.

Storage System Size Comparison

The following tables compare the approximate size of various storage systems for two thermal storage systems:

- 1 MW_e net plant output; 1 hour storage capacity
- 10 MW_e net plant output; 3 hours storage capacity
- 50 MW_e net plant output; 6 hours storage capacity

Table 5-4
Storage System Sizes for 1 MWe Net Generation With 1 Hour of Thermal Storage

	Storage Medium	Inlet/Outlet Temp (C)	Thermal Storage Capacity (MWht)	Volume of Storage Inventory Required (m^3)	Number of Tanks Required	Hot Tank Size-Diameter/Height (m)	Hot Tank Design Point Heat Loss (kWt)	Number of HX per Tank Pair
2T Indirect	Binary Salt	293/390	3	41	1/1	7.6/2.4	16	1
2T Direct	Binary Salt	293/500	3	18	1/1	5/2.4	9	-
2T Hot Water	Water	130/205	5	118	1/1	9.9/2.4	16	-
Thermocline	Binary Salt	293/500			1			-
Concrete Block	Concrete	293/390	4	187	-	1*	-	-

Table 5-5
Storage Systems Sizes for 10 Mwe Net Generation With 3 Hours of Thermal Storage

	Storage Medium	Inlet/Outlet Temp (C)	Thermal Storage Capacity (MWht)	Volume of Storage Inventory Required (m^3)	Number of Tanks Required	Hot Tank Size-Diameter/Height (m)	Hot Tank Design Point Heat Loss (kWt)	Number of HX per Tank Pair
2T Indirect	Binary Salt	293/390	89	1,230	1/1	16.4/7.3	84	1
2T Direct	Binary Salt	293/500	82	527	1/1	14.2/4.9	67	-
2T Hot Water	Water	130/205	165	3,535	1/1	20/12.2	94	-
Thermocline	Binary Salt	293/500			1			-
Concrete Block	Concrete	293/390	110	5,242	-	28*	-	-

Table 5-6
Storage Systems Sizes for 50 MW_e Net Generation With 6 Hours of Thermal Storage

	Storage Medium	Inlet/Outlet Temp (C)	Thermal Storage Capacity (MWht)	Volume of Storage Inventory Required (m^3)	Number of Tanks Required	Hot Tank Size-Diameter/Height (m)	Hot Tank Design Point Heat Loss (kWt)	Number of HX per Tank Pair
2T Indirect	Binary Salt	290/390	880	11,885	1/1	34/14.6	356	6
2T Direct	Binary Salt	290/500	815	5,217	1/1	25.1/12.2	238	-
2T Hot Water	Water	54/96	1660	35,579	2/2	40.6/14.6	307	-
Thermocline	Salt/Quartzite	290/500	880					
Concrete Block	Concrete	290/390	1100	51,480	-	275*	-	-

*Number of concrete modules required, according to DLR design of basic storage module with dimensions 18 m x 4 m x 2.6m

The size estimates in these tables effectively illustrate some of the differences between the different two-tank options. Due to the larger temperature difference between the hot and cold inventory in a two-tank direct system using molten salt, the system can store a large quantity of energy at a relatively small size compared to an indirect system. As a result, the storage tanks and other system components will be smaller. Also as previously noted, the direct system eliminates the need for oil-to-salt heat exchangers; the larger indirect storage system requires six oil-to-salt heat exchanger trains to provide sufficient heat transfer area, which will translate to an added system cost in addition to larger tanks. With regards to system size, heat losses, maximum operating temperature, and other characteristics of system design and performance, the direct system offers some clear advantages over the indirect system. However, the use of molten salt as the heat transfer fluid leads to issues with freezing and has yet to be proven feasible in a parabolic trough plant.

These tables also demonstrate why two-tank hot water storage is an acceptable option for smaller TES systems, but becomes less attractive as more storage is required. With its comparably lower thermal capacity and much lower operating temperature, a two-tank water system will require a much larger storage inventory to provide the desired storage capacity. For a 50 MW six-hour system, multiple tanks at significantly larger sizes than for a molten salt system are needed to accommodate the required storage inventory. The large system sizes and low operating temperature of the hot water storage system indicate that a water storage system is best suited for small storage systems for low-temperature applications.

Storage System Cost Comparison

A cost comparison of these storage systems was prepared for a plant similar in size to Andasol 1, which assumes the following:

- 50 MWe net generation
- 6 hours equivalent full load capacity storage system

The estimated size of these systems is found in Table 5-6 in the previous section. Recent increases in commodity prices will result in higher storage system costs than previous estimates indicated. The cost of nitrate salt in particular has increased greatly, from around $0.50/kg in 2006, to $1.41/kg in November 2008. SQM of Chile provided current cost estimates for potassium and sodium nitrate. Figure 5-2 shows a comparison of cost estimates for several TES technologies.

The cost of the storage material comprises the single largest expense for a thermal energy storage system, as the cost breakdown in Figure 5-2 clearly shows. This fact has led storage system developers to focus on reducing the cost of the storage material, by using an inexpensive medium such as concrete, for example. Per unit mass, concrete is expected to be cheaper than any of the salt options, however in the figure above, the storage material for a two-tank system appears to cost less than the storage material required for a concrete block storage system, despite recent increases in the price of the nitrate salt components, potassium and sodium nitrate. This likely reflects the fact that an Andasol-sized storage system requires a very large amount of concrete. The two-tank indirect system remains the most costly technology, but it is also currently the most developed technology. It must also be remembered that thermal storage systems are typically custom designed and built, one-of-a-kind systems. It is expected that the costs of these storage systems will decrease if a manufacturing supply chain for such components as the tanks becomes established.

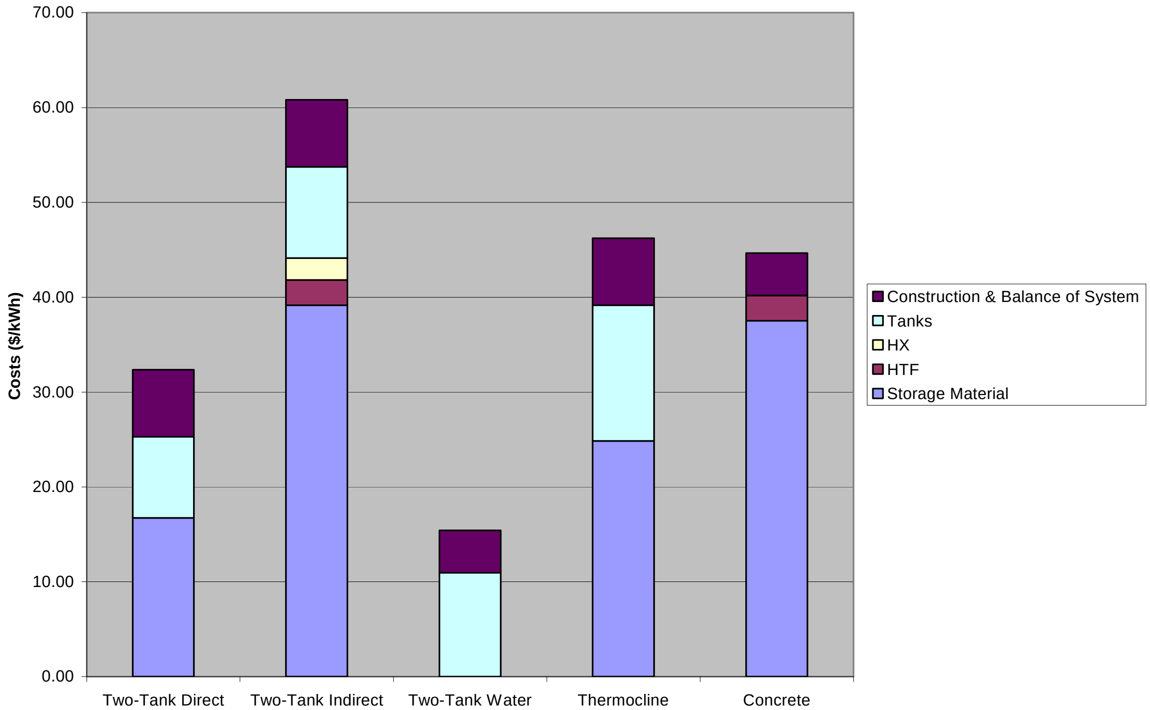

Figure 5-2
Cost Estimates and Breakdown for Two-Tank, Thermocline and Concrete Thermal Storage Systems

While the cost estimate appears to indicate that a two-tank water system offers the lowest levelized cost, it is important to note that any system using water as a storage medium is severely temperature-limited. The two-tank water system included in this estimate would have a maximum operating temperature of 100 °C; a two-tank water system of this size would also be significantly larger than other systems of a comparable size due to the low temperature range of the storage medium. Furthermore, while the direct thermocline system may prove to be less costly than a comparably sized two-tank system, the indirect thermocline whose cost is included in the figure above does not produce particularly large cost savings over the indirect two-tank system. However, the limited amount of data available for thermocline tanks leads to a very rough cost estimate, so the cost savings remain to be seen.

6 CONCLUSIONS

The following table offers a summary of the positive and negative attributes of the most common thermal storage systems, which are described in this report. This summary assumes that commercial maturity is not a factor in the comparison.

Table 6-1
Summary of Thermal Energy Storage System Attributes

Storage Technology	Positives	Negatives
Two-Tank Indirect	• Current state-of-the-art • Ease of operation • Capable of providing very large storage capacities	• Expensive • Heat losses in the oil-to-salt heat exchanger negatively impact plant performance
Two-Tank Direct	• No heat exchangers required to transfer energy into storage • Very high operating temperatures • Capable of providing very large storage capacities	• High-melting point salts can lead to issues with freezing • Some components currently not available for use with molten salt (ball joints)
Two-Tank (Hot Water)	• Inexpensive storage medium • Storage medium is easy to use	• Very low operating temperatures • Not suitable for large storage capacities
Thermocline	• Promises cost decreases by combining hot and cold storage medium into a single tank • Possible to replace a large percentage of expensive nitrate salt or synthetic oil with inexpensive filler storage materials, such as sand	• More complicated operation and controls • Thermal gradient in the storage medium negatively impacts plant performance • May not be scaleable to larger storage capacities
Concrete Block	• Inexpensive and widely available storage medium • Ease of operation	• Low heat transfer rates
Graphite Block	• Very high operating temperatures • Direct steam generation • Receiver, storage and steam generation provided by one block	• Not compatible with generation technologies other than central receiver in its current form
Phase Change Materials	• Ideal for direct steam generation • Small storage volumes due to large amount of energy associated with phase change	• Low thermal conductivity
Steam Accumulators	• Ideal for buffer storage • Simple and inexpensive storage medium	• Require pressurized tanks, limiting systems to small capacities • Inefficient • Produce variable-pressure steam

Table 6-1
Summary of Thermal Energy Storage System Attributes (Continued)

Storage Technology	Positives	Negatives
Thermochemical Ammonia Storage	• Long-term isothermal storage • Extensive experience in ammonia industry • Components readily available • Single storage tank possible	• Complex system may make scale-up difficult

Thermal energy storage holds the promise of providing an efficient and cost-effective way to transform solar thermal energy from a variable resource into a firm, more dispatchable source of electricity. Studies have shown that a thermal energy storage system improves the performance of a solar thermal plant by smoothing power production and/or allowing it to continue during brief periods of lost solar resource, such as intermittent cloud cover, or into the evening hours when the solar resource is no longer available. Used in this way, thermal storage can increase the utilization of the power block and the annual capacity factor of a CST facility, decrease the levelized cost of electricity produced by the plant, and facilitate the incorporation of solar thermal power plants into the utility grid.

The TES systems described in this report fall into three main categories of energy storage: systems that store energy in the form of either sensible or latent heat or by initiating a reversible chemical reaction. Systems that rely on sensible heat transfer for energy storage are currently the most common. Sensible heat systems require relatively simple designs, involving chemically inert media that remain in a single phase throughout the storage charging and discharging process. However, while simple, sensible heat storage systems tend to be rather large in size and require a large investment of capital to build. Latent heat storage designs could theoretically lead to much smaller, and thus less expensive, storage systems, but storing latent heat involves more complex designs, and storage systems using phase change materials remain in the early stages of research and development. Storing energy in a reversible chemical reaction also shows promise for decreased costs and system sizes, but, like latent heat storage systems, chemical storage will require a significant development effort to become economically viable.

On the spectrum of commercial maturity, the two-tank indirect molten salt system represents the current state-of-the-art for thermal energy storage, with one project recently completed and several more scheduled to begin construction. Two-tank direct systems are close behind, both for central receiver CST plants and parabolic trough plants if molten salt proves viable in a parabolic trough collector field. The logical next step for the concrete block, thermocline, and PCM systems is a pilot plant or a small commercial unit that can validate the operation of the storage system outside of the laboratory. Given the expanding numbers of CST plant deployments, there is ample room for further development in the field of thermal energy storage. In addition to further testing and validation in the field, standardized design and modeling procedures for each of the various storage systems would be a valuable addition to TES system design to improve the design process and speed up production and deployment of thermal energy storage systems.

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HISTORICAL EXPERIENCE WITH TES

This excerpt was provided courtesy of the National Renewable Energy Laboratory:

> Pilkington Solar International, “Survey of Thermal Storage for Parabolic Trough Power Plants”, Prepared for NREL, Subcontract Number AAR-9-29442-06 under Prime Contract DE-AC36-98GO10337. 2000.

State of the Art

Existing TES Systems in Solar Thermal Plants

Of eight installed thermal energy storage systems in solar thermal electric plants, seven have been of an experimental or prototype nature and one has been a commercial unit. Table A-1 gives the characteristics of the existing units. All have been sensible heat storage systems: two single-tank oil thermocline systems, four single medium two-tank systems (one with oil and three with salt) and two dual medium single-tank systems. To put the size of these systems in perspective, a 30-MWe SEGS plant with a plant efficiency of 35% would require about 260 MWht for a 3-hour storage capability. This is considerably larger than any other solar thermal electric storage system built up to now.

All of these systems were successful to varying degrees, recognizing that most were development units that were expected to reveal design flaws or issues as a basis for future design improvements.

Two important characterizations of storage systems are the "round-trip efficiency" and the cost per unit of thermal energy delivery ($/kWt). The round-trip efficiency is, simply, the ratio of the useful energy recovered from the storage system to the amount of energy initially extracted from the heat source. This efficiency is affected by the laws of thermodynamics and by heat losses in the tanks, piping, and heat exchangers in the system; electric parasitic losses needed to circulate storage system fluids constitute additional losses.

Efficiency and cost experience from existing systems are informative but of limited relevancy to commercial plants because most of the existing facilities were one-of-a-kind development projects. Nevertheless, round-trip efficiencies of more than 90% were measured in many of the systems listed in Table A-1, though some systems were as low as 70%. Both the oil systems and molten salt systems were shown to be technically feasible. While various problems arose due to mistakes in design, construction or operation, no fundamental issues surfaced for these approaches.

The SEGS I storage system cost $25/kWt in 1984 dollars, with the oil representing 42% of the investment cost. The oil used in the later SEGS plants for operation up to 400°C costs approximately eight times more than the SEGS I oil. This was reason enough that a storage system similar to the SEGS I storage concept was not repeated in later SEGS plants. However, there were other important considerations, such as total system investment, very large tank size requirements, and inflexibility compared to a back-up system.

Table A-1
Existing TES Systems

Project	Type	Storage Medium	Cooling Loop	Nominal Temperature Cold (ºC)	Nominal Temperature Hot (ºC)	Storage Concept	Tank Volume (m^3)	Thermal Capacity (MWh_t)
Irrigation pump Coolidge, AZ, USA	Parabolic Trough	Oil	Oil	200	228	1 Tank Thermocline	114	3
IEA-SSPS Almeria, Spain	Parabolic Trough	Oil	Oil	225	295	1 Tank Thermocline	200	5
SEGS I Daggett, CA, USA	Parabolic Trough	Oil	Oil	240	307	Cold-Tank Hot-Tank	4160 4540	120
IEA-SSPS	Parabolic Trough	Oil Cast Iron	Oil	225	295	1 Dual Medium Tank	100	4
Solar One Barstow, CA, USA	Central Receiver	Oil/Sand/ Rock	Steam	224	304	1 Dual Medium Tank	3460	182
CESA-1 Almería, Spain	Central Receiver	Liquid Salt	Steam	220	340	Cold-Tank Hot-Tank	200 200	12
THEMIS Targa-sonne, France	Central Receiver	Liquid Salt	Liquid Salt	250	450	Cold-Tank Hot-Tank	310 310	40
Solar Two Barstow, CA, USA	Central Receiver	Liquid Salt	Liquid Salt	275	565	Cold-Tank Hot-Tank	875 875	110

Summary of Work Performed Before 1990

This section reviews the most relevant investigations and evaluations carried out prior to about 1990. Selected literature from this period has been listed in the References, but only selected works are explicitly discussed here. A valuable overview of the applicability of thermal storage to solar power plants was provided by Geyer 1991. Table A-2 shows the storage systems initially considered there, though of these only a few were investigated in detail. The final systems are listed in the following paragraphs.

Dual medium sensible heat systems

Two single-tank alternatives were analyzed, one in which HTF oil flows through a storage medium of concrete and another in which the storage medium is solid salt. Cast iron and cast steel were eliminated as storage media due to high cost, even though they offered thermodynamic advantages.

Table A-2
Candidate Storage Concepts for SEGS Plants

TES Concepts	Storage Type	Status*	Assessment
Sensible Active	Two-Tank Oil	T	Basic concept, state-of-the-art
	HITEC	T	2 variants analyzed based on existing PSA/THEMIS designs
	Thermocline	T	Proved on pilot scale, no advantages over basic two tank system
Sensible DMS	Oil/Cast Iron	T	Proved on pilot scale, no advantages over basic two tank system
	Oil/Steel	LR	Used in chipboard presses
	Oil/Concrete	MR	Several variants analyzed
	Oil/Solid Salt	MR	Several variants analyzed
PCM	Oil/PC Salts	HR	Several cascade arrangements analyzed
Chemical	Oil/Metal Hybrids	HR	Early state of development, no lead concepts, no cost data
* Nomenclature: T: Tested / LR: Low Risk / MR: Medium Risk / HR: High Risk			

Sensible heat molten salt system

A two-tank system (similar to SEGS I) utilizing the HITEC salt was chosen. HITEC is a eutectic mixture of 40% $NaNO_2$, 7% $NaNO_3$ and 53% KNO_3 with a 142°C melt-freeze point.

Phase-change systems

These higher-risk systems were judged to have high uncertainty in technical feasibility and cost, but were evaluated for their potential in this application. Three different phase change concepts were evaluated. The first was a LUZ design using five PCMs in a series, or cascade, design (SERI 1989); the second was a design by the Spanish company INITEC, which also used five PCMs but in a different heat exchanger configuration; the third design originated with the German companies Siempelkamp and Gertec (SGR) and used three commercially available PCMs along with concrete for the higher temperatures.

Overview of Results

Storage system designs for the SEGS conditions based on these five concepts were developed in Dinter et al. 1990. Summary results are presented here giving overall system volume, thermal storage capacity and utilization, and specific costs in $/kWht of capacity.

The utilization measure is an interesting aspect of storage systems. Earlier discussion described some of the aspects of temperature differences within the HTF fluid and between the HTF and a solid storage medium. Another aspect of storage design is the temperature difference within the medium itself. In a two-tank liquid system, for example, the entire fluid is heated to a charged temperature and hence the entire storage medium is utilized. PCM systems theoretically also have very high utilization factors. In a solid system, however, temperature gradients required for thermal conduction through the media itself prevent full utilization of the material. In this case, 100% utilization would be achieved if the entire solid medium were heated to the full charging temperature. Hence, the "potential" storage capacity might be two or three times higher than the practical storage capacity. Detailed heat transfer calculations on specific designs provide this type of information.

Figure A-1 gives results on the total volume, storage capacity and utilization, and specific cost of the six candidate systems analyzed for SEGS plants. For comparison purposes, we will select the INITEC PCM design as representative of the PCM class, with the qualifier that there is much more uncertainty and technical risk in the PCM results than in the sensible heat oil-solid systems or in the sensible heat HITEC molten salt system.

With regard to volume, the concrete and salt media fill about 6,900 and 5,200 m^3 of space, respectively, whereas the molten salt and PCM system need 2,600 m^3. If the cross-sectional area perpendicular to the flow measured 13m by 13m, the length of the concrete system would be 41 m compared to a 15-m length for the PCM system. A major reason for the larger sizes of the concrete and solid salt systems is the poor volume utilization. The concrete system, for example, is utilized at 36% of its full potential capacity. The molten salt and PCM systems, on the other hand, have utilization factors up to 100%. The concrete system does, however, have cost advantages due to the very low cost of concrete, which results in a low system cost even though there is more structure required for this larger volume system.

Generally, the storage costs developed in this assessment vary from $25-$50/kWht (on the order of $65-$130/kWhe). At the low end, TES units of 270 and 450 MWht capacity would have a capital cost of 6.8 MUSD and 11.3 MUSD, respectively.

Figure A-1
Results of TES Evaluations for Reference SEGS Plant (Dinter et al. 1990)

SEGS TES Workshop

A symposium workshop (SERI 1989) on TES systems for SEGS plants, held in 1989 and sponsored by the Solar Energy Research Institute (SERI.now the National Renewable Energy Laboratory.NREL), discussed several of the options presented above. While the workshop focused on phase-change material concepts, both sensible heat storage and chemical storage were also included in the agenda. The more detailed evaluations reported in Dinter et al. 1990 were completed subsequent to the workshop.

With respect to sensible heat storage, the workshop concluded that this approach could result in a cost-effective system. While no new research would be required, thorough and careful engineering development and small-scale testing would be necessary. Issues such as thermal expansion, potential leakage, heat transfer configuration, and heat exchange optimization require more detailed design within the context of a design concept.

Latent heat (or phase-change) storage was considered to be in a more primitive state of development. While the concept is promising, considerable research, system development, and proof-of-concept testing would be required. Concerns on heat transfer characteristics and heat exchange configuration were expressed. Of several possible configurations, it was concluded that both shell-and-tube heat exchangers and a system of encapsulated particles of phase-change salts were worthy of exploration, with the latter approach having both more potential for cost-effectiveness and a lower probability of success.

Experience and Research on TES Since 1990

To analyze the work that has been done since 1990 on thermal storage for troughs, a thorough literature review was carried out. This review included a computerized literature search in the Energy Technology Data Exchange (ETDE) Energy database.

The ETDE Energy Database contains more than 3.8 million bibliographic records with abstracts for energy research and technology information from around the world. The EDTE, a multilateral information exchange program, was established in 1987 under the auspices of the International Energy Agency (IEA). Member countries share their energy research and technology information through the Energy Database. The database covers journal articles, research reports, conference papers, books, dissertations, computer software, and other miscellaneous types. Of all the records, 7.1% are devoted to energy storage and conservation.

Sixty-five references that met the criteria defined through the keywords were identified. After evaluating the 65 abstracts, a lesser number (21) were applicable to TES systems in parabolic trough technology.

Table A-3, summarizing the literature analysis, lists all identified works that may help in the selection of a candidate storage concept. The main results for the most promising options are discussed below.

Table A-3
Results from Literature Review (after 1999)

Author	Year	Storage Concept	Type of Work*	Temperature Range	Capacity
M. Mitzel et al.	1990	Hydrid/Magnesium Thermochemical Storage	TH	?	--
Brown et al.	1991	Oxide/Hydroxide chemical storage	TH	300ºC-400 ºC	--
D. Steiner, M. Groll	1995	MgH2/Mg Chemical Storage	EX-LS	280ºC-480 ºC	14 kWh
K. Lovegrove A. Luzzi et al.	1999	Ammonia Based Thermochemical Storage	EX-LS	450ºC-650 ºC	?
B. Beine, F. Dinter, R. Ratzesberger et al.	1992	Concrete	EX-LS	290ºC-400 ºC	50 kWh
J. Pacheco, D.B. Kelly et al.	1999	Molten-Salt 2-Tank	EX-FS	290ºC-566 ºC	114 MWh
H. Michels, E. Hahne	1996	Cascaded PCM	EX-LS	250ºC-450 ºC	8.5 kWh

* TH theoretical work

EX-LS experimental work in lab scale

EX-FS experimental work in full scale

In addition to the experimental works listed in Table A-3, more theoretical works on TES were performed by Brower 1992, Lund 1994, Meier and Winkler 1993, Steel and Wen 1981, and Steinfeld et al. 1991.

Overview of Progress

Experience at Solar Two

The most significant recent work on molten salt storage comes from the experience in the Solar Two Project. This prototype facility, decommissioned in 1999, was a 10-MW power tower system using a nitrate eutectic molten salt as the HTF. A schematic of the system is shown in Figure A-2. Molten salt is pumped from the cold storage tank through the tower receiver and then to the hot storage tank. When dictated by the operation, the hot salt is pumped through the steam generation system and then back to the cold tank. Solar Two is capable of producing 10 MWe net electricity. A number of lessons on the equipment design, material selection, and operation of molten salt systems were learned during the 1-1/2 years of testing and evaluation.

Figure A-2
10 MW_e Solar Two Central Receiver Project in Barstow, California

Solar Two used an efficient, molten nitrate-salt thermal-storage system (Pacheco and Gilbert 1999). It consisted of an 11.6-m-diameter by 7.8-m-high cold-salt storage tank, a 4.3-m-diameter by 3.4-m-high cold-salt receiver sump, an 11.6-m-diameter by 8.4-m high hot-salt storage tank, and a 4.3-m-diameter by 2.4-m-high hot-salt steam generator sump. The design thermal storage capacity of the Solar Two molten salt system was 105 MWh_t–enough to run the turbine at full output for 3 hours. The measured gross conversion efficiency of the 12-MWe (10-MWe-net) Solar Two turbine was 33%. Actual thermal storage capacity based on the mass of salt in the tanks, accounting for (subtracting) the 3-foot heels in each tank, and with design temperatures–1050°F hot salt, 550°F cold salt–was 114 MWh_t.

The system contained 1.5 million kilograms of nitrate salt composed of a mixture of 60% $NaNO_3$ and 40% KNO_3, provided by Chilean Nitrate Corporation (New York). This salt melted at 220°C and was thermally stable to about 600°C.

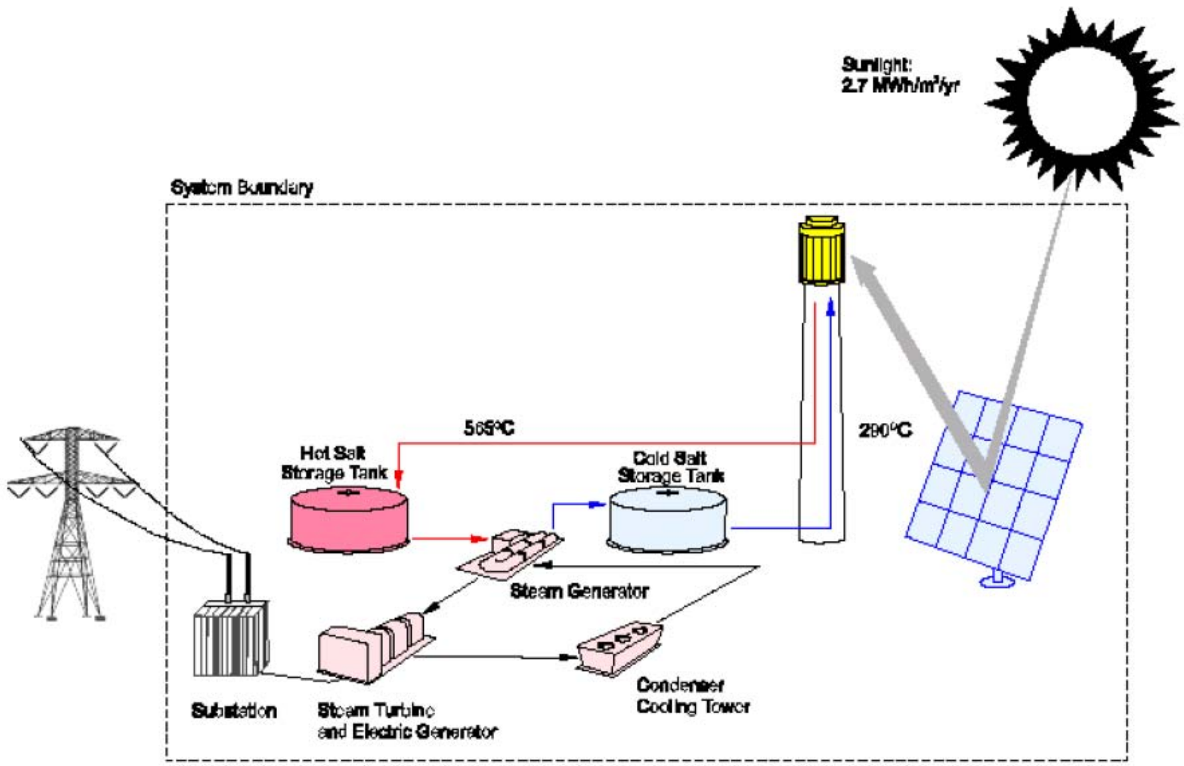

Figure A-3
Molten Salt Power Tower System Schematic

Heat Losses

Several tests were conducted to quantify the thermal losses of major pieces of equipment throughout the plant and to compare the values to calculated estimates. The major pieces of equipment evaluated were the hot tank, cold tank, steam generator sump, and receiver sump. There were two methods of measuring the thermal losses in the tanks and sumps. One method was to turn off all auxiliary heaters and track the rate of decay of the average tank or sump temperature. By knowing the salt level, and thus the volume of salt in the vessel, an estimate of the heat loss could be made. Another method was to have the heaters energized and regulate the inventory at a set temperature. Once the vessel was at steady state, the power consumption of the heaters was measured over a long period of time. The electrical power consumption was assumed to be equal to the heat loss rate.

A summary of the measured and calculated thermal losses is shown in Table A-4. The thermal losses for the tanks and sumps were equal to the calculated values within experimental error, except for the steam generator sump heat loss rate. The losses for the steam generator sump were higher than predicted, possibly because the insulation may have degraded significantly since it was installed. Salt had leaked out of the sump through flanges and into the insulation, which adversely affected its insulating properties. Based on the measured heat loss rates, the total energy lost to the environment over the course of a typical operating year corresponds to a 98% annual thermal efficiency.

Table A-4
Measured and Actual Thermal Losses of Major Equipment

Major Equipment	Calculated Thermal Loss, kW	Measured Thermal Loss, kW
Hot Tank	98	102
Cold Tank	45	44
Steam Generator Sump	14	29
Receiver Sump	13	9.5

Operating Experience[33]

The capacity of the system is a function of the hot and cold salt temperatures. Hot salt temperatures at the bottom of the downcomer were typically only 1025°F because some of the isolation ball valves between the riser and downcomer leaked, attemperating the salt coming out of the receiver (which typically exited at 1050°F). The lower salt temperature derated the capacity of the thermal storage system by 5% to 108 MWht.

The fractional amount of the energy sent to thermal storage that was later discharged to the steam generator to make electricity is nearly 1, but is a function of the availability. The thermal losses are basically a fixed loss to the environment. When the plant availability is high, the collected energy increases and the losses are a smaller fraction of the total energy sent to storage. For example, on Dec. 2, 1997, on a sunny winter day, the receiver collected 217 MWh, which was sent to the steam generator system to make electricity. Based on a constant thermal loss of 185 kW from the hot and cold tanks, and the receiver and steam generator sumps, the total energy lost to the environment that day was 185kW x 24 h = 4.43 MWh or 2.0% of the collected energy. In contrast, on a sunny summer day.June 18, 1998.the receiver collected 334 MWht and the thermal losses were 1.3% of the collected energy. Even with the very prototypical nature of Solar Two (i.e., poor availability, frequent outages, first year operation, etc.), over several months the fractional amount lost to the environment was only 6% of collected energy. If the plant ran with higher availability, i.e., typical mature operation, the factional amount of stored energy lost to the environment would only be about 2% of collected energy.

There were no major operational problems with the thermal storage system and, in general terms, the system ran satisfactorily. Typically, the plant started using the stored energy within an hour or two after the receiver began collecting energy. Scenarios were also run, however, to demonstrate dispatching energy several times or to demonstrate the production of a constant output of electricity at night and through clouds. A number of practical lessons were learned, and no barriers to future implementation were evident.

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[33] Comments provided by James Pacheco, Sandia National Laboratories Albuquerque, December 15, 1999.

Concrete

Limited prototype testing has been done on the concrete-steel thermal storage concept. Between 1991 and 1994, two concrete storage modules were tested at the storage test facility at the Center for Solar Energy and Hydrogen Research (ZSW) in Stuttgart, Germany (Ratzesberger et al. 1994). Figure A-3 shows the prototype concrete module installed in the center's laboratory.

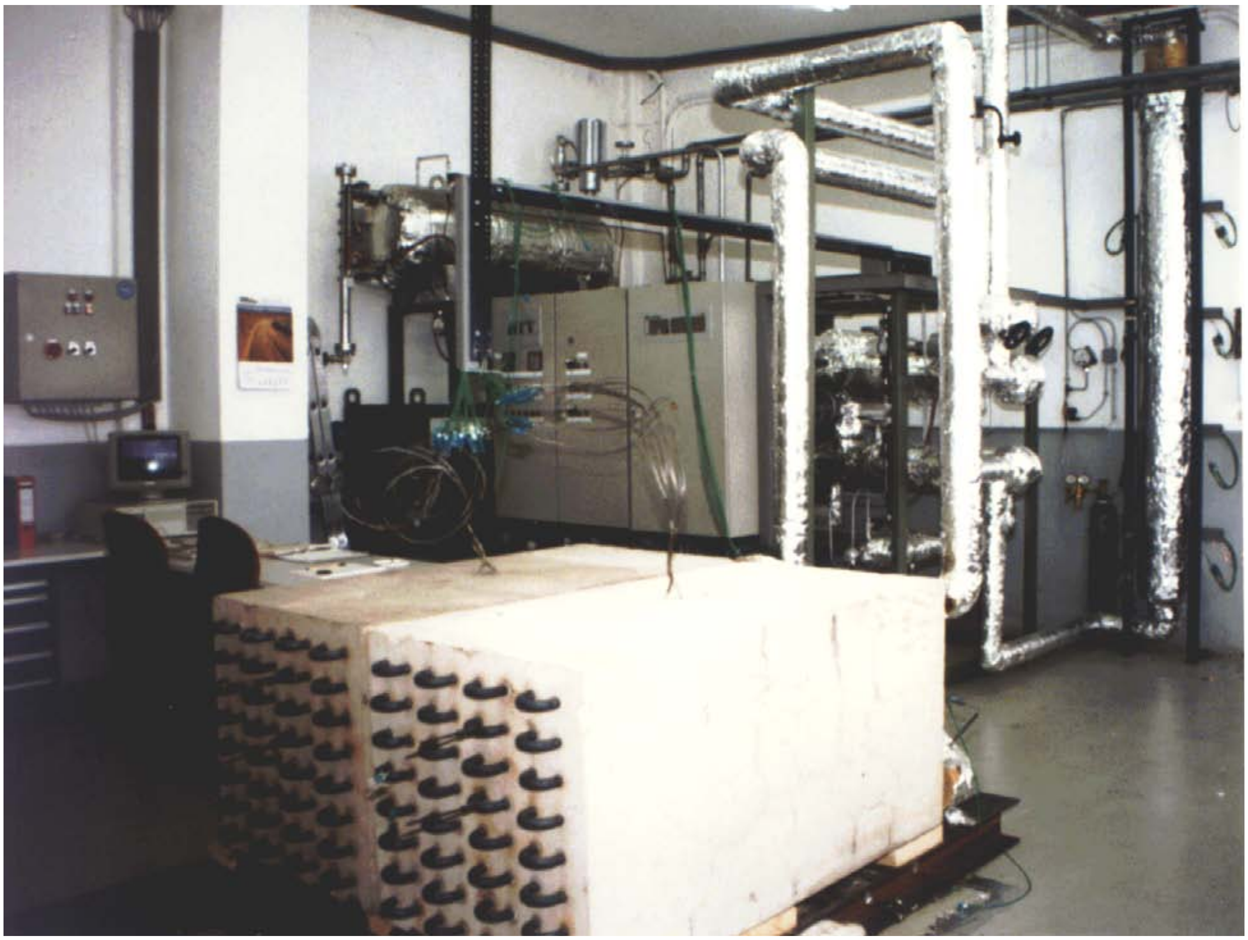

Figure A-4
Test Facility for TES With Two Concrete Storage Modules at ZSW

The test results gained at ZSW in principle confirm the performance predictions given by Baddruddin, Dinter et al. 1992. Based on these tests, a numerical calculation model for concrete storage was developed by Ratzesberger 1995. He also proposed a slightly different design that results in the same performance but with considerably lower pressure loss in the storage module. According to his results, the pressure loss in a 200-MWh module can be reduced from 4.3 to 1.9 bar. The integration of a sensible heat storage system like concrete storage into a SEGS plant is depicted in Figure A-4.

Ratzesberger recalculated the cost for storage and obtained a price of $40/kWh in 1994 U.S. dollars. This is slightly higher than the number given by Dinter. As a next step in the development of concrete storage, a project has recently been proposed to the EU (European Union) by a European team (CONTEST 1999). The proposed project consists of a prototype module with a capacity of 1.2 MWh to be erected at the PSA and connected to a parabolic trough solar field. The project, if funded, will be led by the German company Siempelkamp Giesserei GmbH & CO KG. In the company's proposal, it is projected that storage costs of $26/MWh in commercial scale can be realized.

Summarizing the work performed on concrete storage up to now, it can be concluded that this concept presents a relatively cheap option of thermal storage. The feasibility has already been proven in laboratory tests. The highest uncertainty still remains in the long-term stability of the concrete material itself after thousands of charging cycles. Special tests in a climatic chamber dedicated to investigation of this potential problem are included in the aforementioned EU proposal.

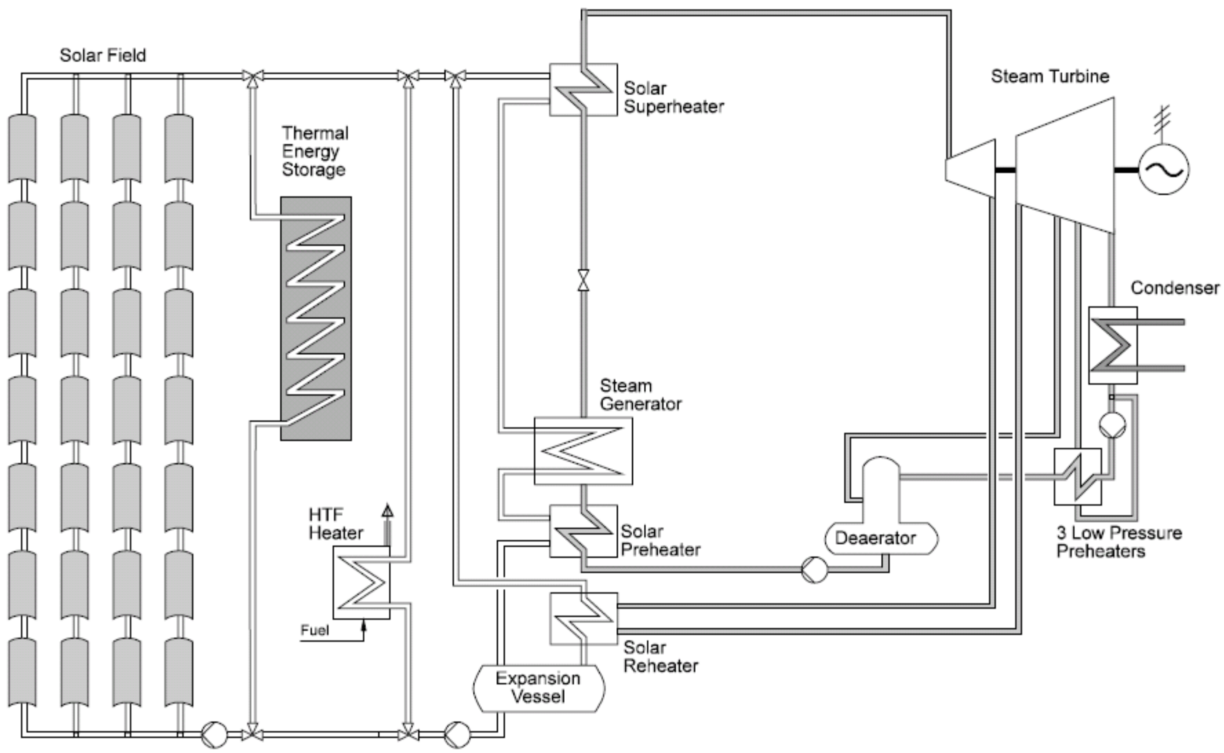

Figure A-5
Schematic Diagram of a SEGS Plant With TES

Phase Change Material

Following the recommendations of the SERI workshop held in 1988 (SERI 1989), the ZSW, Germany, started to investigate storage using PCM. It was found by Dinter et al. 1990 that PCM storage has a relatively high heat capacity per volume and offers the lowest cost of all concepts investigated in this study (see also Figure A-1).

A storage test facility has been set up in ZSW.s laboratory allowing the investigation of various storage concepts independent from the sun. Electrical heating is the heat source, and a cooling tower is the heat sink. Figure A-5 shows the flow diagram of the test loop with three PCM modules connected to the system. The modules can be charged by the HTF flow separately or connected to each other in series or in parallel.

A major objective was to investigate the heat transfer mechanism of different PCM salts during phase change and of liquid salts (Hunold et al. 1994, 1992, 1992, and 1994). In the work of Hunold, only one storage module filled with one salt was investigated in each case. Hunold showed that phase change storage is technically feasible and proposed a storage design built out of a shell and tube heat exchanger in a vertical orientation. By adjusting the vertical orientation of the tubes, natural convection and heat transfer can be improved. He selected the nitrate $NaNO_3$, with a melting point at 305°C, as appropriate storage material for the SEGS-type power plants.

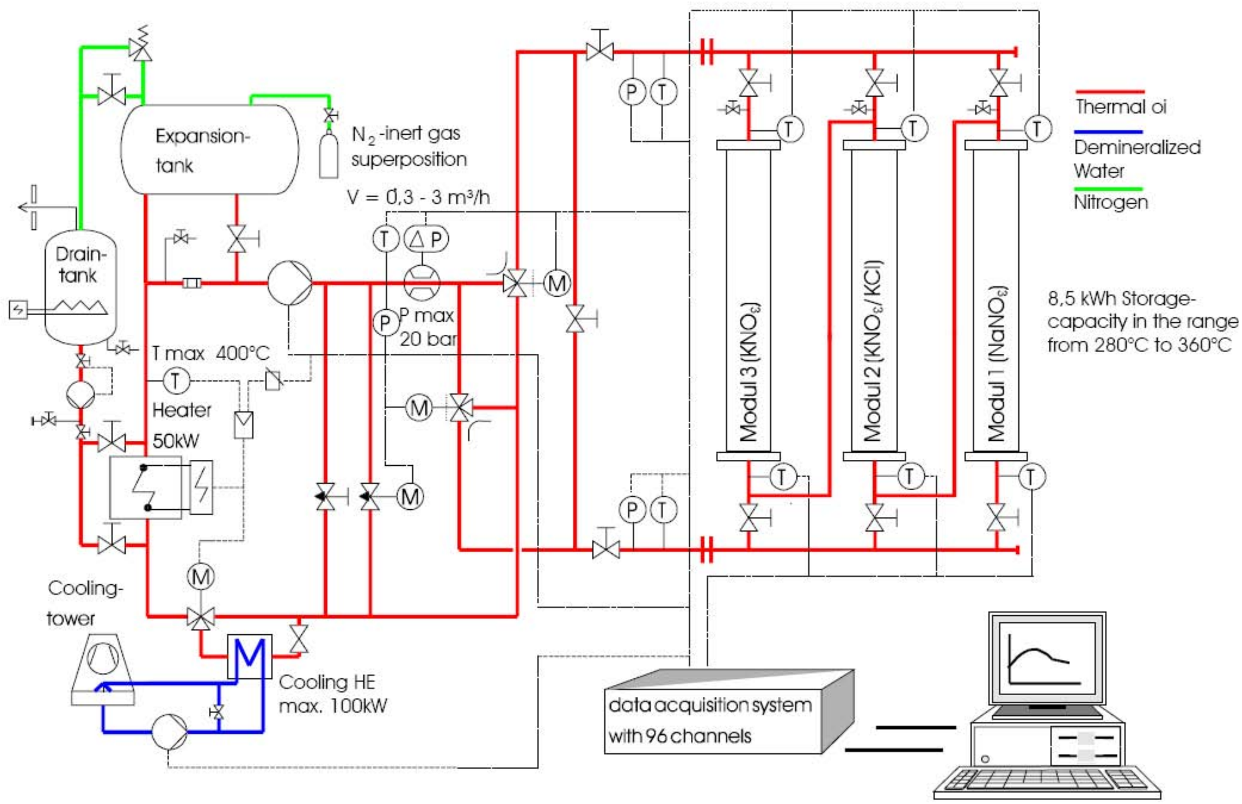

Figure A-6
Flow Diagram of Storage Test Loop at ZSW (Michels and Hahne 1996)

However, one can only take full advantage of PCM storage by connecting several modules with different salts and different melting points in series as shown in Figure A-6. Michels 1996 explained, by means of Figure A-7, the reason for this. The left diagram shows the HTF temperature at the end of charging and discharging and the melting temperature of a single-stage salt storage as investigated by Hunold. During discharging the HTF temperature in the biggest part of the storage module is higher than the melting temperature of the salt. This means that a major portion of the salt would not freeze during discharging and the high latent portion of the stored heat can not be extracted from the storage. Consequently, the utilization factor of the system would be relatively low.

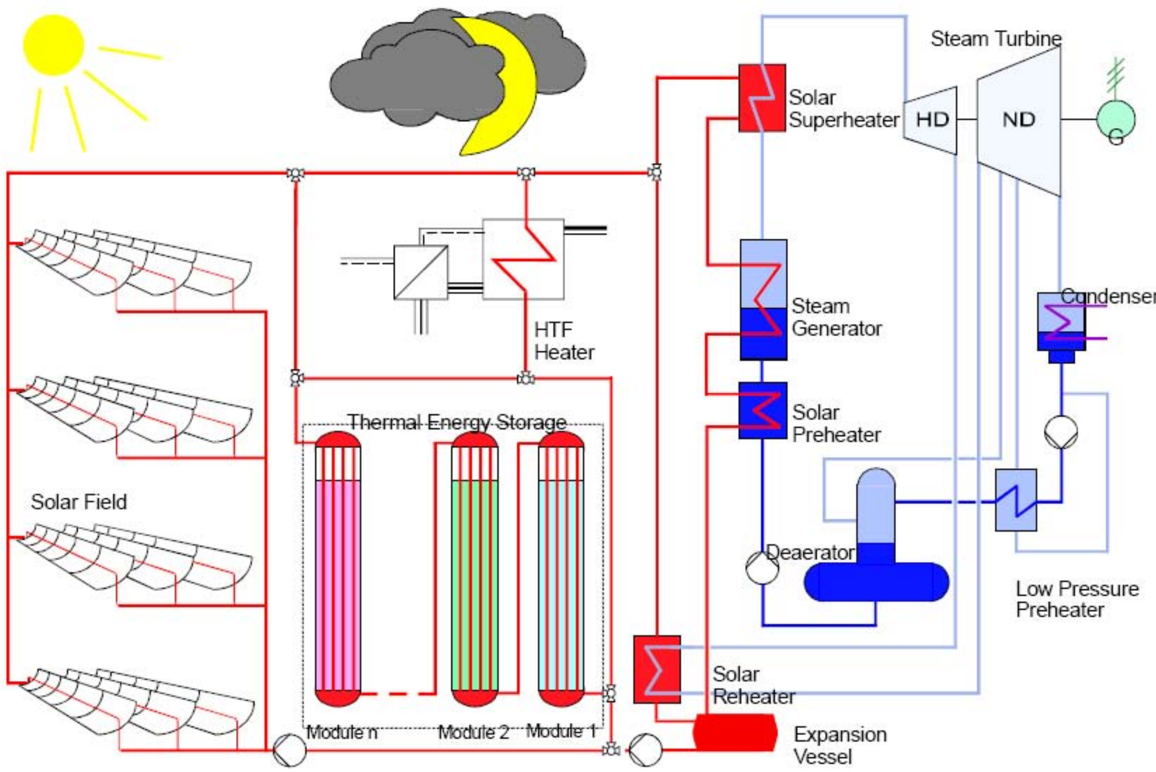

Figure A-7
Possible Process Scheme of a SEGS With Integrated PCM-TES (Michels and Hahne 1996)

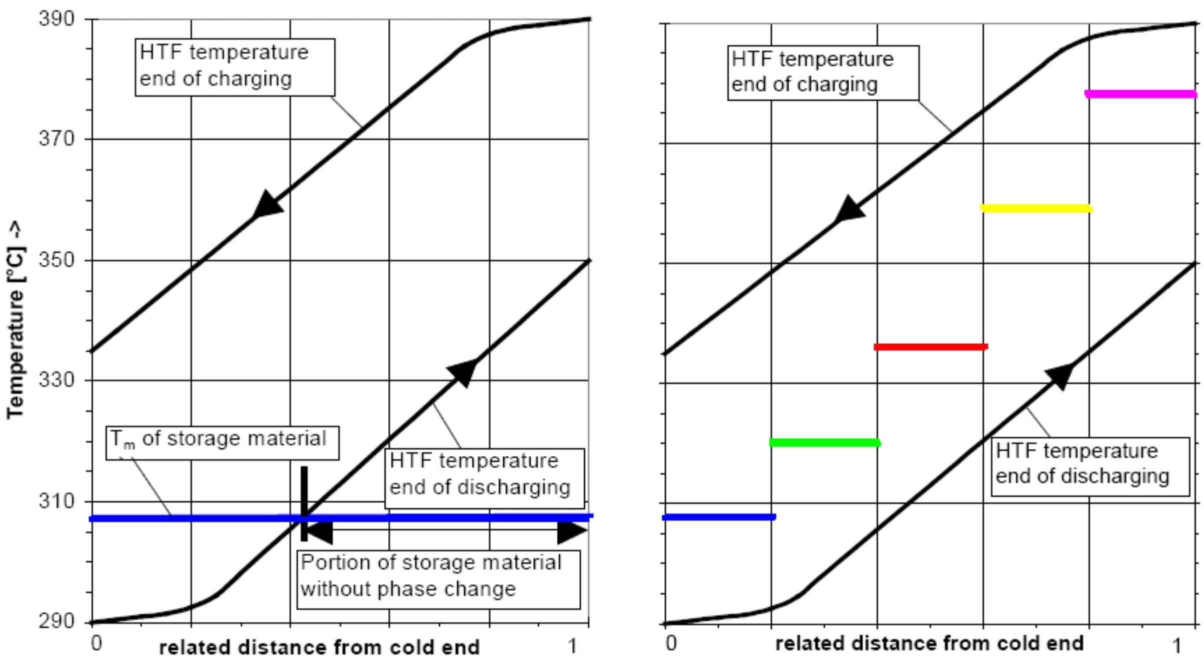

Figure A-8
Theoretical Temperature Distribution in a PCM-TES for SEGS

The latent heat can only be used completely if, during charging, the temperature of the HTF is always higher than the melting point of the storage medium and, during discharging, always lower. This is shown in the right-hand diagram of Figure A-7. According to Michels, five different PCMs have to be used for an optimized storage operating in the temperature range of a SEGS plant.

Michels experimentally investigated a configuration of three different modules connected in series (Michels and Hahne 1996). He used the nitrates KNO_3, KNO_3/KCl and $NaNO_3$. Figure A-8 shows the measured temperature distribution in the test modules during charging.

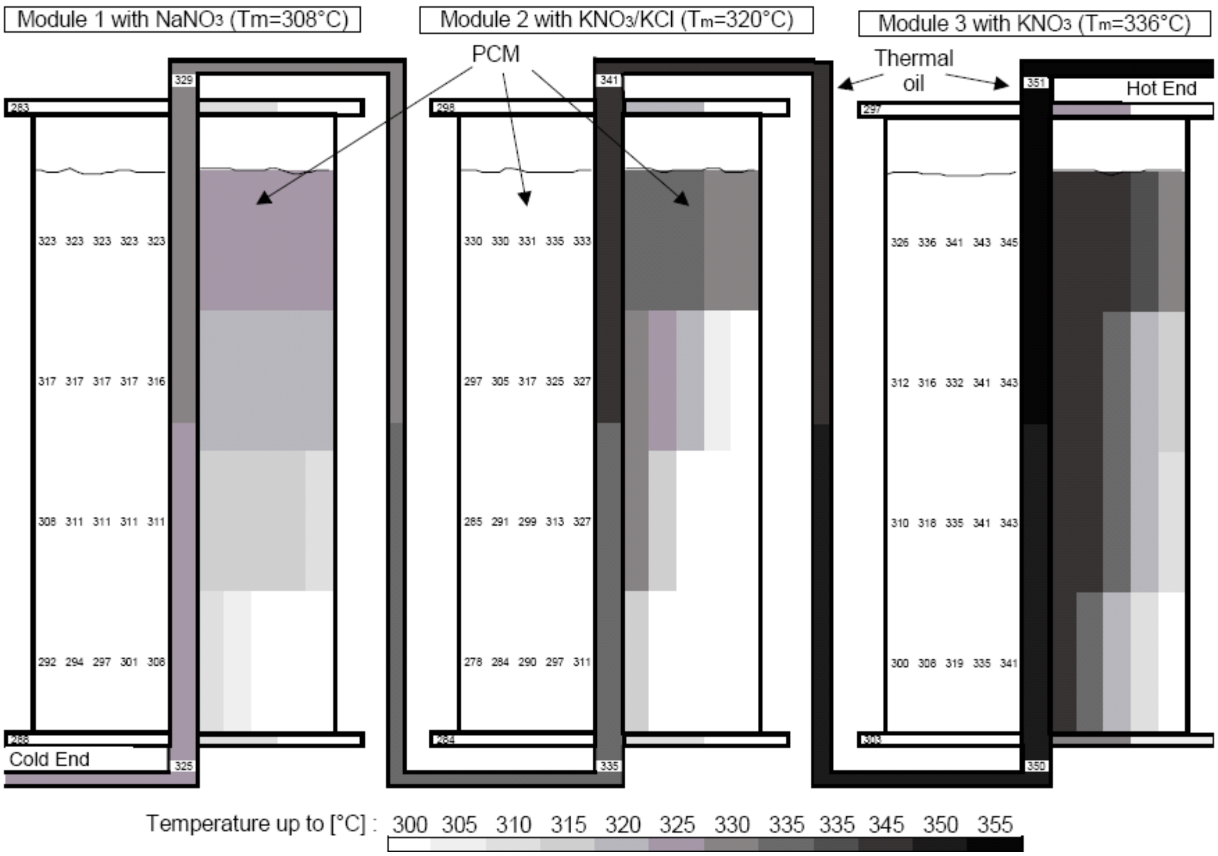

Figure A-9
Temperature Distribution Inside the Cascaded PCM Test Modules During Charging

In his experiments, Michels proved the high utilization factor of a cascaded PCM storage. However additional experiments are required to verify the feasibility of a five-stage cascaded storage. Also additional design studies have to be performed to optimize the sizes of each stage, to select the appropriate material for the storage tank for each salt and to evaluate the cost.

Further works are concerned with PCM as storage material for parabolic troughs with Direct Steam Generation (Solomon 1991) and with the development of special measurement devices to observe the phase-change (Jaworske 1991).

A combined configuration of one sensible heat storage module, like concrete, and of two PCM modules at each end as proposed by Ratzesberger et al. (1994) seems to be a reasonable approach as a next step in the development of PCM storage.

Chemical Energy Storage

In the SERI workshop it was concluded that chemical energy storage is an attractive option in longer term and may offer relatively low cost. Based on a preliminary cost assessment the hydroxide/oxide reaction between CaO and H_2O was mentioned as one possibility (NASA 1979).

Subsequently, the Pacific Northwest Laboratory (PNL.now the Pacific Northwest National Laboratory.PNNL) conducted a study funded by the U.S. Department of Energy to investigate the potential feasibility for a chemical energy storage based on this reaction. The report (Brown et al. 1991) concluded that this type of storage is, in principle, applicable under the SEGS temperature conditions. However, the study was based only on theoretical analysis and basic experimental investigations, and information was somewhat limited due to proprietary restrictions. The authors could not determine if the dynamics of the reaction fit to the requirements of storage for solar power plants, and also concluded that the question of proper integration into the solar power system remained unsolved. Costs were roughly estimated to be about $45/kWh. No further development of this type of storage could be identified through the literature review, and it appears that considerable work is required to develop a chemical energy storage system with hydroxide/oxide reaction for commercial application.

Development of another type of chemical storage seems to be much advanced, namely the solar ammonia energy storage developed by the Australian National University (Kreetz and Lovegrove 1999, Lovegrove et al. 1999, and Luzzi et al.). In this system, liquid ammonia is dissociated in a solar reactor into hydrogen and nitrogen. The energy is recovered in an ammonia synthesis reactor. The ammonia system was developed for use with parabolic dishes, but theoretically can also be used in the temperature range of parabolic trough collectors.

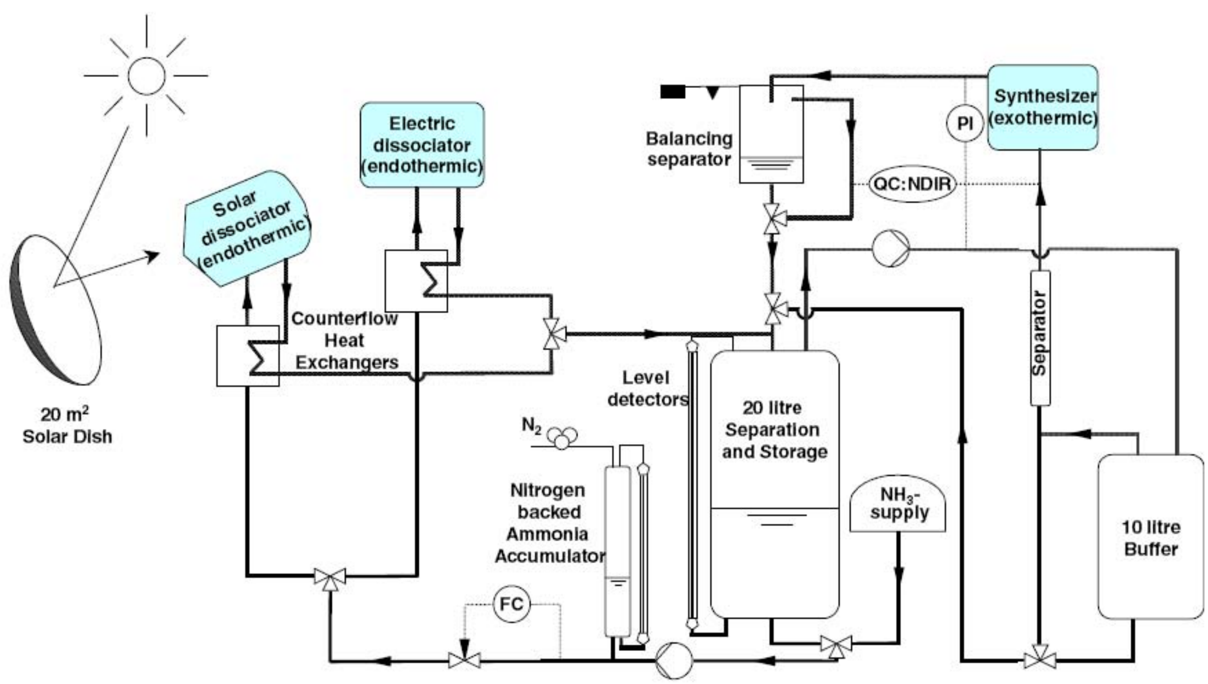

Figure A-10
Test Loop Set Up for Solar Ammonia Energy Storage (Lovegrove et al. 1999)

The first small-scale solar test facility was set up and has been operating for more than a year. Figure A-9 shows the flow diagram of the test installation. The nominal solar input into the system is 1 kW. At this scale, it is clear that potential scale-up to a multimegawatt system would be a significant undertaking.

Current estimates are that a 10-MW plant built largely from industry standard or proven components will cost about $100 million (U.S. 1999) (Luzzi et al.).

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