THERMAL ENERGY STORAGE

10/11/2013

INTRODUCTION

Energy storage is contemplated to compensate for the intermittence that characterizes the renewable energy sources of:

1. Hydroelectric power,
2. Wind power,
3. Solar thermal
4. Geothermal energy,
5. Solar Photo-Voltaic, PV,
6. Biomass.
7. Wave and tidal systems.

With their wide acceptability in the world and their adoption, the price of the energy produced from them is expected to decrease with their increased market penetration.

Table 1. Projected electrical energy costs.

Production method	Production cost [¢/kWhr]	
	2009	2020-2030
Concentrated Solar Power, CSP	15-40	4-10
Wind Power	4-15	3-8
Solar Photo Voltaic, PV	25-80	6-25
Coal	3.5-6.0	4-5.5
Coal with Carbon Capture and Storage, CCS	-	6.0-8.5
Natural gas	4-7	5-8
Natural gas with Carbon Capture and Storage, CCS	-	7-10

FUTURE PROSPECTS

Theoretically, 3 percent of the area of the Sahara Desert if covered with Concentrated Solar Power, CSP plants could meet the present world’s electricity demand.

In the Desertec initiative, European companies such as Siemens, Deutsche Bank, E.On, and ABB are aiming at developing Wind and CSP plants in the Middle East and North Africa to supply 15 percent of Europe’s electricity demand by 2050.

CSP is best deployable in regions with high insolation between 35 degrees in latitude south (e. g. Buenos Aires, Cape Town, Canberra) and north (e. g. Memphis, Tehran, Kyoto, Gibraltar).

A classification according to operational conditions of CSP plants are:

1. Low temperature collectors used for instance for swimming pools heating or bath showers.
2. Medium temperature collectors producing hot water for residential and commercial buildings.
3. High temperature installations to produce electricity.

Whilst PV converts solar radiation into electricity, CSP uses a thermodynamic cycle such as the Stirling, Brayton (Gas turbine) or the Joule (Steam cycle) for the conversion process. CSP methods are more appropriate than PV for the central station utility oriented generation of electricity.

An advantage of CSP is that it readily offers the possibility of energy storage, allowing extended turbine operation when the sun is not shining during the night or on cloudy days. Thermal energy storage avoids the thermal cycling, detrimental to components, of a plant that operates during the day and is shut-down during the night.

Solar thermal energy can be stored in solid or liquid media such as concrete, ceramics or molten salts. This allows for peak and base load power operation.

In the Joule Steam cycle version, solar radiation is concentrated using reflectors unto a receiver that contains the heat transfer medium such as synthetic oil. The heat transfer medium is pumped through heat exchangers generating steam that drives a steam turbine to produce electricity.

CSP plants can use hybrid operation where using alternative fuels such as natural gas to produce power during the night or on cloudy days.

These plants work essentially like conventional power stations drawing on the experience of existing technologies with operational and contemplated systems with power capacity of 50-1000 MWe.

THERMAL STORAGE FOR RENEWABLE SOURCES OF ENERGY

The thermal storage of the energy generated in renewable systems can overcome the intermittency problem, particularly in wind and solar systems. In solar power plants, storing solar thermal energy allows its usage during non-solar periods and to dispatch the generated electricity during peak demand hours.

It is suggested that Thermal Energy Storage, TES could raise solar thermal power plant annual capacity factors from 25 percent without thermal storage to 70 percent.

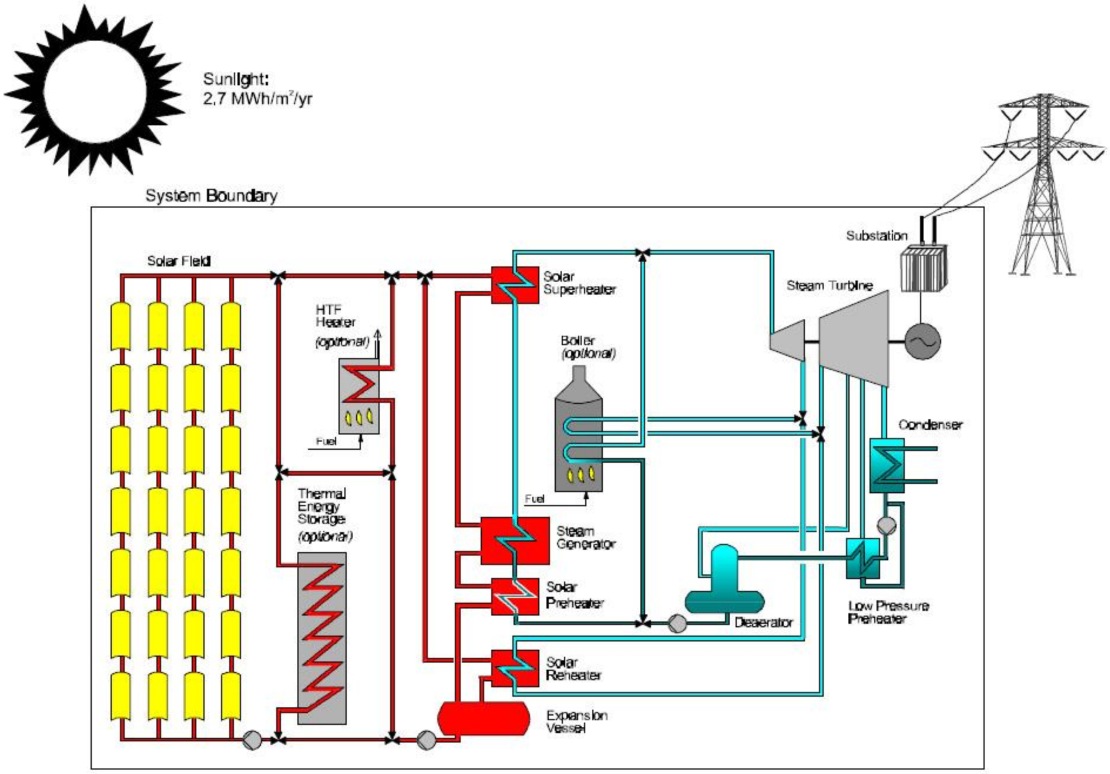

Figure 1. Thermal energy storage and auxiliary heating using an Heat Transfer Fluid (HTF) unit in a solar Rankine cycle with solar superheating thermal system [1].

Table 2. Eutectic mixtures for thermal energy storage [2].

Composition, [wt %]	Melting Point [^{o}C]	Latent Heat	
		[Kcal/kg]	[KJ/kg]
$CaCl_2$-$MgCl_2$-H_2O 41-10-49	25	41.7	175
$Mg(NO_3)_2.6H_2O$-$Al(NO_3)_3.9H_2O$ 53-47	61	35.4	148
Acetamide-Stearic Acid 17-83	65	52.0	218
Urea-NH_4NO_3 45.3-54.7	46	41.0	172

Table 3. Heat capacities and heat of fusion of energy storage materials used in flat-plate solar collectors [2].

Material	Heat Capacity C_p [KJ/(kg.^{o}C)]	Heat of fusion ΔH [kJ/kg]	Temperature T [^{o}C]	Density P [kg/m^3]
Water, liquid	4.19	-	-	1,000
Water, ice	2.2	334	0	-
Rock	0.88	-	-	2,500-3,500

Iron	0.50	-	-	7,860
$Na_2SO_4.10H_2O$ solution		215	31	1,460

THERMAL ENERGY STORAGE MATERIALS

HIGH TEMPERATURE CONCRETE, CASTABLE CERAMICS

Figure 2. Concrete thermal energy storage unit.

Concrete is an economical dense, high thermal capacity thermal energy storage material.

The German Aerospace Center (DLR) constructed a facility at the University of Stuttgart for testing a concrete, thermal energy storage system. It is examining the performance, durability and cost of using solid, thermal energy storage media such as high-temperature concrete and castable ceramic materials for use in conjunction with solat thermal parabolic trough power plants.

The standard Heat Transfer Fluid (HTF) is used in the solar field. The heat transfer fluid passes through an array of pipes imbedded in the solid medium to transfer the thermal energy to and from the media during plant operation.

The advantage of this approach is the low cost of the solid media. Engineering issues include maintaining good contact between the concrete and piping, and the heat transfer rates into and out of the solid medium.

At the Plataforma Solar de Almeria in Southern Spain, Ciemat and DLR performed initial testing that found both the castable ceramic and high-temperature concrete suitable for solid media, sensible heat storage systems.

The high-temperature concrete is favored because of lower costs, higher material strength, and easier handling. There is no sign of degradation between the heat exchanger pipes and storage material.

Design tools have been developed that optimize the storage layout, including the geometric dimensions and piping and module arrangement to minimize pressure losses and optimize manufacturing aspects and costs.

The modular nature of concrete storage allows the storage system to better integrate with the solar field and power cycle.

PHASE CHANGE MATERIALS

Phase Change Materials (PCMs) allow large amounts of energy to be stored in relatively small volumes, resulting in some of the lowest storage media costs of any storage concepts.

Phase change materials were considered for use in conjunction with parabolic trough plants that used a single phase-change material in the solar field.

Another approach uses a cascading set of phase change materials to transfer heat from the Heat Transfer Fluid (HTF). In this approach, thermal energy transfers to a series of heat exchangers containing phase change material that melt at slightly different temperatures. To discharge the storage, the heat transfer fluid flow is reversed. This results in reheating of the heat transfer fluid.

Testing proved the technical feasibility of this approach but further development of the concept was hindered by:

1. The complexity of the system,
2. The thermodynamic penalty of going from sensible heat to latent heat and back to sensible heat.
3. The uncertainty over the lifetime of phase change materials.

In Germany, DLR is evaluating phase-change thermal energy storage for application with direct steam generation in the parabolic trough solar field. This allows for a better thermodynamic match between the phase-change material and the phase-change of steam used in the solar field. A single phase-change material can be used to preheat, boil, and superheat the steam. 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 will be charged or discharged from the material.

A graphite foil has been developed to sandwich the phase-change material for increasing the heat transfer rates.

DIRECT MOLTEN SALT HEAT TRANSFER FLUID

Using a molten salt in both the solar field and thermal energy storage system eliminates the need for expensive heat exchangers. It allows the solar field to be operated at higher temperatures than current heat transfer fluids allow. This combination also allows for a substantial reduction in the cost of the Thermal Energy Storage (TES) system.

Molten salts freeze at relatively high temperatures 120 to 220 °C or 250-430 °F. This implies that special care must be taken to ensure that the salt does not freeze in the solar field piping during the night.

The ENEA research laboratory in Italy has proven the technical feasibility of using a molten salt in a parabolic trough solar field with a salt mixture that freezes at 220 °C or 430 °F.

In the USA, Sandia National Laboratory is developing salt mixtures with the potential for freezing points below 100 °C or 212 °F. At 100 °C the freeze problem is expected to be more manageable.

TANKS THERMAL ENERGY STORAGE

TWO-TANK DIRECT STORAGE

The first Luz trough plant, SEGS I, included a direct two-tank thermal energy storage system with 3 hours of full-load storage capacity.

This system used the mineral oil Caloria heat transfer fluid (HTF) to store energy for later use. It operated between 1985 and 1999 and was used to dispatch solar power to meet the Southern California Edison winter evening peak demand period on weekdays between 5-10 pm.

Solar power plants later moved to higher operating temperatures for improving power cycle efficiency and switched to a new higher temperature heat transfer fluid: a eutectic mixture of biphenyl-diphenyl oxide as Therminol VP-1 or Dowtherm A.

This fluid has a high vapor pressure. It cannot be used in the same type of large unpressurized storage tank system similar to the one used for the SEGS I plant.

Pressurized storage tanks are costly. They cannot be manufactured at the large sizes needed for solar parabolic trough plants.

TWO-TANK INDIRECT STORAGE

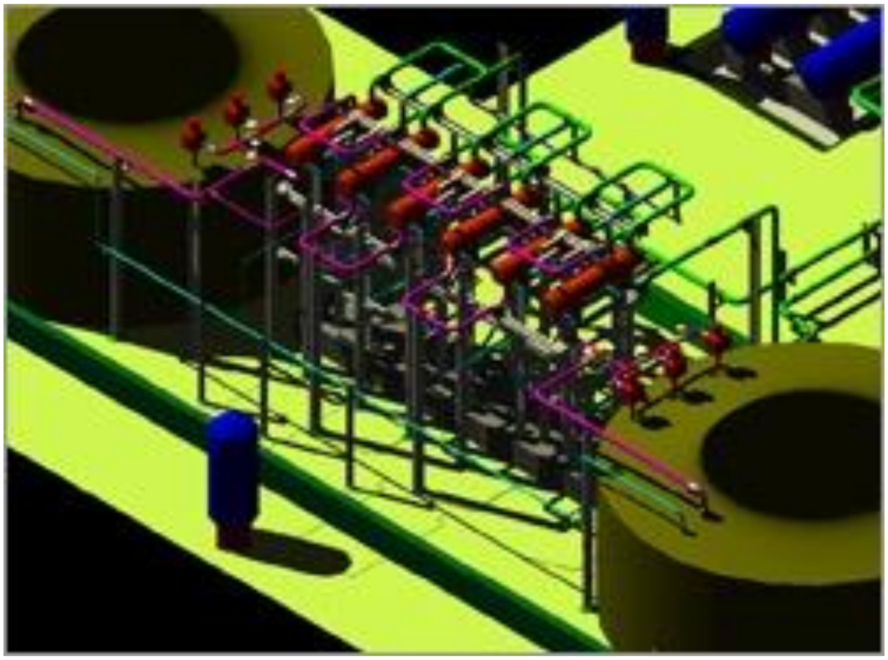

Figure 3. Configuration of a two-tank indirect thermal energy storage system for the Andasol 1 and 2 in Spain. Source: Flagsol.

A new indirect thermal energy storage (TES) approach has been developed that takes advantage of the experience with the storage system used in the Solar Two molten-salt power tower demonstration project, and integrates it into a parabolic trough plant with the conventional heat transfer fluid through a series of heat exchangers.

It is referred to as an indirect system because it uses a fluid for the storage medium that is different from what's circulated in the solar field.

The thermal energy storage system is charged by taking the hot heat transfer fluid (HTF) from the solar field and running it through the heat exchangers. A cold molten-salt is taken from the cold storage tank and run counter currently through the heat exchangers. It is heated and stored in the hot storage tank for later use.

Later, when the energy in storage is needed, the system simply operates in reverse to reheat the solar heat transfer fluid, which generates steam to run the power plant.

Several parabolic trough power plants in Spain use this thermal energy storage concept. For future parabolic trough power plants, a number of alternative approaches are being considered for reducing the cost of the thermal energy systems.

A two-tank indirect thermal energy storage system is relatively expensive. The expense is due to the heat exchangers and the relatively small temperature difference between the cold and hot fluid in the storage system.

SINGLE-TANK THERMOCLINE STORAGE SYSTEM

A single tank for storing both the hot and cold fluid provides a possibility for further reducing the cost of a direct two-tank storage system. The thermocline storage system features the hot fluid on top and the cold fluid on the bottom. The zone between the hot and cold fluids is designated as the thermocline.

In a thermocline storage system most of the storage fluid can be replaced with a low-cost filler material. Sandia National Laboratory has demonstrated a 2.5-MWhr, backed-bed thermocline storage system with a binary molten-salt fluid, and quartzite rock and sand for the filler material.

Depending on the cost of the storage fluid, the thermocline can result in a substantially lower cost storage system. A technical consideration is that the thermocline storage system must maintain the thermocline zone in the tank, so that it does not expand to occupy the entire tank.

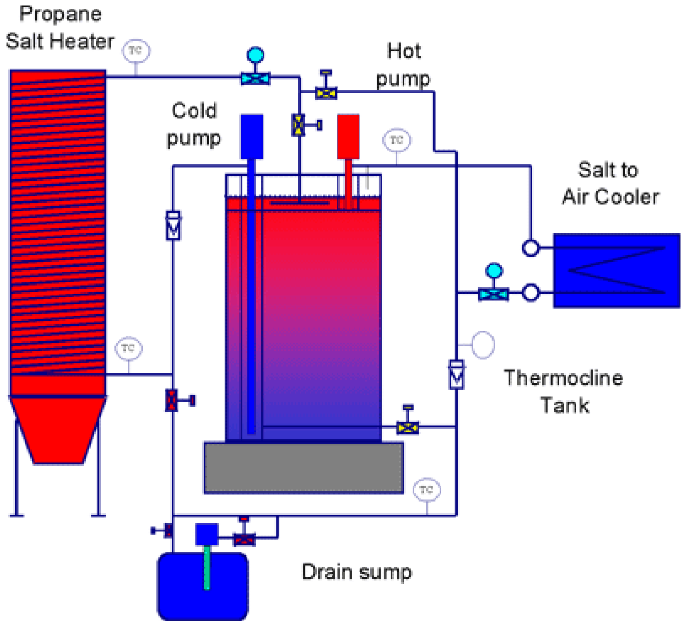

Figure 3. Thermocline test for thermal energy storage confirmation at Sandia National Laboratory.

REFERENCES

1. “Status Report on Solar Thermal Power Plants,” Pilkington Solar International, Report ISBN 3-9804901-0-6, 1996.
2. John A. Duffie and William A. Beckman, “Solar Energy Thermal Processes,” Wiley-Interscience, 1974.
3. “Assessment of Solar Thermal Trough Power Plant Technology and Its Transferability to the Mediterranean Region -Final Report,” Flachglas Solartechnik GMBH, for European Commission Directorate General I External Economic Relations, and Centre de Développement des Energies Renouvelables and Grupo Endesa, Cologne, Germany, June 1994.
4. “Integrated Solar Combined Cycle Systems (ISCCS) Using Parabolic Trough Technology, Phase 1B Technical and Financial Review,” Spencer Management Associates, Diablo, CA: March 1996.
5. "Solar Electric Generating System IX Technical Description", LUZ International Limited: 1990.

6. M. Lotker, "Barriers to Commercialization of Large-Scale Solar Electricity: Lessons Learned from the LUZ Experience," Sandia National Laboratories, Albuquerque, New Mexico, Report SAND91-7014, 1991.
7. C. J. Winter, R. Sizmann, and L. Vant-Hull, eds., "Solar Power Plants - Fundamentals, Technology, Systems, Economics," Springer-Verlag, Berlin, ISBN 3-540-18897-5, 1990.
8. V. Dudley, G. Kolb, A. R. Mahoney, T. Mancini, C. Matthews, M. Sloan, and D. Kearney, "Test Results: SEGS LS-2 Solar Collector," Sandia National Laboratories, Albuquerque, New Mexico, SAND94-1884, December 1994.
9. T. Williams, M. Bohn, and H. Price, "Solar Thermal Electric Hybridization Issues," Proceedings of the ASME/JSME/JSES International Solar Energy Conference, Maui, Hawaii, March 19-24, 1995.
10. M. Muller, "Direct Solar Steam in Parabolic Trough Collectors (DISS)," Plataforma Solar de Almeria (PSA), CIEMAT and DLR, ISBN 84-605-1479-X, May 1994.
11. W. Marion, and S. Wilcox, "Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors," National Renewable Energy Laboratory, Golden, Colorado, NREL/TP-463-5607, April 1994.
12. G. J. Kolb, "Evaluation of Power Production from the Solar Electric Generating Systems at Kramer Junction:1988 to 1993", Solar Engineering - 1995, Proceedings of the ASME Solar Energy Conference, Maui, HI, March19-24, 1995.