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Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts

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ABSTRACT

Thermal energy storage systems are key components of concentrating solar power plants in order to offer energy dispatchability to adapt the electricity power production to the curve demand. This paper presents a review of the current commercial thermal energy storage systems used in solar thermal power plants: steam accumulators and molten salts. It describes the mentioned storage concepts and the results of their economic evaluation. The economic value of the TES system is assessed by the Levelized Cost of Electricity (LCOE) calculation, an economic performance metric commonly used in power generation in order to compare cost of electricity among different power generation sources. Lots of studies have been done in the past to compare the LCOE of a complete solar thermal power plant using thermal energy storage systems. However, no specific studies related to the thermal energy storage levelized cost of electricity itself were done. The objective of this study is focused in the comparison of the TES LCOE where calculations are done for a 100 MW Rankine cycle with different plant configuration and for different storage sizes ranging from 1 to 9 h of equivalent full capacity operation.

1. Introduction

Carbon dioxide is responsible of over 60% of greenhouse gas (GHG) worldwide emissions [1–4], being the largest contributor factor to the climate change. As a result, this climate change has become a real threat and the uncertainty regarding energy supply in future decades will increase. Demand of energy has significantly increased recently due to the growth of worldwide population and the high industrialization [1]. This growth is mainly done in emerging countries where the needs of new generation plants are increasing significantly while in developed countries the growth of energy is related to replacement of end-of-life existing power plants. Renewable energy sources have been a key player to contribute to the world´s CO2 greenhouse gas emission reduction. Therefore, the final drive of renewable energy becomes essential both to the achievement of the objectives set out under the Energy and Climate Policy, and to ensure the future competitiveness of individual countries in a global energy market. Solar thermal, photovoltaic, wind, among others, are presented as key players of renewable energy technologies to achieve these objectives. By 2050 and beyond, a paradigm shift in terms of production, distribution and use of energy should be aligned with an overall energy consumption coming largely from renewable technologies. However, there is a strong mismatch between renewable energy supply and user demand.

Energy storage systems are designed to accumulate energy when production exceeds demand and to make it available at the user's request. They can help match energy supply and demand, exploit the variable production of renewable energy sources (e.g. wind and solar), increase the overall efficiency of the energy system and reduce CO2 emissions [5]. An energy storage system can be described in terms of the following properties [6]:

- Capacity [MWh]: defines the energy stored in the system and depends on the storage process, the medium and the size of the system;
- Power [MW]: defines how fast the energy stored in the system can be charged and discharged;
- Efficiency [%]: is the ratio of the energy delivered during discharge to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle;
- Charge and discharge time [h]: defines how much time is needed to charge/discharge the system;
- Cost [$/kW or $/kWh]: refers to either capacity ($/kWh) or power ($/kW) of the storage system. It can be referred as thermal or electric cost. Commonly, it includes the storage material itself, the heat exchanger for charging and discharging the system and the cost of the space and/or enclosure for the TES

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Due to diversified demand profiles regarding to type, amount and power of needed energy, each energy storage system (electrical, thermal, mechanical or chemical) requires a specific, optimal solution regarding efficiency and economics.

Solar thermal electricity or concentrating solar power, commonly referred to as STE and CSP respectively, is unique among renewable energy generation sources because it can easily be coupled with thermal energy storage (TES) as well as conventional fuels, making it highly dispatchable [7]. It has been operating commercially at utility-scale since 1985 [8] and it generates electricity with a thermal power cycle similar to that used in conventional fuel-fired power plants. One advantage of this type of power cycle is that the thermal inertia in a STE system is generally sufficient to sustain energy production during cloudy periods [9]. Moreover, thermal energy can be stored for later use at a low cost relative to a backup system that uses batteries, having the ability to increase the capacity factor (ratio of the annual electricity generation to potential electricity generation) of a STE plant and thus increase its viability as a base load generator [10].

The easy integration of TES makes STE dispatchable and unique among all other renewable energy generating sources. From some years ago there is a very big increase of solar thermal power generation industry and its associated TES systems. They are crucial to ensure the success of the technology allowing dispatchability enough to supply energy when demanded.

Thermal energy storage has several advantages when compared to mechanical or chemical storage technologies. Generally, TES systems have lower capital costs as compared to other storage technologies [11–15], as well as very high operating efficiencies [16]. The Solar Two project demonstrated a thermal efficiency greater than 98% [17], which was defined as the ratio of the energy discharged to the energy stored in the TES system. The only losses are to the ambient through the insulation, they can be limited according to the amount of insulation used. This is the reason why very high thermal efficiencies mentioned above are reached.

A TES system mainly consists of three parts [7]: (i) the storage material, (ii) the heat transfer equipment, and (iii) the storage tank. The thermal energy storage material stores the thermal energy either in the form of sensible heat, latent heat of fusion or vaporization, or in the form of reversible chemical reactions. The heat transfer equipment supplies or extracts the heat from the storage material. The storage tank holds the storage material insulating the storage material from the surroundings. Depending on the type of storage, there are several requirements that must be considered to ensure optimal storage dynamics and longevity. These requirements are identified as [18]:

- High energy density in the storage material
- Good heat transfer between the heat transfer fluid (HTF) and the storage material
- Mechanical and chemical stability of the storage material
- Chemical compatibility between HTF, heat transfer equipment and storage material
- Complete reversibility for a large number of charging/discharging cycles
- Low cost
- Low thermal losses
- Low environmental impact

Thermal energy storage systems must be designed to meet certain criteria, which depend of the type, size and design of a STE plant. These criteria can be summarized as follows [18]:

- Nominal temperature and specific enthalpy drop in the load (charge and conversion side)
- Maximum load
- Operational strategy
- Integration into the plant

It can be easily understood that more than one storage technology is needed to meet different applications. Consequently, a broad spectrum of storage technologies, materials and methods are needed. The overall target in designing TES systems is the reduction of investment cost and the enhancement of efficiency and reliability. To achieve these objectives, material, design and system integration aspects have to be considered in equal measure.

The assessment of identification and selection of the optimal TES system is not only focused on the storage material. Other important components of the STE plant have also to be taking into account, as for example the storage tank or the heat exchanger. Devices and sub-components, which are needed for operation and integration, such as pumps, valves and control devices are also very relevant for the proper operation [19].

Two different thermal energy storage technologies are currently implemented in commercial solar thermal electricity plants: (i) the steam accumulator for direct steam generation plants, and (ii) the two-tank of molten salts either for parabolic trough with thermal oil or the molten salt tower technology.

Abengoa is the only company whose portfolio includes different thermal energy storage concepts that have been already commercially proven. Based in this experience, the aim of this study is to confirm the need of having different storage technologies available in the market to better adapt the needs of demand/supply balance. The objective of this study is to compare both steam accumulator and molten salt technologies explaining the main advantages, disadvantages, challenges and particularities of each one. Firstly, the main technologies are described and a summary of the current status of the STE operating and under construction plants is presented. An in-depth analysis about commercial TES systems is done including a cost comparison and providing an assessment of the current commercial thermal energy storage systems used in STE plants.

2. Concentrating solar power commercial plants and thermal energy storage systems

2.1. Main CSP technologies

The STE technology can be classified into parabolic trough, tower,

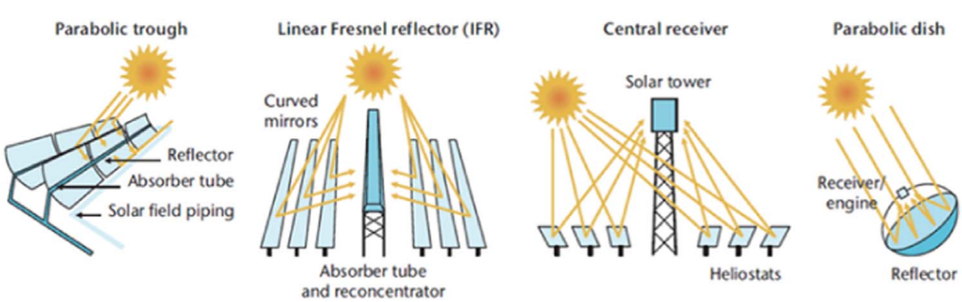

Fig. 1. Main CSP technologies [23].