Definition of key performance indicators (KPIs) to evaluate innovative storage systems in concentrating solar power (CSP) plants

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Abstract

The increasing penetration of renewable energies into the energy system is leading to significant development and deployment of generation plants based on the use of solar energy. On large scale, concentrating solar power (CSP) plants is the starring technology. In those systems, thermal energy storage (TES) is an essential component that allows both providing dispatchability and increasing power production thus improving the plant efficiency and reducing both its size and cost. Current storage technologies are mainly based on solar salts (molten salts) and saturated steam, their main drawback being their operating temperatures. Therefore, the current challenge is to develop innovative solutions that allow CSP plants to work at higher temperatures to increase their efficiency. In order to allow the comparison of new TES concepts, the definition of proper key performance indicators (KPIs) helps to better identify the best storage solutions. This paper reports a preliminary selection of KPIs suitable for TES systems and their validation against the commercially available two-tanks molten salts storage concept for a 100 MW net capacity CSP tower plant to allow the comparison with innovative solutions. The results of this study can be used as a basis for comparison of TES technologies with the available ones, as well as to set the target for the research and development of future storage solutions.

Keywords: concentrating solar power (CSP) plant; solar thermal electricity; thermal energy storage (TES); key performance indicators (KPIs);

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1. Introduction

Solar thermal electricity production represents one of the most effective technology that allows the exploitation of renewable energy sources with the potential to reduce the dependency from fossil fuel, thus decreasing carbon emissions into the atmosphere. According to the European Solar Thermal Electricity Associations (ESTELA, 2021), concentrating solar power (CSP) plants will have a substantial development and deployment before 2050. This growth can be attributed both to cost reduction and support of policies that aim to increase the share of renewables (McPherson et al., 2020). In order to offer electricity dispatchability and to adapt the electricity power production to the demand curve, thermal energy storage is an essential component of CSP plants (González-Roubaud et al., 2017). Furthermore, as reported by Gasa et al. (2021), the use thermal energy storage has a strong positive effect on the environmental impact during the life-cycle of a CSP plant. Current commercial thermal energy storage systems in CSP plants are steam accumulators and molten salts. Steam accumulators had a rapid deployment in the last years and they are used for very short storage periods (i.e. 5 hours). However, this technology is only suitable for small-scale plants due to their high pressure of saturated water used as storage medium, and their cost for high storage capacity (Palacios et al., 2020). On the other hand, molten salts represent the most used technology for CSP plants mainly in two-tank configuration. This storage technology can be used for longer periods (i.e., 8 h to 16 h), and it is characterized by high energy density and high cycling stability and lifetime. However, the main limitation of molten salts is their operating temperature (up to 565 ºC for direct TES systems) because higher temperatures would cause their decomposition. Generally, the need to decrease costs and overcome the actual limitations of the current energy storage technologies is bringing a lot of research on new innovative storage concepts and systems. Those technologies include the use of phase change materials (Prieto

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and Cabeza, 2019), thermochemical energy storage (Prieto et al., 2016), and sensible material such as concrete (Boquera et al., 2021) and liquid metals (Lorenzin and Abanades, 2016). Due to the difference between the different storage systems that bring their own advantages and limitations, the comparison between different thermal energy storage concepts is difficult and, consequently, the identification of an optimal storage solution for a specific CSP plant configuration is a challenging task.

In this case, the identification of suitable key performance indicators (KPIs) is important to allow the comparison between thermal energy storage systems and to set the target for the potential development of innovative storage solutions to overcome the limitation of commercial storage technologies. The main aim of this study is to define simple KPIs able to carry out a preliminary comparison between different thermal energy storage solutions. Furthermore, the KPIs analyzed in this study were quantitatively evaluated for a commercial molten salts storage system. The results reported in this study can be used as baseline in future studies to compare actual technologies with other innovative thermal energy storage systems. Future research would include the use of such indicators in alternative TES technologies, such as concrete, thermochemical, or PCM storage allowing their comparison for the optimization of CSP plants.

2. Methodology and KPIs definition

A KPI can be defined as a parameter to evaluate the progress or the achievement of an operational strategic goal. The choice of the correct KPI is important to identify and understand the parameters that are relevant in a specific technology and allow a comparison amongst the different ones. Indeed, the most suitable technology for a general application can vary according to its boundary conditions. A general classification of existing KPIs can be:

- Technical performance indicators
- Economic performance indicators
- Environmental performance indicators

In the field of thermal energy storage, there is no clear definition and agreement about the KPIs to be used to compare different storage solutions. This is mainly due to their large range of applications and the low level of penetration of some of TES technologies. In order to select the most proper KPIs, different methods were developed in the literature. A first attempt to collect KPIs for TES in CSP plant was published by Cabeza et al. (2015) that listed and quantitatively compared different performance indicators. Palomba and Frazzica (2019) developed a methodology for KPI definition and proposed a set of KPIs to be used to compare different TES. However, analyzing the literature, the relevant characteristics that should be considered in TES systems can be identified. Important features that a KPIs should have are simplicity, clear and unique definition, and meaningfulness. Furthermore, a proper KPI should consider the requirements of both system (in this case CSP plant) and stakeholders. In this paper, a preliminary selection of KPIs was done by the authors based on the literature available and the requirements of stakeholders involved in this study related to the installation and maintenance of CSP plants. In order to select the KPIs, the first issue is to decide the boundaries of the system to be considered. Indeed, indicators suitable to characterize a thermal energy storage integrated into a CSP plant can be calculated at different levels, starting from system level (all CSP plant), sub-system level (tower system and the storage system until the heat exchanger of the power block), component level (only thermal energy storage) until KPIs at material level (TES medium). KPIs selected at different levels could be interesting to evaluate different aspect of TES. KPIs at thermal energy storage level are useful to compare the different storage technologies, but it is important to consider also the effect of the integration of TES into the CSP plant. Indeed, as demonstrated by Gasa et al. (2021), the integration of thermal energy storage highly affects the performance of the whole CSP plant such electric energy consumption that affects directly the CO_2 emissions,. In this paper, some relevant KPIs that can be applied to most of the storage technologies were selected at thermal energy storage level and reported as follows (Cabeza et al., 2015; Del Pero et al., 2018; Gasia et al., 2017; Palomba and Frazzica, 2019):

- KPI 1 – Nominal capacity [MWh_{th}]: amount of energy that can be stored in the storage at nominal conditions. Capacity is measured as the total net energy used to charge the storage system from 0% to 100% at nominal temperature and it depends on the storage process, the storage medium, and the size of the system.

- KPI 2 - Charge and discharge time [in h]: duration of the charge and discharge phase of the thermal energy storage system. It can be calculated as the ratio between the energy delivered by (or supplied to) the thermal energy storage [MWh] and the nominal power discharged by the storage [MW] fixed in the characteristics plate.
- KPI 3 - Operating temperature range [ºC]: it is the temperature range in which the storage material can operate. This is important for sensible TES. For latent heat TES, since the thermal energy is stored and released at almost constant temperature, the phase change temperature will be the key parameter.
- KPI 4 - Efficiency [%]: ratio of energy delivered during discharge between the energy stored during the charge. Therefore, it can be calculated as:

$$\eta = \frac{|Q_{discharge}|}{|Q_{charge}|} \quad \text{(eq. 1)}$$

where $Q_{discharge}$ is the heat delivered from the TES during the discharge [MWh] and Q_{charge} is the heat absorbed by the TES during the charge [MWh]. This performance indicator is affected by the energy losses of the system and the heat transfer efficiencies of the charging and discharging processes, respectively.

- KPI 5 - Cost [in $/kW or $/kWh]: cost referred to the power or capacity of the storage system; it can be referred as thermal or electric cost.
- KPI 6 – Environmental impact [kgCO_2eq./MW_{th}]: In this case, this performance indicator is only related to the production and the disposal of energy storage system. To evaluate the impact throughout all the life-cycle of the TES, the energy consumed during the operational stage (electricity consumption from the grid) has to be known.

Although, other performance indicators can be used to compare different thermal energy storage technology, these six basic KPIs can be considered useful for a preliminary evaluation of different thermal energy storage systems. Nevertheless, other than the preliminary KPIs reported above, additional key performance indicators can be defined for future comparison of energy storage solutions in CSP applications, considering the requirements of the new key role of TES such as:

- Technology Readiness Level (TRL): it indicates the maturity of a given technology. The TRL spans over nine levels. This KPI is especially relevant when comparing solutions under different stages of development with commercial solutions.
- Days of storage at nominal conditions [day] for seasonal storage application.
- Response time [minutes]: it indicates time of the TES to change its output level from rest to nominal power.

Furthermore, KPIs at system and material level can be considered in future studies to have a complete comparison between different storage technologies integrated to CSP plants.

3. Case study validation

In this study, the identified six KPIs are calculated and validated against a two tanks direct system used in a commercial CSP plant shown in Fig. 1. The plant (solar power tower (SPT)) consists of a solar field, a receiver system (solar tower), a thermal energy storage system, and finally a power block to generate electric output. The main characteristics of the plant are:

- Net capacity: 110 MW
- Receiver power level: 690 MW
- HTF mass: 46,000 metric ton
- TES storage capacity: 4,695 MWh_{th}
- Annual net electricity fed to the grid: 776.24 GWh_{el}

The thermal energy storage system consists of the following elements: storage medium (molten salt), hot and cold storage tanks, and molten salt circulation pumps. In this plant, the heat transfer fluid (HTF) and the storage media is the same material. The solar salt used as storage media is a mixture of 60wt.% $NaNO_3$ and 40wt.% KNO_3, with a melting point of 220 ºC, maximum operation temperature of 565 ºC, specific heat of 1,495 J/kg·ºC, density of 1,899 kg/m^3 (at 300ºC), and a cost of 1.30 $/kg.

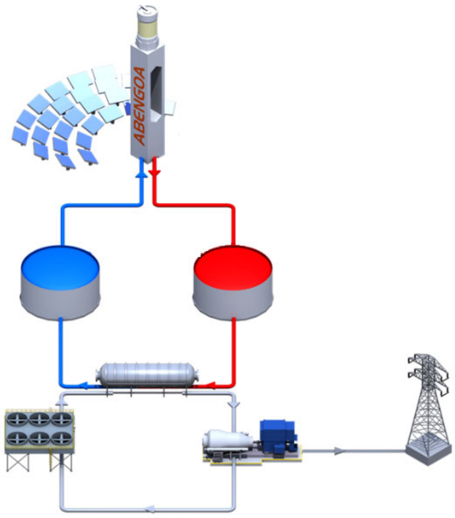

Fig. 1. CSP plant configuration used in this study to calculate the KPIs (Gasa et al., 2021)

In this system, heliostats concentrate sunrays by reflecting them to a tubular-type receiver that transfers the energy flux to the HTF. During this step, the salts are heated up to 565 ºC and pumped into the thermal energy storage tank (hot tank). The hot salt can then be stored or directly used to produce steam, which is used in the power block to generate electricity through a turbine. The cooled salt (around 290 ºC) is then returned to a second thermal energy storage (cold tank) ready to be heated up again when the solar field is available. In this plant, thermal energy storage act as a buffer for the molten salt steam generator to supply energy during periods of no solar radiation such as night or cloudy days. However, TES can be implemented in CSP plants using different strategies: intermediate load configuration, delayed intermediate load configuration, peak load configuration, and baseload configuration ([IEA] - International Energy Agency, 2010). Thermal energy storage tanks in CSP plants need special design features to limit mechanical stress resulting from the thermal effects due to their high temperature operation. Cold storage tanks are commonly fabricated with carbon steel (ASTM A-516 Gr.70), while hot storage tanks are fabricated with stainless steel (ASTM A-347H or ASTM A-321H) (Gasa et al., 2021). The thermal energy storage of the CSP plant used to validate the KPIs proposed in this study had a storage capacity in molten salts of 17,5 equivalent hours at nominal conditions, allowing for a 24/7 electric baseload production (Tab. 1~~Tab. 1~~).

Tab. 1. Key performance indicators for a commercial TES

Key performance indicator		Value	Unit
KPI - 1	Capacity	4,695	MWh
KPI – 2	Charge and discharge time	17.5	hours
KPI – 3	Nominal operating temperature range	290-565	ºC
KPI – 4	Efficiency	>99.5	%
KPI – 5	Cost	< 20	c€/kWht
KPI - 6	Environmental impact	$1.16 \cdot 10^4$	$kgCO_2eq./MW_{th}$

4. Conclusions

This study reports a first selection of KPIs that can be used for the comparison between innovative thermal energy storage technologies and actual commercial solutions. The selection was done based on the literature available on thermal energy storage considering the requirements of stakeholders involved in the installation and maintenance of CSP plants. A list of six basic KPIs was reported and calculated for a commercial operating CSP plant with a capacity of 110 MW, containing a storage system based on a two-tank molten salt configuration that uses solar salt (mixture of 60wt.% $NaNO_3$ and 40wt.% KNO_3) with a maximum operating temperature of 565 ºC as storage material. The KPIs selected include capacity, operating temperature, efficiency, charge and discharge time, cost, and environmental impact. Nevertheless, other additional key performance indicators can be defined for future comparison of energy storage solutions in CSP applications considering the requirements of the new key role that thermal storage has in the energy market and also indicators at different level. The values calculated for the thermal energy storage of the commercial plant reported in this study can be used as benchmark to compare different TES technologies and to set the target for the research and development of future storage solutions.

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