# A REVIEW OF THE USE OF THERMAL SOLAR ENERGY WITH CAES SYSTEMS

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***Abstract.*** *Considering the importance of studying energy production and its storage, this paper conducts a survey of the most relevant publications already realized about the use of thermal solar energy with compressed air energy storage (CAES). Once solar energy devices meet some needs of CAES, they allow its usage for electricity generation in a much more clean way, without the necessity of burning fossil fuels. Moreover, when coupled to another store system like the thermal energy storage (TES), they enable compressed air use even during moments of no sunlight. These possibilities are treated here by gathering some works which best represent them. Also motivated by the fact that such promising combination still has a lack for new research, the authors propose a different system to be studied in future. All this data and the best references can be found in this paper and used to proceed with new investigation in this area.*

***Keywords:*** *Thermal solar energy, CAES, TES*

## 1. INTRODUCTION

Solar energy is appointed today as one of the most promising alternative energy sources. However, it still faces the availability problem during peak demand, since it cannot be produced at any time of the day. Based on it, this paper presents a review of the use of thermal solar energy in conjunction with the compressed air energy storage (CAES). Together, they represent an interesting option to produce energy and provide it when there is no more sun light, besides reducing the greenhouse gases emission. Moreover, when compared to the number of studies already done about conventional sources, the amount of researches connecting these devices is still very low and spread, what brings the necessity for joining these information and doing new investigation.

The basic concept of CAES is the air compression and storage in suitable geologic structures underground, when there is energy supply, and its further use to produce power when additional generation is needed. The two main operating CAES plants in the world, in McIntosh, Alabama, and in Huntorf, Germany, store air in excavated salt caverns produced by solution mining, although recent studies demonstrate the possibility of storage in different geological formation, McGrail *et al.* (2013). Many authors have analyzed CAES based on the Huntorf plant data. Xia *et al.* (2014), for example, used Huntorf information to study the effects of the heat exchange between cavern air and the surrounding environment, while Raju and Khaitan (2011), validated their dynamic simulation model for CAES. A detailed description of the Huntorf plant can be found in the work made by Crotogino, Mohmeyer and Scharf (2001), in which they presented its main components, common for traditional CAES systems: a compressor train, a motor-generator unit, a gas turbine and a storage cavern.

As explained by Mohamadabadi (2014), a major disadvantage of the conventional CAES is the fuel demand, as much for its economic aspects as environmental factors too. In order to increase the power output of the plant, the compressed air that leaves the cavern needs to be heated up by the combustion fuel before being expanded in the turbines. This procedure also prevents the turbine being damaged by the freezing of the air moisture. By proposing the usage of thermal solar energy with the CAES, researchers have pursued to eliminate or at least soften these problems, making the system feasible and at the same time no pollutant. In this way, this works aims to gather the principal studies already carried out over the world, in order to build a current data source as complete as possible. The next sections present and discuss them, analyzing how these hybrid systems may be configured, followed by some proposal for future research.

## 2. METHODOLOGY

The thermal solar energy is the use of solar radiation to generate heat, normally used to warm fluids through the utilization of solar panels or concentrators, ANEEL (2005). The first and apparently simpler way of using these devices with CAES systems is to directly heat the compressed air that leaves the storage medium, allowing it to pass by the turbines without damages. On the other hand, but with the same goal, it can be used like a supporting resource, being used with a second storage system, normally the thermal energy storage (TES). Fig. 1 summarizes both ideas through diagrams. These two approaches will be treated as direct and indirect, respectively, and presented in the next sections.

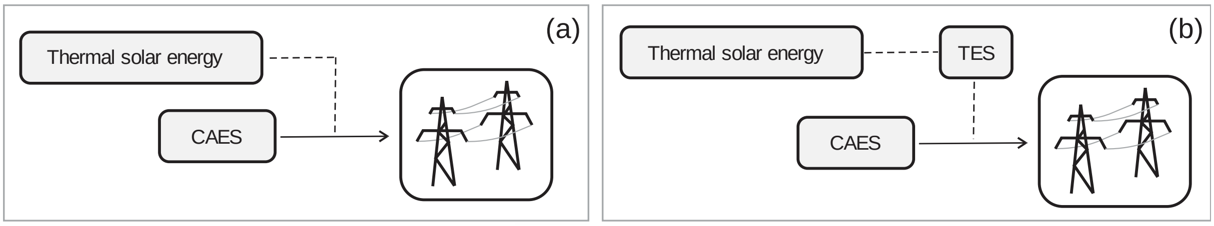

Figure 1- Usage of thermal solar energy with CAES (a) as a direct resource and (b) as an indirect resource.

### 2.1 Thermal solar energy as a direct resource

Following the first approach, recent research has been conducted in order to evaluate the compressed air warming by solar devices. Zhang and Zhao (2014), for example, proposed a system in which the compressed air was heated by a solar panel. According to their mathematical models, an optimum air temperature for the solar heater outlet would be 500K and an optimum pressure ratio for the compressor would be three. A major problem that could be related to their idea is the achievement of these values, worsen by the fact they have not done experimentation.

In order to reach higher outlet temperatures not possible in solar panels, other works have focused on using concentrated solar power (CSP). A prominent work has been done with the so called SolarCAT system, a CSP technology developed by the American company SolarCat Inc. The equipment is composed by a parabolic dish solar collector which reflects and concentrates incident sunlight in focal receivers, where the air passes and is heated after being piped. Their plants are being thought to use power of wind to store air at night and during peak demands of the day using the SolarCAT system, which can reach temperatures of approximately 927 degrees Celsius and generate 200 kW through its four turbo-alternators, Sperling *et al.* (2009). An image of the device can be seen in Fig. 2(a).

In the same research line, Nakatani, *et al.* (2012), studied the performance of solar receivers for compressed air in tower-type solar power plants. The solar receivers are heat exchangers that draw thermal energy from the solar energy collected by an array of heliostats. The heat receiver they created was tested in a solar plant in Australia and reached the same temperature of 850°C previously predicted in thermal-fluid analysis software. Two years later, Kim *et al.* (2014), also developed and tested solar receivers with similar proposal. They tested them in the solar furnace of the Korea Institute of Energy Research (KIER), finding the best performance in the circular receiver. An image of the square and circular solar receivers they tested along with a diagram showing the air flow path are shown in Fig. 2(b).

Figure 2- (a) SolarCAT system developed by SolarCAT Inc. company and (b) solar receiver developed by Kim *et al.* (2014).

Despite all efforts to improve these technologies and make possible to combine solar energy and CAES in a direct way, this kind of combination still faces some big challenges. One of them is how to meet demand for energy at any time of the day. If the peak demands occur during sun hours, the system will be able to provide energy, otherwise different sources will have to be used in order to yield it. If this latter is obtained by fuel burning, most advantages of using heat supplied by solar energy could be compromised. Moreover, these systems normally take electricity from the grid to compress air into the storage, what can represent a problem if there is no off-peak power availably. One possible way of avoiding these problems is building hybrid systems with different generation sources, like the SolarCAT project did. They got around these challenges by implementing wind power and biomass along with the solar energy. Obviously it is not trivial, once it requires as much financial resources as many kinds of technologies and trained staff.

## 2.2 Thermal solar energy as an indirect resource

As already mentioned, the configuration presented in the last section still faces the fact of not being able to meet demand that happens during moments of no sunlight. A possible solution to this issue could be the usage of another storage system besides the CAES, more specifically the thermal energy storage (TES), as represented in Fig. 1(b). The baseline concept of this storage method is the energy placement in the form of heat or cold in a storage medium for a particular duration and its retrieving from the same location for later usage, Kalaiselvam and Parameshwaran (2014). Following this idea, the solar energy device could feed the TES, by working during at sunlight time, and enable its usage afterwards to warm compressed air from the cavern.

In general, most of the existing work which proposes TES utilization analyses its usage only from the energy recovery of the CAES system. Once the air compression process releases heat, their main idea is to recover and reuse this heat during expansion. Grazzini and Milazzo (2008), for example, elaborated a thermodynamic analysis for the CAES with thermal recuperation, when they showed how the efficiency increased along with the number of compressors and turbines. In other paper, the same authors made an exergy analysis of compressed air energy storage with thermal recovery energy and showed that for a low volume CAES of 136 m³ it would be necessary approximately 45 m³ of water storage, which in turn would reach a maximum temperature of 405 K.

Porto *et al.* (2014) explored in a similar manner the usage of CAES and TES. The authors explain the simplest possible configuration through the scheme shown in Fig. 3(a), in which the thermal energy transferred to the air during compression is stored in a single insulated tank, constituted by a static heat exchanger, made with concrete and glass wool insulation. According to them, a better configuration can be achieved if two tanks are used, a hot and a cold one. This change avoids the necessity for a large temperature gradient inside the single tank. Although they do not present a specific analysis for the thermal storage system as they do for the filling and emptying process of the CAES cavern, they mention the possibility of using solar heaters in conjunction with the energy recover to feed TES. Fig. 3(b) shows their proposal for the system with two thermal tanks and solar heaters, considering the utilization of photovoltaic power plants as an electricity source.

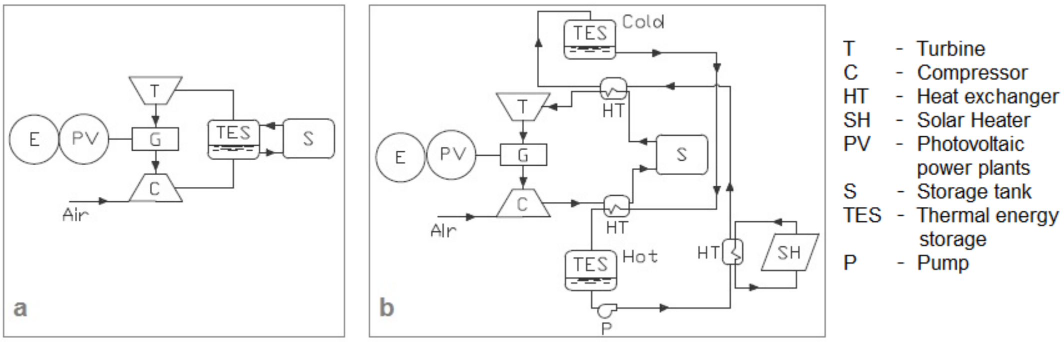

Figure 3- (a) CAES with a single TES and (b) CAES with two TES and solar Heater, Porto *et al.* (2014).

Garvey (2012), in turn, made a very detailed analysis of both storage systems used with solar energy. He studied the viability of storing heat offshore in conjunction with compressed air. Simulations were done for a baseline system comprising 2.25 GW (rated) of primary compression power and sufficient air and thermal stores to absorb four complete days of rated generation. Tab. 1 presents some of the values considered for the nominal evaluated system.

Table 1 - Parameters values considered for the nominal system evaluated by Garvey (2011).

| PARAMETER | DIMENSION |
|---|---|
| Peak generation capacity | 2.5 GW |
| Compressed air storage at 70 bar | $1.3 \times 10^9$ kg |
| Average solar thermal collection | 140 MW |
| Total thermal mass | 40 TJ/K |
| Wind power generation | 2 GW |
| Wave power generation | 250 MW |
| Volume of the thermal store | $16 \times 10^6$ m³ |
| Volume of air storage | $15 \times 10^6$ m³ |

Garvey system includes a multi-stage expansion and a multilevel thermal store. This latter, shown in Fig. 4(a), is a single tank filled with molten salts in its highest temperature levels, which constitute the hot stratum and reach values higher than 820 K, and seawater in the lower temperature levels, the cold stratum of the tank. Between them, in the middle-temperature layers, it is considered the utilization of mineral oils as the heat transfer fluid, which can reach values among 420 K and 770 K. By considering an average temperature swing of 50 K between "hot" and "cold" parts and 100 TJ of stored heat, the author exemplifies the calculus of tank dimensions through the specific heat equation (in this case he finds a total physical size of $1.3 \times 10^6$ m³ for TES, about $4.8 \times 10^5$ t of seawater). He also took into consideration for this reckoning the specific heat capacity of 4.18 kJ/kg K of seawater and assumed a mean value of 1.50 kJ/kg K for the materials in the inner thermal stores. In addition, the author pointed that the introduction of solid material as quartzite and silica sand into the heat transfer salt reduces its necessary volume and make it possible the heat last many days inside the tank. Some of his results showed that the solar thermal input has the effect of maintaining the large temperature difference between the three highest-temperature levels and the next level below that. Fig. 4(b) proves that the first sixth temperature levels in the stores do not exceed 460 K throughout the year and the three hottest layers are more influenced by solar energy than the others. Garvey also concluded that the use of large amounts of solar thermal power is only viable if thermal and compressed air stores of considerable magnitude are used too. The benefits of using some concentrated solar thermal power were above 60%.

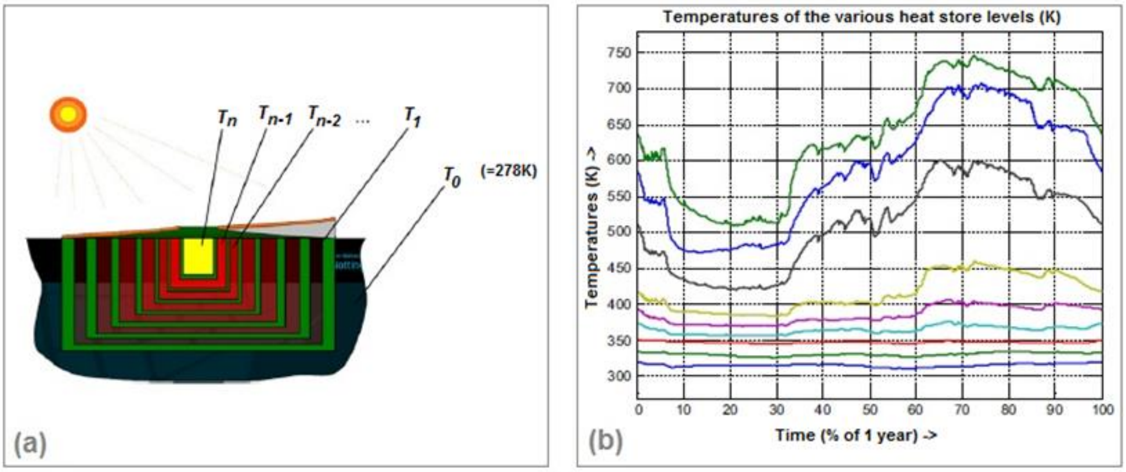

Figure 4- (a) Single multilevel thermal store ($\boldsymbol{T_0}$,$\boldsymbol{T_1}$,… $\boldsymbol{T_n}$ are temperatures in increasing order from ambient) and (b) temperatures of the levels throughout the year, Garvey (2012).

Similarly, Garisson and Webber (2014) estimated the thermodynamic performance and cost of energy production from an integrated system consisting of wind and solar energy devices coupled to compressed air and thermal energy storage. The authors calculated the amount of heat required per unit air mass flow and estimated the sizes of the CSP and thermal storage units based on an assumed generation time window. They considered a rated capacity of 100 MW and a generation time window of 4 h during the peak time period of the day. With this the thermal solar energy and TES capacity were assumed adequately supplied. A power system efficiency of over 46% for the combination of all components was found.

## 2.3 New setting proposal

The application of TES in the CAES facility has proven itself as an excellent solution for the energy production at any time of the day without stop using thermal solar sources. In an attempt to combine this setting with the direct heating of the compressed air, explained in section 2.1, the authors of this paper propose the plant configuration shown in Fig. 5. During some hours of peak demands which occur at moments of sunlight, it could work as represented in Fig. 5(a), by direct warming inside the focal receivers of the solar tower. During the rest of the time of sun incidence, the exit of the cavern is closed and ambient air is blown into the same receivers to capture and transfer energy next to the thermal storage. By doing this, later CAES utilization would be possible just directing its output to TES and then to the turbines (Fig. 5(b)). Obviously this simplified scheme constitutes just a representation of a setting idea, so multiple compressors and turbines, dual TES, heat exchangers and energy recovery are not symbolized. All these possibilities, in conjunction with thermodynamic, economic and experimental analyses are still to be carried out.

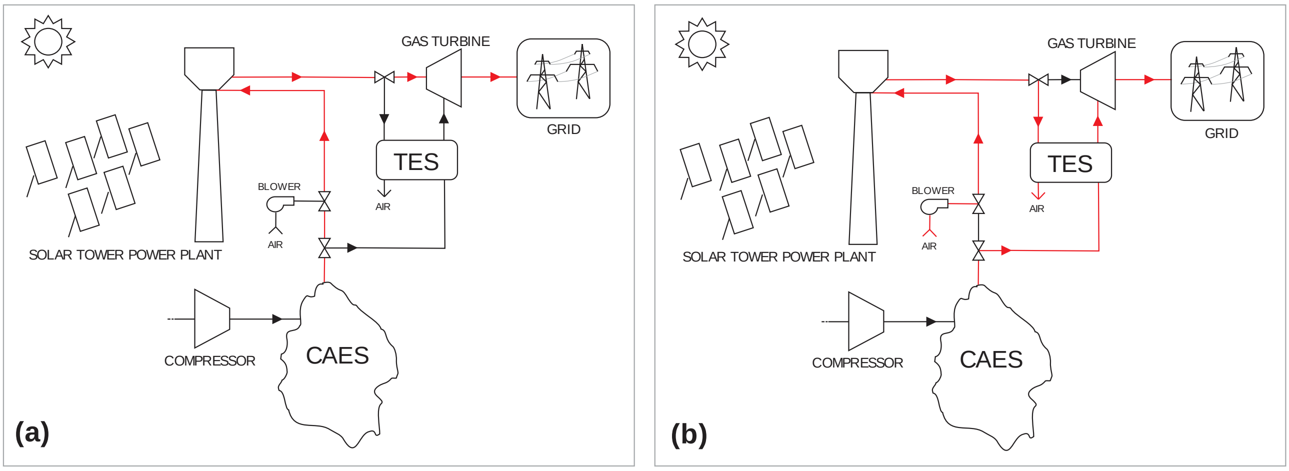

Figure 5- (a) Use of CSP to heat compressed air and attend peak demands during sun hours. (b) Utilization of CSP at moments of sun incidence with no grid demand to feed TES, which will warm the compressed air posteriorly.

## 3. CONCLUSION

The possibilities of combining thermal solar energy and CAES systems have been described in this paper through a complete literature survey data.

Two main approaches have been presented here. The first one regards to the very recent and prominent area of compressed air heating by concentrated solar power. While some researchers have studied the configuration and efficiencies of these plants, analyzing their thermodynamic cycles, others have focused on developing new devices resistant enough to be used as focal receivers on top of the solar towers, designed to warm air at temperatures up to 1000 degrees Celsius. Their works have pointed to the possibility of simplifications in energy production facilities. Due to their high technology, the amount of necessary equipment has been reduced, especially when compared to traditional established systems like plants of steam generation. This type of combination between solar energy and CAES is particularly suitable for situations of high demands which happen during sunlight time, not permitting later utilization of the energy, what constitutes its principal disadvantage. The second configuration which has been portrayed here includes the TES utilization with CAES and thermal solar energy. The works carried out over the world have proved that this setting is one of the most propitious to combine solar devices with CAES in order to yield energy at any moment of the day. A proposal of a new hybrid system which joins both approaches has also been presented, what increases the possibilities of working with solar devices and compressed air.

It has been possible to perceive a strong tendency to combine other renewable sources with CAES too, besides the solar energy, in order to operate the compressors and fill the cavern. Unless there is off-peak power available from the grid, sources like wind energy have shown to be the best option to keep the non-pollutant hybrid system and make it viable, with low costs at least in long term-time.

Although the number of publications about thermal solar energy and CAES is still relatively small, this paper has been able to gather the principal ones, in a manner that other researchers can find some of the best references and ideas to give sequence in this prominent area.

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