# CLIMA 2016 - proceedings of the 12th REHVA World Congress

*volume 4*

Heiselberg, Per Kvols

*Publication date:*
2016

*Document Version*
Publisher's PDF, also known as Version of record

# Design and Dynamic Simulation of a Compressed Air Energy Storage System (CAES) Coupled with a Building, an Electric Grid and a Photovoltaic Power Plant.

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**Abstract**
*The conversion of renewable energies such as solar or wind is usually difficult due to their intermittency and their variability. Reunion Island, a tropical French island situated 200 km off the West coast of Mauritius, has no possibilities to be grid connected to other countries. As the island expects to reach the electric autonomy by 2030, Renewable Energy like Photovoltaics has recently encountered a huge increase. Nevertheless, the development of large scale PV farms directly connected to the grid may create instabilities. For the same reasons, it is difficult to supply a building only with intermittent electric sources. Then, making the large-scale integration of PV farms for the decentralized electricity grids becomes a real challenge. One of the solutions for a deployment of intermittent sources such as PV is the integration of an energy storage system. However, the most common technology is based on the use of batteries, which suffer from being not environmentally friendly. A Compressed Air Energy Storage (CAES) appears as a solution to this disadvantage. A model that reflects the instant behavior of a system composed of a photovoltaic plant, an air compressor, a storage tank, a turbine, a building and the power grid is proposed in order to evaluate its feasibility. A sensitivity analysis on key parameters of the system is performed and the simulation results such as the overall efficiency, the load coverage ratio and the energies involved are presented in this paper. This model allows to assess the size of these components by minimizing the solar electricity sold and bought so as to reach autonomy.*

***Keywords: CAES; Storage; Net Zero Energy Building; Modeling; Simulation; Photovoltaics***

## 1. Introduction

The issues of emission of greenhouse gases resulting from the increasing demand of energy, have contributed to the research of new solutions for energy production and management. Many countries are moving towards the development of renewable energy in general and of photovoltaic (PV) technology in particular. As other ways to produce electricity, solar photovoltaic is an intermittent and variable source of energy. That is one of its main disadvantages that complicates its development in the energy mix of different countries. These consequences are particularly perceived in an unconnected area such as the French island of La Reunion where renewable energy has reached in 2014 34 % of the total electricity generation of the island. Then, a large scale PV plant directly connected to the grid may create instabilities in the electric network. One of the solutions to the different challenges cited above may be the energy storage that allows to postpone the dispatch of energy after its production. Currently, the most common technology for energy storage is based on the use of batteries, which suffers from remaining not environmentally friendly. Despite their good performances observed in recent years, the management of old batteries becomes a challenge and their destruction or recycling can cause energy consumption and many effects to the environment.

A Compressed Air Energy Storage (CAES) system appears as a promising way for energy storage in the future [1]. This technology has been known and used since the nineteenth century for different industrial applications including mobile ones [1]. In general, it consists in storing the air at high pressure in a tank during the period where the energy source is abundant, cheap or if the energy demand is low. This air is expanded later through an air turbine to provide electricity during period of high demand or lack of energy source or if the electricity becomes very expensive. Formerly, the compressed air for the power plant was firstly stored in an underground volume such as natural cavities previously used for the extraction of coal or salt [2], [3]. Nowadays, only two power plants with a CAES are operating. These plants are situated in Huntorf in Germany which started firstly in 1978 with 290 MW and has been up-rated to 321 MW recently, and Electric Corporation (AEC), located in McIntosh, Alabama, USA, built in 1991 [4]–[6] and reaching a production of 110 MW.

The CAES system has an efficiency ranging between 40 % and 70 % depending of compression heat management [4], [7], [8]. During the relaxation through the turbine, the air has to be pre-heated by an external source such as coal or gas in order to avoid the freezing of the air in the turbine. The use of fossil source to heat the air, not only decreases the overall performance of the system (about 52 %) but also contribute to the global warming through greenhouse gas emission. Otherwise, the heat coming from the compressor can be stored in another tank in order to be used later to re-heat the air before expanding. This kind of system is called Adiabatic Compressed Air Energy storage (A-CAES) and its performance can reach

70% [2]. Other projects about CAES system are planned around the world in order to improve this technology which remains used for high power (hundreds of megawatt) [9], [10] [3] and where the storage phase can take a long time for filling the air vessel. Now, the researchers are studying the feasibility to store the compressed air in an artificial tank instead of natural cavities as cited above.

Some studies about CAES modeling can be found in the literature. Raju *et al.* [11] have presented a model of the Huntorf plant, their study is validated by the operating data. In 2014, Xia *et al.* [9] proposed a model of a CAES based on a simplified and unified analytical method. They focused on the use of a constant mass flow rate during the charging, the storage and the expanding period of the system. Jannelli *et al.* [8] proposed a model of a CAES coupled with a PV plant to supply the loads of a radio station. This system integrates a battery bank storage and an air conditioning system. Hartmann *et al.* [12] compared the different existing configuration of the CAES model to compare their efficiencies. They conclude that the efficiency of a two-stage compression and one stage relaxation of the A-CAES plant is expected to be between 49% and 61%. They also show that the efficiency can reach 70% with an isentropic compression and relaxation. Another study on the A-CAES has been done by Zhang *et al.* [13] for coupling CAES to a wind power plant. Most of these models are used to simulate high power plants and do not deal with instantaneous behavior, especially in the case of the use of renewables.

In this paper, a dynamic simulation model is developed in order to study the feasibility of a CAES system applied to a photovoltaic plant coupled with a building. In this case, the electric loads reach approximately a dozen kilowatt. This model reflects the instant operation of the system composed of the photovoltaic plant, the air compressor, the storage and the expansion module, the power grid and a building. The inputs are on one hand the climate parameters such as ambient temperature and the solar irradiation and on the other hand the load curve of an administrative building from our University. Many operating situations have been thought about by looking at the various constraints of the system. In the following lines, a dynamic modelling is firstly presented with the different operation *scenarii*. The different energies involved in the system during the operation are instantly calculated. A sensitivity analysis on key parameters of the system is performed and the global simulation results such as the overall efficiency, the load coverage ratio and the energies involved are presented in this paper. The results obtained based on this model are described and discussed at the end.

## 2. Climate Conditions and Location of the Energy System

Reunion Island is located in the sub-tropical area in the southern hemisphere (200 km West of Mauritius in the Indian Ocean). Reunion Island has an important solar irradiation (~ 2000 kWh/m$^2$/year). The daily ambient air temperature ranges between 22 °C and 30°C during the summer and it is between 17 °C and 25 °C during winter.

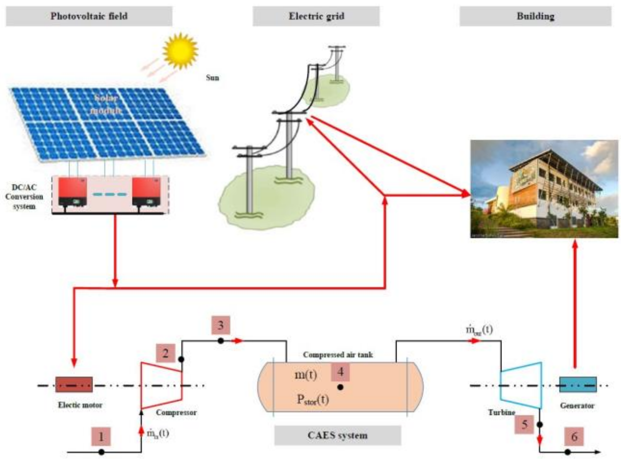



Fig. 1: System configuration: The CAES system is coupled with a Net Zero Energy Building model. The overall configuration is connected to the grid

The overall system is composed of four main parts connected together (Fig.1):

- **The building model:** The building loads have been generated thanks to real data measurements of a Net Zero Energy Building called ENERPOS [14] coming from a Building Monitoring System at the time step of one minute [15]. This particular building is an academic one and is composed of offices and of 7 classrooms. It is the first Net Zero Energy Building of the French overseas countries [14]. It has been designed and built in order to have a very low energy consumption. The building model net floor area is approximately 1000 m$^2$. The model is equipped with a PV roof. The PV area is variable as this is one of the parameter of our study;
- **The photovoltaic power plant:** The CAES will be coupled to a small scale photovoltaic power plant. The current produced by the photovoltaic field is converted with DC/AC inverters to supply the

loads (building loads or compressor) or to be injected into the electric grid;

- **The electric grid:** The photovoltaic power plant, the building and the storage system are all connected to the grid, which is assumed to be always available;
- **Compressed Air Storage:** The studied system is composed of a compression module supplied by the PV plant, an air tank and an expanding module equipped with an air turbine (Fig 1).

## 3. System Modelling

The modeling of the whole system is based on the analytical formulation of each component behavior. The model detailed further is built using the main following hypothesis:

- The air is assumed to be ideal with a constant heat capacity;
- The maximum and minimum pressure in the tank are fixed for operational and safety reasons;
- The tank overall heat transfer exchange coefficient is assumed to be constant;
- Accumulation (mass and energy) only occurs in the tank. The latter is supposed to be homogenous at every step type and described by uniform variables (temperature and pressure in particular);

The Compressed Air Energy Storage (CAES) circuit is described by six nodes (see Table 1) corresponding to the points of the major transformation of the air in the system (Fig. 2).

Table 1 : Main nodes of CAES circuit

| *Node* | *Situation* | *Node* | *Situation* |
|---|---|---|---|
| *1* | Air input | 4 | Air inside the tank |
| *2* | Compressor isentropic output | 5 | Turbine isentropic output |
| *3* | Compressor real output | 6 | Turbine real output |

To assess the instantaneous behavior of the system, the different thermodynamic variables and parameters are calculated at each node described above using the relationships according to ideal gas law, energy and mass balances. Thus, at each time step and at each node of the circuit, the thermodynamic variables of the air such as the temperature, the pressure, the specific volume, the specific enthalpy, the specific entropy and the specific internal energy are calculated. Between node 2 and node 3, assuming an isentropic transformation (1 to 2) the compressor is modeled by mean of its isentropic efficiency defined by the following relation:

$$\eta_{is,cp} = \frac{\Delta h_{is}}{\Delta h_{real}} = \frac{h_2(t) - h_1(t)}{h_3(t) - h_1(t)} \quad (1)$$

In the air tank, the mass and energy balance equation are written:

$$\begin{cases} \dfrac{dM(t)}{dt} = \dot{m}_{in}(t) - \dot{m}_{out}(t) \\ \dfrac{d(Mu)}{dt} = \dot{Q}_{tk}(t) + \dot{m}_{in}(t)h_3(t) - \dot{m}_{out}(t)h_4(t) \end{cases} \quad (2)$$

The heat losses, the compressor mass flow and the volumetric efficiency are calculated by:

$$\begin{cases} \dot{Q}_{tk}(t) = K_{tk} \times A_{tk} \left(T_4(t) - T_{ext}(t)\right) \\ \dot{m}_{in}(t) = \eta_{v,cp} \dfrac{\dot{V}}{v_1(t)} \text{ with } \eta_{v,cp} = 1 - \left[\left(0.05 \times \beta_{cp}(t)\right)^{\frac{1}{1.4}} - 1\right] \end{cases} \quad (3)$$

Where $K_{tk}$ is the overall heat exchange coefficient between the tank and the environment, $A_{tk}$, the external area of the tank, $\eta_{v,\ cp}$ the volumetric efficiency of the compressor and $\beta_{cp}$ the compression ratio.

The power needed by the compressor, the power produced by the turbine and the instant power supplied by the PV plant are calculated by:

$$\begin{cases} \dot{W}_{cp}(t) = \dfrac{1}{\eta_{m,cp}} \times \dot{m}_{in}(t) \times \left(h_3(t) - h_1(t)\right) \\ \dot{W}_{tb}(t) = \eta_{m,tb} \times \dot{m}_{out}(t) \times \left(h_7(t) - h_5(t)\right) \\ \dot{W}_{pv}(t) = \eta_{pv} \times K_{pv} \times GTI \times A_{pv} \end{cases} \quad (4)$$

Where $\eta_m$ stands for mechanical efficiencies, $\eta_{pv}$ for PV panel efficiency, GTI for Global Tilted Irradiation and $A_{pv}$ for the PV panel area.

The indicators defined to analyze the results are the overall efficiency $\eta_{caes}$ and the coverage ratio $CR_{CAES}$ due to CAES integration are respectively calculated by:

$$\eta_{caes} = \frac{E_{tb}}{E_{cp}} \; ; \; CR_{CAES} = \frac{E_{tb}}{E_{bd}} \quad (5)$$

Where $E_{cp}$, $E_{tb}$ and $E_{bd}$ respectively represent the compressor energy consumption, the turbine energy production, and the total building demand over the considered period of time.

## 4. Scenarii of Operation

The balance of the power between the different elements of the model and the storage management are done according to the following assumptions:

- The total loads demand are balanced with at least one of the available electricity sources and in priority order: the PV power plant, the CAES through the turbine, the electric grid);
- The compressor is always supplied by the rest of the electricity coming from the PV plant, after having supplied the load of the building;
- The compressor is switched on only if the required amount of power is achieved and if the pressure in the tank has not reached yet the maximum fixed value.
- The eventual rest of the power coming from the PV after having supplied the building and after having supplied the compressor is injected to the grid;
- The turbine produces power for the building in the case where the production of the PV cannot totally supply the load and if the pressure in the tank has not reached yet the minimum fixed value;
- If the building cannot be supplied by the PV or by the CAES system, the grid balances the loads.

These assumptions and constraints lead to eighteen *scenarii* corresponding to four energy situations of the overall system:

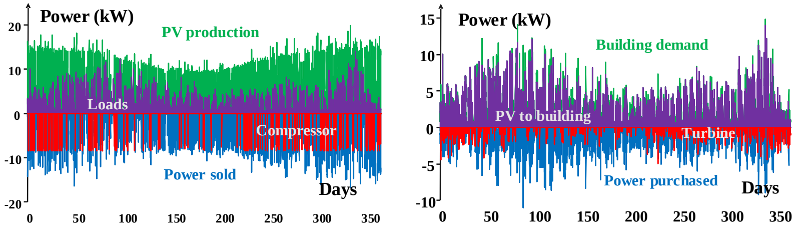
- **Situation 1:** The PV supplies the loads and the rest is injected into the grid;
- **Situation 2:** The PV supplies both the loads and the compressor, and the rest is eventually injected to the grid;
- **Situation 3:** The CAES supplies the building loads through the turbine;
- **Situation 4:** The loads are completely or partially powered by the electric grid.

## 5. Results and Discussion

The proposed numerical model has been applied considering a minimum and maximum pressure of 10 and 80 bars, isentropic efficiencies for both the compressor and the turbine of 90%, mechanical efficiencies for both of 90% also and an overall heat transfer coefficient of 5 $W/m^2/K$ between the tank and the ambient air. Simulations have been done over a whole year. As it can be seen on Fig. 2, the model is able to manage at every time step the different *scenarii* so as to distribute the energy accordingly. Values for the compressor swept volume flow, tank volume and PV area are given in the table 2.

Table 2 : simulation parameters

| Parameters | Main value | Range of variation |
|---|---|---|
| Compressor swept volume flow | 100 $m^3.h^{-1}$ | 20-180 |
| Tank volume | 5 $m^3$ | 1-50 |
| PV area | 100 $m^2$ | 50-300 |




(a) (b)

Fig. 2: Power level reached by the components over a year: on the PV side (a) and on building side (b) for a 1000 m$^2$ building equiped with 100 m$^2$ PV panels area.

To obtain a more global analysis, Fig. 3 gives the amount of energy integrated over one year for each source of energy production or consumption.

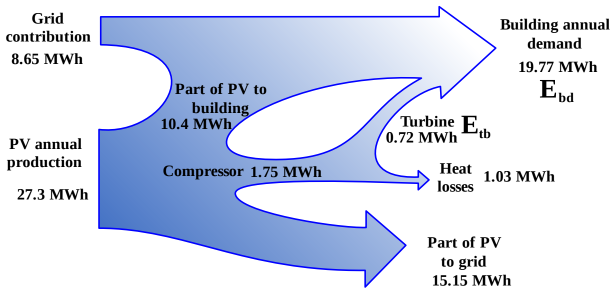



Fig. 3: Energy Sankey diagram applied to the system

The system overall efficiency calculated by using the equation (5) is about 41.1% and the coverage ratio of the building loads due to CAES integration is about 4 % in the investigated case (see Table 2). Since no particular strategy has been adopted here regarding heat released by the compressor, eventually stored and in the end re-used by the turbine, the level of the CAES efficiency is finally in the range it was supposed to be (about 40%) as seen in the literature. Varying main parameters according to the range given in the table 2, it is notable that the latter does not seems very affected by the changes applied to the PV area, the swept volume flow of the compressor or the tank volume as shown in Fig. 4. On the contrary, the amount of energy provided by the turbine (and consequently the coverage ratio $CR_{CAES}$) is relatively dependent to design parameters and in particular to the size of the compressor and PV panels area. Nevertheless, this increase also increases the part of PV annual production and consequently the amount of energy released to the grid.

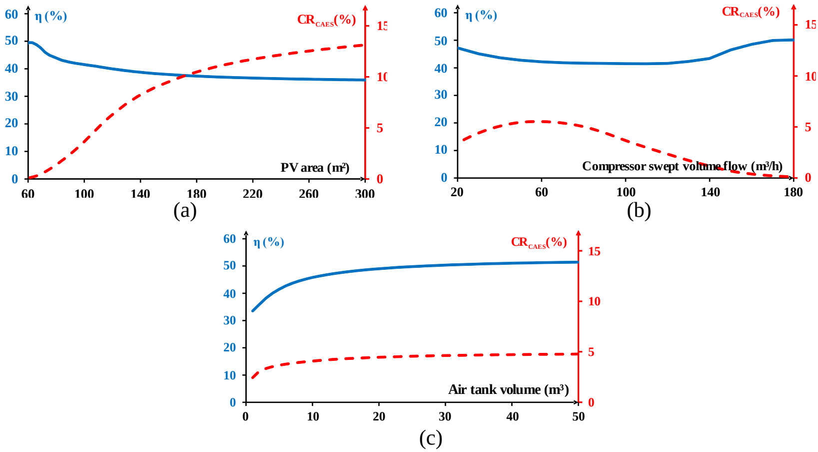



Fig. 4: Evaluation of the overall efficiency and of the coverage ratio vs the PV area (a) , the swept volume flow of the compressor (b) and the tank volume (c).

Fig. 4b points that, for a fixed PV area, an optimal compressor size can be determined to maximize the CR – e.g. for a PV area of 100 m$^2$, CR$_{max}$ can be obtained for a volumetric flow of 60 m$^3$/h. Considering Fig. 5, one can note that the maximum coverage ratio increases with the size of the couple compressor/PV area.

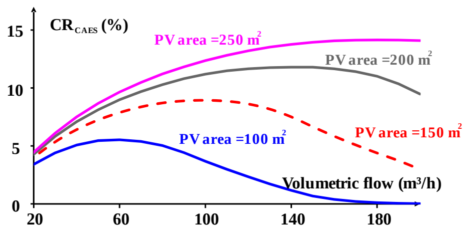



Fig 5: Evaluation of overall efficiency and coverage ratio depending of the PV area and the volumetric flow

## 6. Conclusion

Future investigations have to be carried out now to optimize the coverage ratio due to CAES with a better use of the amount of energy entering in the system. This is also a challenge to reach the energy autonomy, to optimize the mismatch factor and to lower the dependency of the system to the grid by reducing as much a possible the grid contribution and the energy released to the grid. In conclusion, the feasibility of using a compressed air energy storage coupled to a building in the case of PV production has been demonstrated in this paper. The proposed model is adapted to small scale systems. The study also points out that it is necessary to optimize the different parameters of the model in order to have both a high efficiency and a high coverage ratio. The overall system optimization and the management of the compression heat are two ways currently under investigation to increase the system performance.

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