Sensitivity analysis and optimization of a compressed air energy storage (CAES) system powered by a photovoltaic plant to supply a building

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Sensitivity analysis and optimization of a compressed air energy storage (CAES) system powered by a photovoltaic plant to supply a building

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Abstract

One of the handicaps of the large-scale integration of solar energy is due to its variability and its intermittency. The main way to overcome this issue is the energy storage technology. Knowing the high cost of batteries and their impact on the environment, we simulate a storage system based on compressed air and acting as a battery system.
The CAES consists in storing the air at a high pressure in a tank during the period when the energy source is abundant, i.e., cheap, or when the energy demand is low. The compressed air is later expanded through an air turbine which generates electricity during the high demand periods, i.e. when the energy source becomes very expensive for instance. This system could be used for decentralized electricity supply or in an area with no electric grid. In order to evaluate the feasibility of a Compressed Air Energy Storage system coupled to a photovoltaic plant and a building that represents a reduced power demand, a numerical model that reflects the instant behaviour has been built. The system is composed of a photovoltaic power plant, an air compression system, a storage vessel, an expansion module, a power grid and a building. The inputs used are, on the one hand, the climate data such as ambient temperature and the global solar irradiation and, on the other hand, the load curve of a building or of the group of buildings, which has to be supplied by electricity. The overall system optimization has then been performed after having done a sensitivity analysis of the key parameters. This optimization allows us to find the most suitable size for each component of the system: compressor, tank size and photovoltaic area.

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Keywords: Energy storage, photovoltaic; Compressed air; Smart grid; intermittency ; Renewable energy

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Nomenclature					
T	Temperature, K	M	Mass ,kg	bd	Building
P	Pressure, Pa	GNI	Global Normal Irradiation, $W.m^{-2}$	imp	Imported
h	Specific enthalpy, $J.kg^{-1}$	Cp	Heat capacity, $J.kg^{-1}.K^{-1}$	exp	Exported
s	Specific entropy, $J.kg^{-1}$ K^{-1}	$\dot{Q}$	Heat flux, W	Pv/bd	PV to building
u	Specific energy, $J.kg^{-1}$	$\dot{m}$	Mass flow rate, kg $.s^{-1}$	tb	Turbine
v	Specific volume, $m^3.kg^{-1}$	$\dot{W}$	Mechanical power, W	cp	Compressor
A	Area, m^2	t	Time, s	tk	Tank
V	Tank volume, m^3	**Subscripts**		in	Input
E	Energy, J	PV	Photovoltaic	out	Output

1. Introduction

In general, the compressed air energy storage consists in storing the air at a 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 a period of high demand or lack of energy source or if the electricity becomes very expensive. Formerly, the compressed air for power plants was firstly stored in an underground volume such as natural cavities previously used for the extraction of coal or salt [1]. In this study, air is stored in an artificial tank. Some studies about CAES modeling can be found in the literature [2]. All of these works are focused on a long time or seasonal storage system. 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 working on a daily basis. In the case investigated, the electric loads reach approximately a dozen of kilowatts. This model reflects the instant operation of the whole system composed of several elements detailed hereafter. Many operating scenarios have been thought about by looking at the various constraints of the system. In the following lines, the dynamic model is firstly presented and a sensitivity analysis on the key parameters of the system is performed in order to find out the influence of each of them on the overall efficiency and on the ratio of the energy imported and exported.

2. System description and modelling

2.1. Description

The studied system is composed of a photovoltaic field, a building, an electric grid and a compressed air energy storage part formed by a compressor, a turbine and an air tank (Fig. 1). The photovoltaic field should be able to supply both the building and the compression system to store air in the tank during the period of exceeding production. The grid is only used if the PV and the storage system cannot satisfy the electric building loads. 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;
- Accumulation (mass and energy) only occurs in the tank. The Compressed Air Energy Storage (CAES) loop is described by six nodes corresponding to the points of the major transformation of the air in the system (Fig. 1).

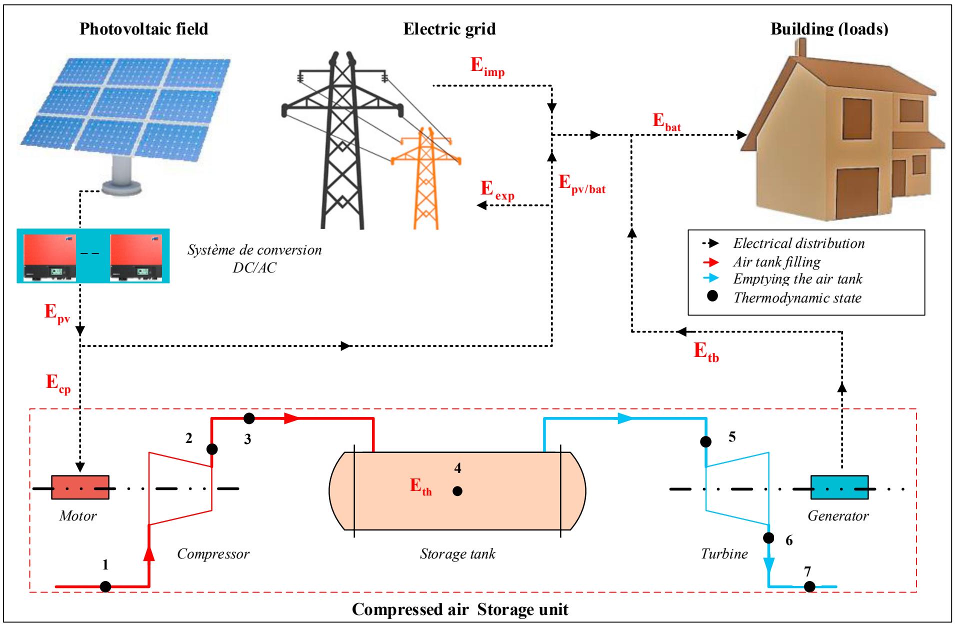

Fig. 1 : Studied system

2.2. Modelling

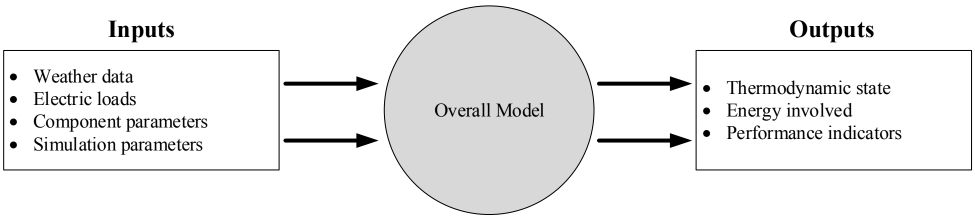

Fig. 2 : Model structure

Fig. 2 shows the global structure of the model with main inputs and. The mass and energy balance equation are written every step time :

$$\begin{cases} \dfrac{dM}{dt} = \dot{m}_{in} - \dot{m}_{out} \\ \dfrac{d(Mu)}{dt} = \dot{m}_{in} h_3 - \dot{m}_{out} h_4 + \dot{Q}_{tk} \end{cases} \quad (1)$$

Where $\dot{m}_{in}$ and $\dot{m}_{out}$ are respectively the air mass flow entering the tank and leaving the tank, $\dot{Q}_{tk}$ represents the heat exchanged from the storage tank to the surrounding. The instant power supplied by the PV plant, the instant power needed by the compressor, and the instant power produced by the turbine are calculated using respectively the following equations:

$$\dot{W}_{pv} = \eta_{pv} \times K_{pv} \times GTI \times A_{pv} \quad (2)$$

$$\dot{W}_{cp} = \frac{1}{\eta_{m,cp}} \times \dot{m}_{in} \times (h_3 - h_1) \quad (3)$$

$$\dot{W}_{tb} = \eta_{m,tb} \times \dot{m}_{out} \times (h_7 - h_5) \quad (4)$$

h_3 and h_7 are evaluated thanks to the definition of the isentropic efficiency applied to the compressor and the turbine. η_m stands for mechanical efficiencies, η_{pv} for PV panel efficiency, GTI for Global Tilted Irradiation and A_{pv} for the PV panel area. 4 different scen ario are possible depending on simulation conditions:

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

The indicators defined to analyze the results are the overall efficiency (η_{st}), the ratio of the energy imported from the electric grid (τ_{imp}) and the ratio of the exceed energy exported to the electric grid (τ_{exp}) and written:

$$\eta_{st} = \frac{E_{tb}}{E_{cp}}; \; \tau_{imp} = \frac{E_{imp}}{E_{bd}}; \; \tau_{exp} = \frac{E_{exp}}{E_{pv}} \quad (5)$$

Where E_{cp}, E_{tb}, E_{bd} and E_{pv} respectively represent the compressor energy consumption, the turbine energy production, the total building demand and the total photovoltaic production over the considered period of time (one year in our case). These performance indicators will be used to optimize the system.

3. Sensitivity study and optimization

3.1. Sensitivity

The proposed numerical model has been applied considering a minimum and maximum pressure of 5 and 100 bars, isentropic efficiencies for both the compressor and the turbine are 90 %, mechanical efficiencies for both of 98%. The values for the main components are set as:

- Area of the photovoltaic panels: 100 m^2, corresponding to the 10 kWp installed;
- Compressed air tank volume: 5 m^3;
- Compressor volumetric flow: 10 $m^3.h^{-1}$

Weather data are measured in Saint-Pierre (a city of La Reunion, a French overseas island situated in the Indian Ocean close to Mauritius and Madagascar) and the electric loads reflect the real operation consumption of a building (Net Zero Building) installed in the same place.

After simulation, the system overall efficiency is about 53 %, the importation ratio 38 % and the ratio of the energy exported equal to 58.20 %. In this configuration, the autonomy of the system, which represents the part of time where the building is only supplied by the PV or the storage system, is about 56 %.

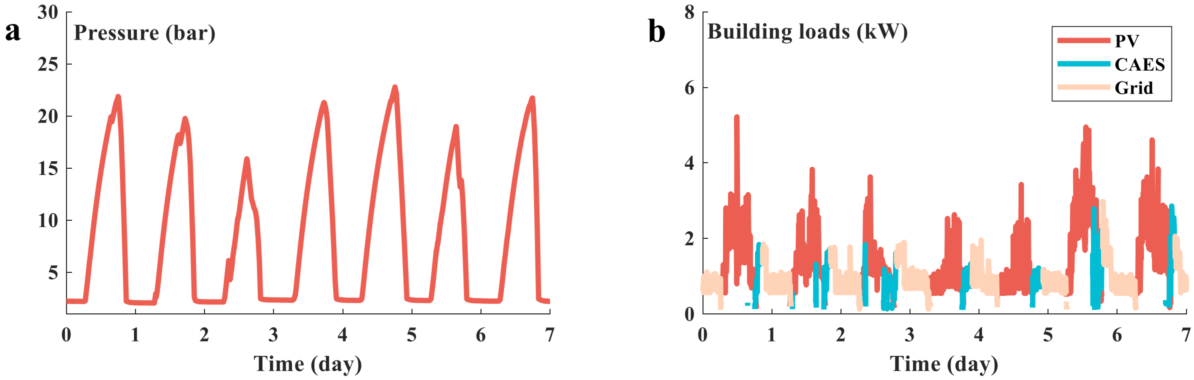

Fig. 3 : Evolution of air pressure (a); method of powering of the building with three sources (b)

Fig.3a shows the evolution of compressed air mass and pressure over a week, and the fig.3b represents the evolution the way the loads of the building are supplied during this period. These results show that this type of configuration can operate instantaneously using intermittent energy sources as photovoltaic. But, the main components choose for simulation are led to the best efficiency of the system. Thus, we represent the evolution of mains indicators on the fig. 4 to view the influence of the parameters for each and all the indicators.

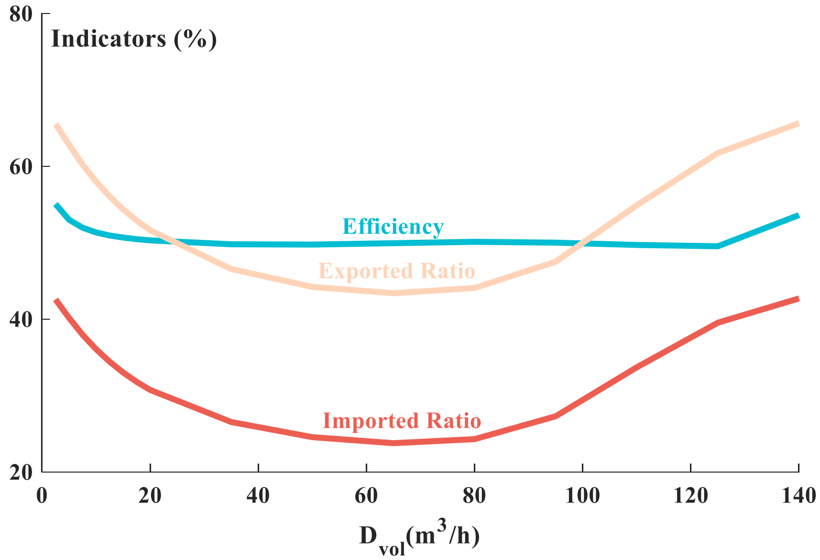

Fig. 4 : Evolution of the main performance indicators

Setting the volume of the tank to 5 m^3, and the PV power installed to 10 kWp, the evolutions of the main indicators are presented in the Fig.4 as a function of the compressor size. It appears that the storage efficiency remains almost constant in the range of investigated compressor size, while the importation ratio and the exportation ratio present both a minimum value (Fig. 4) corresponding to a configuration where the autonomy of the building is maximum.

3.2. Optimal design of the system

To find the optimal size of the system, all the indicators have to be considered *i.e.* get the maximum storage efficiency, obtain the lowest importation ratio and also obtain the lowest part of the PV production that is sent to the grid (ratio of energy exported). Thus, a multi-objective optimization has been set up. It consists in building an objective function by combining the sub-functions (imported ratio, exported ratio and storage efficiency). According to Marler [3] several approaches for solving multi-objective optimization problems exist, we choose a linear combination method defined by:

$$f(x) = \tau_{imp} + \tau_{exp} + \left(1-\eta_{st}\right) \qquad (6)$$

To determine the corresponding values of the compressor volumetric flow, the air tank volume of the PV field size a simplex algorithm to solve the problem has been chosen and the results are represented in table 1.

Table 1: Results of optimization

Parameters	Volumetric flow	Tank volume	PV Power installed	Objective value
Unit	**$m^3.h^{-1}$**	**m^3**	**kWp**	**-**
Range of variables	0 - 100	0.5 - 100	0 - 20	-
Optimal value	72.66	65.12	9.62	0.97

4. Conclusion

At the optimal operating point characterized by a compressor mass flow rate of 72.7 $m^3.h^{-1}$, a storage volume of 65.12 m^3 and an installed PV capacity of 9.6 kWp, corresponds a minimum importation ratio of 16. 29 %, an exported ratio of 34.17% and a storage efficiency of 53.43%. For this optimal configuration, the self-consumption ratio and the self-production ratio of the system are respectively about 73.4 % and 61.8 %. With this design, the autonomy of the building increase of about 35 % and reaches 78.7 %. Nevertheless, the storage efficiency of the storage system remains a bit low when compared to values found in the literature and ranging between 40 and 65% [4, 5]. In conclusion, the model developed allows us to demonstrate the feasibility of a small power compressed air storage system working under instantaneous operation and powered by a photovoltaic field. The optimal design adopted allows having a system maximising the use of the PV production and minimizing the contribution of the grid.

Reference

[1] E. Jannelli, M. Minutillo, A. Lubrano Lavadera, G. Falcucci, A small-scale CAES (compressed air energy storage) system for stand-alone renewable energy power plant for a radio base station: A sizing-design methodology, Energy. 78 (2014) 313–322. doi:10.1016/j.energy.2014.10.016.

[2] M. Raju, S. Kumar Khaitan, Modeling and simulation of compressed air storage in caverns: A case study of the Huntorf plant, Appl. Energy. 89 (2012) 474–481. doi:10.1016/j.apenergy.2011.08.019.

[3] R.T. Marler, J.S. Arora, Survey of multi-objective optimization methods for engineering, Struct. Multidiscip. Optim. 26 (2004) 369–395. doi:10.1007/s00158-003-0368-6.

[4] I. Ortega-Fernández, S.A. Zavattoni, J. Rodríguez-Aseguinolaza, B. D'Aguanno, M.C. Barbato, Analysis of an integrated packed bed thermal energy storage system for heat recovery in compressed air energy storage technology, Appl. Energy. 205 (2017) 280–293. doi:10.1016/j.apenergy.2017.07.039.

[5] B. Mauch, P.M.S. Carvalho, J. Apt, Can a wind farm with CAES survive in the day-ahead market?, Energy Policy. 48 (2012) 584–593. doi:10.1016/j.enpol.2012.05.061.