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Modeling of a compressed air energy storage connected to a PV field for NZEB in tropics

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Abstract

Producing electricity for houses or buildings often provided by mean of photovoltaic panels is relatively tricky especially because of the stochastic character of the solar radiation and of the storage influence. There exist some solutions and among them, the one consisting in converting electricity in high-pressure compressed air seems promising. Due to a refurbishing project of teaching classes at Reunion University (a French island situated in the Indian Ocean, at the east of Madagascar), this option is under investigation in parallel to reducing consumption in the building. The aim in terms of consumption is $25 \text{ kWh}_{PE} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ leading, if possible to a NetZEB (Zero Energy Building). So, it has been envisaged to produce the electricity by mean of PV panels, to consume the major part and to store the extra production in order to be used at night and during lower shining periods. The solution that has been investigated consists in compressing air in high pressure storage tanks (from a few tens to two hundred bar) and to produce electricity later thanks to a turbine. Nevertheless, the system remains electrically connected to the external network if extra electricity is required by the building and while the turbine is under operation or if too much electricity is produced and not being able to be stored instantaneously. A dynamic numerical model has been built, considering a specific given load profile and local climatic data in order to estimate the production.

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Keywords:

1. Introduction

The energy demand has dramatically increased those last ten years and has contributed to the research of new ways of production. Among the various techniques to produce electricity by mean of renewable source, the one consisting in using photovoltaic (PV) panels has known a very important growth. This is

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particularly the case in small areas where the ratio of electricity produced by renewable can reach values higher than 30 %, as this is the case in our island (La Réunion), a French department situated in the Indian Ocean, at the east of Madagascar. The main drawback in using such a source is due to the stochastic character of the solar radiation that contributes to highly transient and almost unpredictable variations of the electricity production. As an example, our island has just experienced its first electric black-out a few weeks ago. The most efficient way to avoid this is to store the electricity when available and to reuse it when a lack of sun radiation happens. This has to be considered on a time scale (night/day intermittency, clouds,) as well as on a geographic scale (a place being cloudy while another one is sunny) especially in a mountainous area such as a Reunion. There exist numerous solutions for storing energy from electricity conversion (chemically, mechanically, potentially...) depending on the power level produced and consumed and also on the amount of energy stored. On the scale of building (residential for instance) the most used system consists in storing electricity in batteries. This solution suffers from being relatively heavy and non-environmentally friendly. The one consisting in converting electricity into high-pressure compressed air, seems promising as the technology required is relatively mature, available and has a moderate environmental impact. Such storages have been tested since the 80's but mainly for high power level (a few hundred MW [1]) and there is a lack in small scale Compressed Air Energy Storage (CAES) systems. Due to a refurbishing project of classrooms at Reunion University, this option is under investigation in parallel to reducing consumption in the building. The aim in terms of consumption is 25 kWh_{PE}.m⁻².year⁻¹ leading, if possible, to a NetZEB (Zero Energy Building). So, it has been thought to produce the electricity by mean of PV panels, to consume the major part and to store the extra production in order to be used at night and during lower shining periods. The solution that has been investigated consists in compressing air in high pressure storage tanks and to produce electricity later, thanks to a turbine. Nevertheless, the system remains electrically connected to the external network if extra electricity is required by the building or if too much electricity is produced by panels and is not stored instantaneously. A dynamic numerical model has been built, considering a specific given load profile and local climatic data in order to estimate the production. The energetic analysis of the whole system is calculated and integrated other a year in order to access to the global performance of this CAES. The main objective is to reduce the amount of energy provided by the external network .

2. Principle and modelling

The whole project being investigated consists in refurbishing a 1400 m² classrooms building at Reunion University. The first step that has been looked at concerns the electric loads that are required for such a building and such uses. Fortunately, a new Net Zero Energy Building (NZEB) has been built and monitored since 2009 relatively close to this area on another campus of the University [2]. So, an important amount of data is available to analyze the behavior of this building and in particular load profiles. As the case being investigated is a similar classrooms building, the estimated electricity load profile for the refurbishing case has just been correlated to the latter, taking into account respective areas of each building. The level of power required by the building is integrated in the model and is presented at the end of the paper.

Of course, in parallel, a particular effort has been made on the re-design of that building in order to reduce the global consumption and in particular, to avoid, as much as possible, the use of air conditioning by promoting free cooling, to reduce the use of artificial light and to promote the use of sun shading materials. Secondly, it has been thought to partially cover the roof with PV panels (see figure 1a), so as to produce during sunlight period, approximately the amount of energy required by the building during the whole day. The produced electricity has then being estimated considering the efficiency of the PV panels, their implementation on the roof and local climatic conditions.

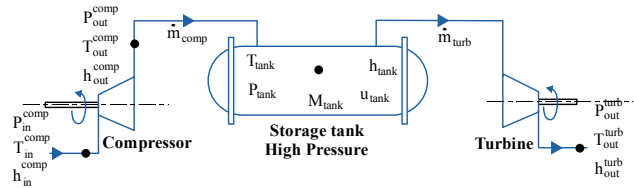


Fig. 1. (a) Project under study; (b) CAES Scheme

In order to match loads and production over time, a Compressed Air Energy Storage has been considered. A typical CAES system is mainly composed of a compressor, a storage tank and a turbine as shown in figure 1b. As one of the objectives is to design such a system and to predict the behavior of the whole building, a dynamic model has been built to determine the main components of the system.

A set of equation has been written to take into account the mass and thermal inertia of the storage tank thanks to mass and energy balances (eq. 1). Compressor and turbine energy fluxes (\dot{W}_{comp} and \dot{W}_{turb}) and mass flow rates (\dot{m}_{comp} and \dot{m}_{turb}) have been integrated (eq. 2), considering their particular design over the definition and the use of isentropic and volumetric efficiencies (eq. 3), these latter mainly depending on time to time working conditions (pressure ratio in particular). Considering the range of pressure and temperature investigated, an ideal gas law revealed sufficiently accurate to depict pressure (P), temperature (T), enthalpy (h), internal energy (U) and specific volume (v) interactions.

$$\begin{cases} \frac{dM_{stor}}{dt} = \dot{m}_{comp} - \dot{m}_{turb} \\ \frac{dU_{stor}}{dt} = \dot{m}_{comp} h_{comp} - \dot{m}_{turb} h_{turb} + \dot{Q}_{stor/ext} \end{cases} \quad (1)$$

$$\begin{cases} \dot{W}_{turb} = \dot{m}_{turb} (h_{turb}^{out} - h_{turb}^{in}) \\ \dot{W}_{comp} = \dot{m}_{comp} (h_{comp}^{out} - h_{comp}^{in}) \end{cases} \quad (2)$$

$$\dot{m}_{comp} = \frac{\eta_v Vol}{v}, \eta_{comp}^{is} = \frac{h_{comp}^{out, is} - h_{comp}^{in}}{h_{comp}^{out} - h_{comp}^{in}}; \eta_{turb}^{is} = \frac{h_{turb}^{out} - h_{turb}^{in}}{h_{turb}^{out, is} - h_{turb}^{in}} \quad (3)$$

Even in the exposed quite simple case, an important number of *scenarii* have to be considered to drive the whole system over time. At each step time, a first test has to be done in order to know whether the instantaneous production is higher than the consumption. If this is the case, the compressor can be turned on in order to store energy. As the compressor is a previously defined one (in terms of size as in performance), this extra production has to be compared to the one required by the compressor to start. If this is not the case, the missing power is taken from the electric network to get the necessary required power level to drive the compressor. On the contrary, even if the compressor is turned on, if there is still an extra production power, this latter is given back to the network. Each time the compressor is turned on, another test is done in order to check if a previously defined delay (3 mn here) has been reached since last compressor start-up in order to prevent this latter from short cycle behavior and bad working conditions.

At night or during cloudy period, the consumption can be lower than the production so as the turbine can provide the difference. Contrarily to the case of the compressor, the mass flow rate of air flowing through the turbine and leaving the storage tank has been here considered as controlled to match the exact required difference between electric loads and PV panel production, leading in this case to a null dependency regarding the electric network. Of course this can only be done if the amount of air and the storage pressure are sufficient to drive the turbine and meet these requirements. If not, this is an important point to mention as it reveals a down-sized tank and definitively stops the simulation in order to find a

more accurate volume for the storage vessel. In addition to this technical selection criterion, another value has been particularly studied: the net energy flow, calculated by integrating over time the electrical power entering or leaving the network. One of the objectives of the system and of the design is to reduce as much as possible the dependency to this electrical network.

3. Simulation and results

The results presented hereafter are for the first two weeks in order to see what is happening in detail. Figure 2a is relative to the power produced by the PV panel field and to the power consumed by the building. It can be seen on the graph that there is no consumption during the first week in order to store an initial amount of energy in the tank. On both evolutions, difference between night and day is clearly marked as well as for the consumption, the difference between the week-end and the rest of the week. The figure 2b gives the pressure evolution inside the tank over the days. The average pressure after a few days of normal behavior is situated about 70-80 bar. Figure 2c plots the power supplied or given to the electric network.

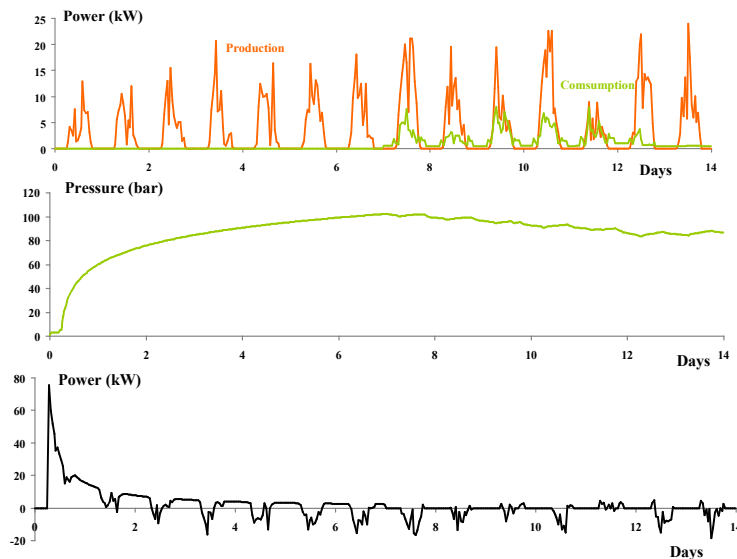


Fig. 2. (a) power produced and consumed by the system; (b) pressure evolution, (c) power exchanged with the network

The simulation has been extended to a whole year in order to test the system, varying mainly PV panel area, storage tank volume and particular manufactured compressors. The systematic study is under way to find the best configuration, the objective criterion being the net energy exchanged with surroundings (i.e. the integration of the power represented figure 2c).

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