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# Assessment of design and operating parameters for a small compressed air energy storage system integrated with a stand-alone renewable power plant

M. Minutillo*, A. Lubrano Lavadera, E. Jannelli

*Department of Engineering, University of Naples "Parthenope", Centro Direzionale Isola C4, Naples, Italy*

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A B S T R A C T

The renewable energy systems promotion in the field of the distributed generation is linked to the development of efficient energy storage systems. This study analyzes the behavior and the performance of a photovoltaic power system that, integrated with an adiabatic CAES (compressed air energy storage) unit, supplies electric power to a small scale off-grid BTS (base transceiver station) using only a renewable resource. The adiabatic condition of the CAES system is assured by realizing a TES (thermal energy storage) unit that recovers the heat from the inter-cooling compression for satisfying the inter-heating expansion without using additional fossil fuels. The power system is also designed to obtain a cooling effect from the cold air (3 °C) at the outlet of the turbine, useful for the refrigeration of the telecommunications equipment.

The aim of this study is to assess the optimal plant operating parameters, in terms of average storage pressure and operating pressure range of the air tank, considering the plant installation in three different climatic zones.

The analysis has been carried out by introducing some performance parameters such as the system storage efficiency, the energy supply factor and the cooling supply factor.

Results have highlighted that the best performance can be obtained by choosing both the lowest average pressure and the highest operating pressure range of the air tank.



## 1. Introduction

Renewable energy can perform an essential position in meeting the main purpose of replacing large component of fossil fuels [1]. However, the intermittency of renewable power sources such as wind and photovoltaic presents a major obstacle to their extensive penetration into the grid.

In order to enhance the utilization of the renewable energy sources for the power generation, energy storage solutions are indispensable. As a matter of fact, the interest in electrical energy storage systems is due to their ability in decoupling the electric power generation and consumption [2–4].

The main existing storage technologies, based on various processes, include electrochemical batteries, supercapacitors, thermal-storage materials, flywheels, pumped hydro (PH), superconducting magnetic energy storage (SMES), chemical storage (hydrogen and synthetic natural gas) and compressed air energy storage (CAES). These systems are characterized by different storage capacities, storage efficiencies and discharge times and thus, the choice of the best technology depends on its application [5–12].

Compressed air energy storage is one of the technologies with the highest economic feasibility, which may contribute in creating a flexible energy system based on the utilization of renewable energy sources. CAES is a modification of the basic gas turbine technology, in which low-cost electricity is used for storing compressed air that, during peak demand hours, is heated and expanded in a gas turbine in order to produce electricity [13].

There are two different types of CAES systems: diabatic and adiabatic. In the first case, the working fluid (ambient air) is compressed and stored in an underground cavern (the caverns can either be drilled in salt and rock formations or already existing cavities such as in aquifer strata). The thermal energy, which results from the compression process, needs to be dissipated to avoid deterioration of the cavern. During the discharging process, natural gas is injected in a combustion chamber in order to heat the

* Corresponding author.
*E-mail addresses:* mariagiovanna.minutillo@uniparthenope.it (M. Minutillo), antonio.lubrano@uniparthenope.it (A. Lubrano Lavadera), elio.jannelli@uniparthenope.it (E. Jannelli).

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**Nomenclature**

| | |
|---|---|
| $W$ | Electric power (kW) |
| COP | Coefficient of performance of the cooling system |
| $E$ | Electric energy (kWh) |
| $t$ | Time (s) |
| $\gamma$ | Number of PV base modules |
| $M$ | Air mass (kg) |
| $T$ | Temperature (°C) |
| $\dot{m}$ | Flow rate (kg/s) |
| $^{c}p$ | Specific heat for a constant pressure (kJ/kgK) |
| $\beta$ | Compression/expansion ratio |
| $p$ | Pressure (bar) |
| $k$ | Isentropic expansion factor |
| $\eta_{pol}$ | Turbo-machinery polytropic efficiency |
| $\psi$ | Mass increasing ratio |
| $Q$ | Thermal/cooling energy (kWh) |
| $\dot{Q}$ | Thermal/cooling power (kW) |

Subscripts and superscripts

| | |
|---|---|
| $d$ | Demand |
| el | Electric |
| cool | Cooling |
| PV | Photovoltaic plant |
| $i$ | Day |
| * | Single Photovoltaic module |
| e | Expansion |
| c | Compression |
| a | Air |
| av | Average |

air before expanding in the turbine. The adiabatic CAES stores the thermal energy after the compression in a thermal storage and the compressed gas in an underground cavern. During discharging process the compressed air is heated by the heat transfer out of the thermal storage. The addition of natural gas is neglected [14].

Historically, CAES has been deployed for grid management applications such as load shaving, load following, load shifting and regulation. Thus, this technology has been applied for large-size power plants; there are only two CAES plants in the world: the 290 MW plant belonging to E.N Kraftwerke, Huntorf, Germany (1978) and the 110 MW plant of Alabama Electric Corporation (AEC) in McIntosh, Alabama, USA (1991) [15].

Recently, the attention seems to be also devoted to small-size and/or innovative applications as confirmed by the technical literature [16–22].

Baquari and Vahidi [16] proposed a case study of a small-compressed air energy storage (S-CAES) system in Iran metropolises. They analyzed a power system based on a smart power electricity switch, in which the customer has a multi-feed storage system in which both distribution line and wind turbine (or other renewable energy converter) are connected to a smart clutch and the output is connected to an induction motor/generator connected to a compressor. The S-CAES system is operated in low pressure (not more than 10 bars), so it can be used everywhere. It consists of a compressor for changing the air into the reservoir and a turbo-expander. An induction motor/generator is connected through clutches to the compressor and the turbine. During consumption periods, the CAES system is operated in discharging mode and the compressed air is released from the reservoir to the expander in order to provide the needed power. They calculated the total efficiency of the system as function of the pressure ratio (pressure of the initial state and final state) and showed that, in the range from 3 to 9, the efficiency was not noticeable but after 10 it was high (0.4–0.6).

Kim and Favrat [17] performed energy and exergy analyses of different types of micro-CAES systems and proposed some innovative ideas for achieving high efficiencies from these systems. They considered the possibility of using both the dissipated heat of compression for heating load and the compressed air for the power generation and the cooling load. The authors analyzed eight CAES system configurations in which the storage pressure was fixed at 50 bar. These configurations are characterized by: (a) quasi-isothermal or adiabatic compressions and expansions; (b) one or two compression and expansion stages; (c) with or without fuel addition for heating the compressed air before its expansion. The results of their study highlighted that a micro-CAES system, especially with quasi- isothermal compression and expansion processes, is a very effective system for distributed power networks, because it can be the combination of energy storage, generation, air-cycle heating and cooling system, and it has a good efficiency (about 60%). A further innovation proposed by the authors regards charging and discharging processes of a high-pressure vessel where the pressure ratios are changing. They considered a new storage system that combines a constant-pressure air storage and a hydraulic energy storage; as matter of fact, the system produces the required large pressure difference by means of a water column.

Alami [22] presented an experimental evaluation of two compact energy storage devices directed towards wind energy storage applications: (i) a compressed air energy storage (CAES) system, (ii) a buoyancy work energy storage (BWES) system. The CAES system, that was considered as isothermal because maximum pressure is not exceed 3 bar, has an overall efficiency that is function of the cylinder pressure and its maximum value is 84.8%. The maximum theoretical efficiency for the buoyancy work system is found to be around 36%. The systems, considered in the analysis, were compact in size, but the results obtained in terms of performance parameters such as efficiency and electrical output can be generalized as a storage option for real offshore wind farms.

In this study, the authors propose a novel small-scale adiabatic compressed air energy storage (CAES) system in combination with a photovoltaic power unit. This renewable power plant has to supply the energy demand of an off-grid BTS (base transceiver station). The power requirements are due both to the equipment (2 kW) and to the cooling system needed for controlling the temperature in the shelter containing the telecommunication equipment.

The CAES system, that is composed by three compressors, two expanders and a storage tank, has the aim to store the energy surplus coming from the PV unit and to supply electric power when the PV output is insufficient in satisfying the electrical energy demand.

Moreover, in order to optimize the efficiency of the system, a thermal energy storage system is realized; thus, the energy expelled as heat during compression is recovered and reused during expansion. The innovation, introduced with the proposed CAES system, is based on the using of the cold air at the outlet of the last expander (during the discharging process for the energy production) that permits to obtain cooling power for polygeneration purpose.

In this paper, the authors, by applying the original sizing-design methodology presented in [6], aim to assess the optimal CAES system operating parameters, in terms of average storage pressure and operating pressure range of the air tank. This sensitivity analysis has been carried out considering the plant installation in three different climatic zones in order to evaluate the influence of the geographical conditions and of the average irradiation on the