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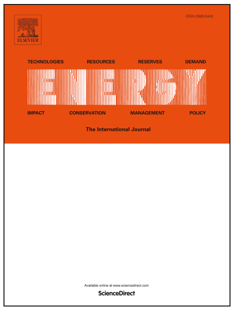

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Experimental study of a PH-CAES system: proof of concept

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Abstract

This article presents the experimental results of a novel energy storage system that combines CAES (Compressed Air Energy Storage) with PHES (Pumped Hydro Energy Storage) technologies. As a reference, we called this system PH-CAES. In this alternative solution two storage tanks, the first with compressed air and the second with water, are separated by a valve. When electric power is required, the valve is opened and water flows to a Pelton turbine, which is coupled to an electric generator. Water from the Pelton turbine is discharged into a third tank. To store energy and recover the initial state, water is pumped back. We built a prototype to assess the PH-CAES performance, with focus on the power generation system. Experimental conversion efficiency was 45%, whilst the rational efficiency remained close to 30%. We also presented a discussion based on the second law of thermodynamics to show that there is a compromise between tanks exergies that maximizes the system performance. We also provide an operating map of this PH-CAES system to assist authors on new studies about this novel technology.

Keywords:
Energy storage system, hydraulic turbine, PH-CAES, CAES.

1. Introduction

The concept of CAES (Compressed Air Energy Storage) systems first appeared in the 1940s, when Stal Laval filed a patent, using an underground cavern for compressed air storage [1]. By the mid-1970s, the interest in the CAES technologies increased, and currently two large-scale CAES power plants are operating [2, 3]. One of them, with a 321 MW current capacity was built in the 1970s in Huntorf, Germany, and the other was built in 1991 in McIntosh, Alabama, USA, with an installed capacity of 110 MW [4–6].

Recent interest in CAES relies on the application to renewable and intermittent sources to pressurize atmospheric air and store it inside natural or artificial caves. This stored compressed air is released and expanded into a turbine [4] generating energy, when needed.

During the compression stage, heat is generated as the air pressure increases. This heat may or may not be stored and recovered to increase the CAES round-trip efficiency. In this sense, authors usually divide CAES systems into three main categories [4]: adiabatic (A-CAES), diabatic (D-CAES) and isothermal (I-CAES). In the first one, heat generated by compression is stored in Thermal Energy Storage (TES) tanks, and recovered when expansion takes place [7–9]. Conversely, on D-CAES, heat is lost to the surroundings, and during the expansion process, the compressed air must be heated by an external source before entering the turbine [10, 11]. On the latter, I-CAES, multi-stage compressors with intercoolers prevent air to change temperature among the stages [12, 13]. Other different approaches can be found in the literature. Facci *et al.* [14] proposes a trigenerative (T-CAES) approach to small scale CAES in which heat is taken from the system between compression stages and returned during the expansion. Sun *et al.* [15], conversely, studied integrating a conventional wind turbine with a CAES system, which in turn, utilizes a scroll turbine, with power conversion efficiency peaking at 55 %. In [16], authors studied the integration of a CAES system to a diesel generator for applications in remote areas, with efficiencies varying from 50 to 77%. Similarly, [17] proposes a hybrid Wind-Diesel-Compressed Air Energy Storage system, in which the energy surplus is stored as compressed air, later used to assist diesel combustion in an electric generator, focusing in isolated rural areas. Kantharaj *et al.* [18] suggested to use compressed air of a CAES system as input of a liquefying cycle, and thus, storing liquefied air close to ambient pressures. In [19], authors examined an offshore underwater Compressed Air Storage System (named OCAES) to store energy coming from offshore wind turbines, and concluded that this concept is not economically viable yet. In [20], it is presented a multiple stage 2 MW underwater CAES (named UWCAES), with exergetic efficiency of around 54%. Cheung *et al.* [21] also worked with UWCAES, but instead of working with an offshore wind turbine, it operates with surplus energy coming from the power grid, and storage takes place underwater in air accumulators. Finally, [22] performed a study in the application of CAES in aquifers (CAESA), coupled with Aquifers Thermal Energy Storage (ATES).

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