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Review

A review on compressed air energy storage: Basic principles, past milestones and recent developments

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HIGHLIGHTS

- A review on the variety of CAES concepts and their historical background is given.
- An extensive classification and comparison of different CAES types is carried out.
- The concept of exergy is applied to enhance the fundamental understanding of CAES.
- The importance of accurate fluid property data for the design of CAES is examined.
- General aspects on CAES applications and upcoming R&D challenges are discussed.

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ABSTRACT

Over the past decades a variety of different approaches to realize Compressed Air Energy Storage (CAES) have been undertaken. This article gives an overview of present and past approaches by classifying and comparing CAES processes. This classification and comparison is substantiated by a broad historical background on how CAES has evolved over time from its very beginning until its most recent advancements. A broad review on the variety of CAES concepts and compressed air storage (CAS) options is given, evaluating their individual strengths and weaknesses. The concept of exergy is applied to CAES in order to enhance the fundamental understanding of CAES. Furthermore, the importance of accurate fluid property data for the calculation and design of CAES processes is discussed. In a final outlook upcoming R&D challenges are addressed.

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1. Introduction

Today the storage of electricity is of increased importance due to the rise of intermittent power feed-in by wind power and photovoltaics. Here, air can serve as a suitable storage medium by compressing it using an electrically driven compressor. At any later point in time the stored compressed air can be released and reconverted to electricity by means of a turbine generator – a very simple process already being applied for decades. There are various approaches to realize this seemingly simple process. Each process has its individual strengths and drawbacks, which have not been analyzed and compared thoroughly so far.

The present article attempts to give an overview on present and past approaches by classifying and comparing CAES processes. This classification and comparison is substantiated by a broad historical background on how compressed air energy storage (CAES) has evolved over time. The concept of exergy is applied to CAES in order to enhance the fundamental understanding of CAES. Furthermore, reasons are given why the usage of accurate fluid property data is especially important for the calculation and design of CAES processes. To summarize, the authors focus on both, theory and technology of CAES. Economic aspects are explicitly excluded because of their strong dependence on country-specific and short-term changing market conditions as well as on the political and regulatory framework. Due to that, an in-depth review of CAES economics would exceed the purpose of this article by far. Nevertheless, some general economic aspects of CAES applications are discussed wherever appropriate.

2. A brief history

In the manufacturing industry compressed air is broadly applied. Here, it is used either as an energy carrier for various processes like drilling or carving or it serves as a process fluid carrier e.g. for cleaning or varnishing. Either way, compressed air is generated almost exclusively on site by employing electrical energy. In Germany, for example, currently 16 TW h_{el} are consumed annually to provide compressed air for industrial purposes, which amounts to about 2.5% of the German overall electricity consumption [1].

Looking at utility scale energy supply, compressed air has never been established as an energy carrier. In comparison to electricity, gas and heat, its power density is lower and transportation losses are higher, which can be considered the main reason for this situation. Nevertheless, compressed air has been and still is applied as a storage medium for electrical energy at utility scale. Fig. 1 shows projects and R&D efforts over time, which will be described in detail later on.

2.1. How it all began

The fundamental idea to store electrical energy by means of compressed air dates back to the early 1940s [2]. By then the patent application "Means for Storing Fluids for Power Generation" was submitted by F.W. Gay to the US Patent Office [3]. However, until the late 1960s the development of compressed air energy storage (CAES) was pursued neither in science nor in industry. This can be ascribed to the lack of necessity for grid connected energy storage. It changed in the 1960s with the introduction of baseload generation in form of nuclear power and ever larger lignite coal fired power plants. Suddenly, there was an economic case to store inexpensive off-peak power from baseload generation capacities and transfer it to peak-load hours. Where possible this added value was taken advantage of by the installation of pumped hydro energy storage (PHES) plants. Nevertheless, PHES relies on suitable topological condi-tions, which limit its application to mountainous regions. In 1969, the need for storage capacity in northern Germany led to the decision to develop a CAES plant in this particular region. The decision was supported by suitable geological formations for storing large amounts of compressed gas in available underground salt domes. These salt domes were already used to build caverns reliably hosting large amounts of compressed natural gas. Furthermore, there was a need for black start capability for the northern German grid, which could be provided by CAES, too [4]. It is interesting to mention that the initial wording for the CAES technology by that time was still different. The utility Nordwestdeutsche Kraftwerke (NKW), which decided to build Huntorf, chose the acronym ASSET to label the new technology. ASSET stood for Air Storage System Energy Transfer plant indicating the utility's basic intention for the storage plant [5]. The technology supplier BBC Brown Boveri instead came up with the term "Gas Turbine Air Storage Peaking Plant" highlighting that CAES was basically derived from gas turbine technology serving as a peak-load capacity. None of the acronyms by that time is still in use today. The technical achievements connected to the development of the Huntorf plant still exist and will be described in greater detail in Section 4.1.

2.2. How the idea spread

Stimulated by the Huntorf project, the general interest in CAES technology began to rise by the mid-1970s [2,6]. Different from Europe, as the Huntorf plant was clearly industry driven, the US Department of Energy (DOE) initiated both an R&D and a predemonstration program for developing CAES, which was coordinated by the Pacific Northwest National Laboratory (PNNL) from the late 1970s to early 1980s [7,8]. The research and development (R&D) of the program focused on the following two major issues:

- Long-term reservoir stability criteria for CAES operating conditions.
- Feasibility of so-called second-generation CAES concepts including adiabatic CAES (A-CAES) aimed at minimizing the use of petroleum fuels for firing.

At the end of the research program diabatic CAES (D-CAES) was considered a technically feasible near-term technology. As a