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Assessment of geological resource potential for compressed air energy storage in global electricity supply

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ABSTRACT

This paper presents the geological resource potential of the compressed air energy storage (CAES) technology worldwide by overlaying suitable geological formations, salt deposits and aquifers. For this study, the world is divided into 145 regions, which are aggregated to 9 major regions. The potential of CAES in each region is assessed and a relevant map is provided. Three constraints have been implemented, allowing for 1%, 5% and 10% of the selected area to be considered for CAES. Among all major regions, in the most conservative constraint (1% of the total area), North America is the leader with 0.26% suitability of its total area, followed by Sub-Saharan Africa and South America at 0.20% and 0.19%, respectively. A sensitivity analysis is implemented to evaluate the validity and reliability of the results. Three scenarios are considered: Optimistic, Moderate and Pessimistic. Underground natural gas storage data for the US is used due to freely and publicly available data. The natural gas storage site is assumed to have the same structure as CAES. The sensitivity analysis shows that the accuracy of the findings lie in the range of 66–85% and 63–82%, depending on the scenarios and reservoir types. The results clearly reveal that CAES is a promising energy storage technology for electricity supply in most of the regions. This research presents the groundwork to identify the untapped potential of CAES, which can be also utilized for the second generation of CAES such as adiabatic CAES and isothermal CAES.

1. Introduction

1.1. Background and motivation

Renewable energy has gained the highest attention among all energy resources in the last decade as its cost has been decreasing rapidly [1,2]. The 'net zero' greenhouse gas emissions target around the mid-21st century agreed upon at the Conference of the Parties (COP21) in Paris clearly guides a pathway towards sustainability [3]. In 2015, renewable energy, excluding large hydropower projects, made up 54% of the installed power capacity of all technologies [2]. However, intermittency of renewable energy, in particular solar and wind energy, for electricity supply increases the need for flexibility, such as energy storage. In the case of onshore wind and solar photovoltaics (PV), outputs over the year are likely to be about 20–45% (1800–4000 full load hours) and 10–23% (900–2000 full load hours) of the capacity factors of each, respectively [2]. Therefore, some sort of balancing is needed to match electricity generation and demand.

Compressed air energy storage (CAES) technology is a known utility-scale storage technology able to store excess and low value off-peak power from baseload generation capacities and sell this power during peak demand periods. The first CAES plant, Huntorf, was established and developed near Huntorf, Lower Saxony in Germany, with a capacity of 290 MW and round-trip efficiency of 42% [4,5]. Another commercial scale CAES plant, McIntosh, was commissioned in 1991 and is located in McIntosh, Alabama, USA with a capacity of 110 MW and round-trip efficiency of 54% [6]. The higher efficiency in the McIntosh plant is due to a heat recuperator, which reuses part of the heat energy from the exhaust of the plant's gas turbine and leads to a reduction of fuel consumption by 22–25% [4,6].

The use of a large-scale power storage method has not been widely applied among storage technologies except for pumped hydro energy storage (PHES). CAES is the least cost utility-scale bulk storage system that is currently available apart from PHES [7,8]. It has to be noted that there are other large-scale thermo-mechanical storage options available as well. According to [9], power-to-heat-to-power (PHP) and pumped thermal energy storage (PTES) could technically be considered for development and utilization as future bulk energy storage. PHP is connected to thermal energy storage (TES) systems that have been advanced for renewable energy, e.g. concentrating solar thermal power. PTES can be implemented by various thermal cycles and working fluid, such as PTES based on water-steam cycle. It has been emphasized that

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Nomenclature

AA-CAES	advanced adiabatic compressed air energy storage
A-CAES	adiabatic compressed air energy storage
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
bcm	billion cubic meters of natural gas
CAES	compressed air energy storage
CAPEX	capital expenditure
COP21	21st yearly session of the Conference of the Parties
D-CAES	diabatic compressed air energy storage
EPRI	Electric Power Research Institute
GDEM	global digital elevation model
IEA	International Energy Agency
KBB	Kavernen Bau und Betriebs-GmbH
km^2	square kilometer
kW	kilowatt
kW h	kilowatt hour
LAES	liquid air energy storage
MENA	Middle East and North Africa
MW	megawatt
MW h	megawatt hour
NaS	sodium-sulfur
OPEX	operational expenditure
PB-KBB	Parsons Brinckerhoff (PB) Energy Storage Services
PHES	pumped hydro energy storage
PHP	power-to-heat-to-power
PNNL	Pacific Northwest National Laboratory
PTES	pumped thermal energy storage
PV	photovoltaic
R&D	research and development
SAARC	South Asian Association for Regional Cooperation
TES	thermal energy storage
TW h	terawatt hour
USD	United States Dollar
€	euro

Subscripts

el	electricity

the minimization of irreversibilities during charging and discharging could result in the best performance of PTES.

Several different studies with various applications and purposes have been carried out to further investigate and develop the concept of CAES. Bouman et al. [10] discuss that CAES in combination with wind can significantly decrease the environmental impact over a number of impact categories such as climate change, freshwater ecotoxicity and human toxicity compared to natural gas with carbon capture and storage technology. Briola et al. [11] implement a mathematical model to design a diabatic CAES (D-CAES) system with a special focus on finding the suitable turbomachinery geometry for the system. An energy and exergy analysis of adiabatic CAES (A-CAES) is performed in [12] using a dynamic mathematical model in order to identify the exergy destruction in different places. CAES and liquid air energy storage (LAES) have been thermodynamically analyzed in a dynamic simulation and the results indicate that LAES has greater benefits than CAES [13]. Lower volume requirement, higher efficiency and no restriction by location have been found to be the merits of LAES.

So far, the role of CAES in energy systems with high renewable energy penetration has been discussed in several studies [14–17]. Barbosa et al. [15] claimed that the need for A-CAES decreased in an energy system that only supplies the electricity demand of the power sector in South and Central America compared to an energy system with additional sector integration. It has been documented that the need for energy storage reduces when additional flexibility is accessible for the system through sector coupling. Denholm and Margolis [16] discussed the importance of energy storage (including CAES) that allows solar PV to effectively substitute for baseload generation by adding reliable capacity and improving the overall system flexibility. Integration of wind energy and CAES has been discussed by Daneshi et al. [18] and results reveal that when CAES is used in the system the power quality and reliability increased while generation cost declined. Sun et al. [19] studied the technical feasibility of a hybrid system by integrating a wind turbine with CAES. They concluded that hybrid wind/CAES is feasible with energy conversion efficiency of up to 55% under well-controlled operation conditions and it can be considered for future industrial applications.

In this paper, the geological resource potential for storing energy through CAES will be discussed from a global perspective. The following sections discuss the principle and technical characteristics of CAES, methodology to determine the geological resources suitable for CAES, and finally the appropriate sites and global potential for CAES. It is assumed that the identified location for storing the compressed air underground can be used for second generation of CAES as well, such as A-CAES and isothermal CAES. A sensitivity analysis is then conducted to evaluate the validity and reliability of the selected CAES area.

1.2. CAES and A-CAES system operations

CAES systems operate similarly to a conventional gas turbine. However, compression and expansion modes occur independently when needed. In CAES, air is pumped into the underground cavern and stored under pressure during off-peak hours in a process called compression mode (Fig. 1) [20,21]. During the compression mode, electricity is used to run the compressor in order to inject the air into the storage reservoir. The air compressor makes use of intercoolers and aftercoolers to achieve economy of compression, reducing the temperature of the injected air and decreasing the moisture content of the compressed air. As a consequence, the compression efficiency increases, the storage volume reduces and thermal stress on the storage walls is minimized.

The release of the pressurized air is implemented during the process called generation mode, and generates electricity when the greatest demand of energy is required. For this purpose, first, the pressurized air from the cavern is released and fed into a heat exchanger, known as recuperator. Next, the hot air enters a high pressure combustion chamber. In the combustion chamber, natural gas is used to heat the air further and then the exhaust in the high pressure expander is re-heated to a higher temperature before entering the low pressure expander. Excess heat is discharged into the atmosphere, e.g. at a temperature of around 138 °Celsius in the McIntosh plant. Then, the low pressure and high pressure expanders rotate the generator to generate electricity [20]. This process is best achieved together with a gas turbine or a turbine of an emergency generator in D-CAES (Fig. 1). A compressor is used to operate the CAES system during the day.

A-CAES has a different process compared to conventional CAES. In A-CAES, a second injection of heat for re-expansion is avoided. Instead, the heat from the compression mode is captured and stored separately in an extra TES facility. Then, the TES device re-injects the heat to overcome the need for other heat sources during the discharge phase (Fig. 1). Therefore, gas co-combustion is not needed to heat the compressed air and the round-trip efficiency of the process is increased substantially, up to 70% [24]. What makes the A-CAES an outstanding technology in comparison to D-CAES is that no fossil fuels are required for the combustion process and this allows the CO_2-neutral provision of peak-load electricity from renewable energy, in particular solar and