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Overview of current development in compressed air energy storage technology

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Abstract

With the rapid growth in electricity demand, it has been recognized that Electrical Energy Storage (EES) can bring numerous benefits to power system operation and energy management. Alongside Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage (CAES) is one of the commercialized EES technologies in large-scale available. Furthermore, the new advances in adiabatic CAES integrated with renewable energy power generation can provide a promising approach to achieving low-carbon targets. The small-scale CAES facilities are also attracting attention for more flexible power system applications. This paper will present an overview of different types of multi-scale CAES, including their working principles, current development, typical technical and economic characteristics, existing facilities, application potentials, challenges and issues associated with the future development of CAES.

Keywords: compressed air energy storage, overview; large and small scale; application area; technical and economic characteristics.

1. Introduction

Electrical Energy Storage (EES) has long been considered as crucial mechanism for ensuring power system operation stability and reliability. In particular, it has recently attracted more attentions due to the rapidly increasing renewable power generation. Pumped Hydroelectric Storage (PHS) is an EES technology with high technical maturity and large energy capacity. With an installed capacity of 127-129 GW in 2012, PHS represents around 99% worldwide bulk storage capacity [1, 2, 3]. In addition to PHS, CAES is another type of commercialized EES technology, which can provide above 100 MW of power output via a single unit as well as having bulk energy storage capacity [4]. CAES operates in the way of storing energy in the form of high pressure compressed air during the periods of low electrical energy demand and then releasing the stored compressed air energy to generate electricity to meet high demand during the peak time periods. CAES can be built to have the scales from small to large and the storage durations from short to long with moderate response time and good part-load performance in comparison

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with other EES technologies. A CAES installation refers to a system which integrates different interacting components, devices and processes, such as compressors, turbines/ expanders and electrical machines. CAES can combine with alternative EES technologies to achieve the required energy capacity, energy density, response time or efficiency.

Nowadays, different types of CAES technologies have been commercialized or are under development. This can make the difficulty to evaluate the current state of this important EES technology. The paper aims to provide an updated picture of the status of CAES technology to support the relevant R&D in both academia and industry. It starts with the introduction of working principles of different types of CAES, and then overviews the CAES technical and economic characteristics, commercialized facilities, the state-of-the-art, application potentials and challenges associated with the future development.

2. Working Principles of CAES

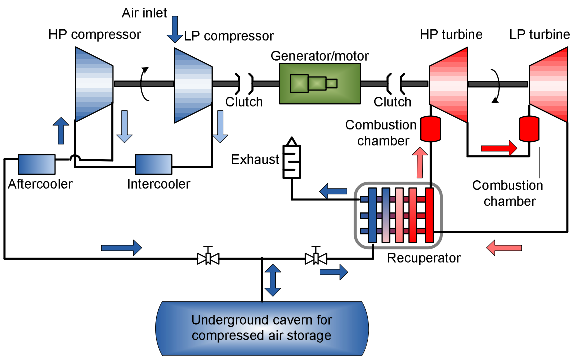

Fig.1 Schematic diagram of a conventional compressed air energy storage system

The working process of a traditional large-scale CAES plant is described as follows. During the compression mode the surplus electricity is used to run a chain of compressors to inject the air into a storage reservoir, normally an underground cavern for large-scale CAES. The compressed air is stored at a high pressure and at the temperature of the surrounding formation. Such a compression process can use coolers to reduce the working temperature of the injected air and thus to improve the compression efficiency (Fig. 1) [4]. During the expansion mode, the stored high pressure compressed air is released, heated, and then expanded through a group of turbines which includes gas turbine(s) and sometimes steam turbine(s) [4, 5, 6, 7]. The combustion process in the gas turbine with the mixed compressed air and fuel (typically natural gas) occurs in the combustion chamber of turbine(s). The turbines are connected to an electrical generator to generate electricity (Fig. 1). The waste heat of the overall system exhaust can be recycled before it is released into atmosphere [4, 5]. The main feature of conventional large-scale CAES plants is that it involves combusting fossil fuels via gas turbines, resulting in CO_2 emissions. Both the commercialized Huntorf (110 MW) and the McIntosh (290 MW) plants were implemented through the conventional CAES technology [4-6].

With the development of technology, several improvements and advanced concepts to large-scale CAES have been proposed. Among these concepts, the most promising CAES scheme is Advanced Adiabatic CAES (AA-CAES). When the AA-CAES system is operated at the expansion mode, by integrating a Thermal Energy Storage (TES) system, the energy stored in the compressed air is converted into the electrical power output without a combustion process involved (Fig. 2). Thus the significant benefit of AA-CAES systems is zero carbon emissions, assuming that the electricity for the compression mode is also from zero carbon energy sources. The processes of cooling airflow through compressors and the heating of input airflow to each turbine are completed by using the heat exchangers (Fig. 2). Theoretically, the overall roundtrip efficiency of AA-CAES is higher than that of the conventional CAES technology because AA-CAES systems reuse the heat generated from the compression process [4, 8].

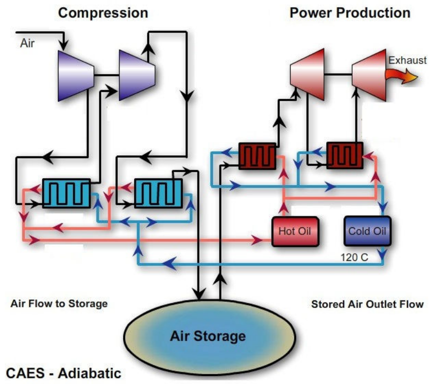

Fig. 2 Schematic layout of an AA-CAES plant [8]

Recently, a range of small-scale EES products (normally from a few kW level to around 10 MW) incorporating CAES have been developed. With the hybrid connection to capacitors/supercapacitors to bridging the transient responses, small-scale CAES appeared in the market as an alternative to the rechargeable battery for various applications. A small-scale CAES facility can use over-ground cylinders with suitable dimensions as a storage facility. The stored high-pressure compressed air can be obtained from an on-site compression facility or delivered to the site in the form of pre-filled high-pressure air cylinders. The air turbine/expander used to drive an electrical generator is the key component in such small-scale CAES facilities, which require high efficiency, fast response and low/free maintenance.

In addition, Liquid Air Energy Storage (LAES) can be considered as a variant of CAES because many components in a LAES system are also required by CAES and they have some similar sub-processes. The working process of LAES is: an electrical machine is used to drive an air liquefier and the resultant liquid air is stored in an insulated tank at atmospheric pressure; when electrical energy is required, the liquid air is released and pumped to high pressure in its liquid state, then vapourised and heated to the ambient temperature; finally the resultant high pressure gaseous air is used to drive a combination of a turbine and an alternator to generate electricity [9].

3. Commercialized CAES Facilities

The world's first utility-scale CAES plant was installed and commissioned by Brown Boveri at Huntorf, Germany, in 1978 [5, 7]. It was designed to provide a load following service and to meet the peak demand whilst maintaining a constant capacity factor in the nuclear power industry [4, 5]. After its operation, its functionality has been updated to buffering against the intermittence of wind energy production in Northern Germany [4]. The Huntorf CAES plant employs two salt dome caverns to store compressed air, which operates at a high pressure range between 4.8 MPa and 6.6 MPa [5-7]. Under working conditions the plant runs in a daily cycle with 8 hours of compressed air charging and 2 hours of expansion operation at a rated power of 290 MW [5]. It has been reported that the plant has operated in good condition and has consistently shown excellent performance with 90% availability and 99% starting reliability [4, 10]. The round-trip efficiency of this plant is about 42% [4, 5].

Another commercialized large-scale CAES facility started operation in McIntosh, Alabama, U.S., in 1991 [5]. The 110 MW plant is capable of continuously delivering its full power output for up to 26 hours. The plant is used to store off-peak power, generate peak power and provide spinning reserves [4, 5]. The plant utilises a single salt dome cavern to store the compressed air in the range of 4.5 MPa to 7.4 MPa [4-6]. The major improvement in comparison with the Huntorf plant is that the McIntosh facility employs a heat recuperator to reuse part of the heat energy from the exhaust of the gas turbine section. This reduces the fuel consumption by 22-25% and improves the cycle efficiency from ~42% to ~54 [5, 6]. Over the operation from 1998 to 2008, the plant has maintained an average starting reliability of between 91.2% and 92.1%, and an average running reliability of 96.8% and 99.5% for the generation and compression section respectively [4].

The hybrid Compressed Air Battery (CAB) system is developed by a UK based company - Energetix Group, with a small-scale power rating range between 2 kW and a few MW [11]. Such products are currently at the early stage to be recognised by market and consumers. The key factor for the success of the hybrid CAB is the adaptation of the newly developed scroll expander technology which has led to high expansion efficiency [12, 13]. As the system uses pre-prepared compressed air, it only focused on the expansion process without considering the compression process. The hybrid connection to supercapacitor pack allows the hybrid CAB system to have fast responses. Thus the hybrid CAB system is a new clean energy technology, appeared in the application areas of Uninterruptable Power Supplies (UPS) and back-up power supplies. The firm claimed that the design has a number of benefits, such as low initial investment and low maintenance cost compared to conventional UPS/standby chemical batteries, and outstanding power reliability [11]. Launched in August 2012, the Cooperative Bank's Pyramid building became the first major data centre in the world to use an Energetix Group compressed air electricity generating system [14]. Energetix Group firmly believes that it can be a direct competitor for traditional electrical battery and large rotary flywheel solutions. The hybrid CAB facilities have been adopted by companies including UK National Grid, Telecom Italia (Italy), Eskom (South Africa), ATK (U.S.) and Harris (U.S.) [11].

4. Current Research and Development

RWE Power, General Electric, Züblin and DLR are now working on the world first large-scale AA-CAES demonstration project, named ADELE, in Germany. Some challenging technical difficulties must be overcome in implementing this large-scale AA-CAES system. For instance, the AA-CAES requires the design of a high-pressure and high-temperature compressor with considerations of thermo stresses and thermal limitations for bearings and lubrication [16]. The ADELE plant will compress air at the period of the available renewables –wind power generation exceeding demand, place the resulting heat in an interim heat-storage mechanism and inject the compressed air into caverns. When electricity demand rises, the stored compressed air can be used to generate power through a turbine whilst recovering the heat [15]. Thus the ADELE plant can store electrical energy completely without CO_2 emissions. The plant is planned to have a storage capacity of 360MWh and a power output of 90MW, with the aim of 70% cycle efficiency [15, 16].

The Iowa Stored Energy Park project was planned by Iowa Association of Municipal Utilities. The project's intention was to build a 270MW CAES plant coupled with 75MW to 100MW of wind capacity, and was planned to be operational by 2015 [17, 18]. The plant was designed to take surplus electrical energy generated by a wind farm at night and use it to compress air into a deep underground aquifer. However, the project had to be terminated in 2011 [17, 18]. After years of study, the investors concluded that the porous sandstone aquifers in Iowa are not suitable for CAES; the air stored in such aquifers cannot provide air flow fast enough to satisfy the requirements to form an effective CAES site [17, 18].

The UK based Highview Power Storage designed and assembled the UK's first pilot LAES facility (300 kW, 2.5 MWh) which has been operated at a 80 MW biomass plant since 2010 [19]. Highview claim that this technology will be capable of supplying tens or even hundreds of MW. In February 2014, this firm was awarded £8 million in funds from the UK government for a new 5MW/15MWh demonstration LAES project; the designed LAES system will be located alongside one landfill gas generation plant in the UK [19].

The Norton Energy Storage project by FirstEnergy Generation Corp (FGCO) was announced in 2009 [4, 20]. The intention is to build The Norton Energy Storage project in several phases, from about 270 MW to a total capacity of up to 2700 MW, with a storage pressure range from 55 bar to 110 bar [4, 5, 20]. In July 2013, it was reported that FirstEnergy Corp has delayed building the proposed CAES project due to current market conditions including low power prices and insufficient demand [21].

In 2007, Luminant and Shell-Wind Energy proposed wind farm projects in Texas [22]. The demonstration plant has planned be used to study the potential to generate base load power using wind power combined with CAES. After a long wait, in 2013, the project began, aiming to host 317 MW of CAES underground [23].

The US based LightSail Energy Ltd. is now developing an AA-CAES facility by using a reversible electric motor/generator unit and a reversible reciprocating piston machine [24]. The heat from compression is captured by the water spray and then stored; during expansion, the stored heat is sprayed into the compressed air. The company claimed that high thermodynamic efficiencies without sacrificing performance can be achieved based on the initial tests [24].

The CAES technology is also attracting attention in the academic area. A research team at the University of Warwick, U.K., are developing a new hybrid wind turbine system to integrate CAES through an innovative mechanical power transmission [25, 26]. The combination of a scroll expander and an alternator is used to serve as an "air-electricity transformer" which will generate electricity during the period of low wind speed. The mathematical model for the whole hybrid system has been described in recent publications and a multi-mode control strategy for this hybrid system was reported [25, 26]. A test rig under construction will be used to verify the model. In addition, the dynamic modelling and the control design of a hybrid EES system based on CAES and supercapacitors had been studied in [27].

5. Technical and Economic Characteristics of CAES

Table 1. Technical and economic characteristics of CAES relevant technologies [1, 4, 5, 11, 28-34]

Technology	Energy density	Power density	Specific energy	Power rating	Rated capacity
Large CAES	2-6 Wh/L	0.5-2 W/L	30-60 Wh/kg	110 & 290 MW	580 & 2860 MWh
small CAES	2-6 Wh/L	0.5-2 W/L	140Wh/kg at 300bar	0.003-3 MW	~0.002-0.01MWh
LAES	4 times than CAES	–	214 Wh/kg	0.3-2.5 MW	2.5 MWh
	Self-discharge	Lifetime	Cycling times	Discharge eff.	Round-trip eff.
Large CAES	Small	20-40 years	8000-12000	~70-79%	42%, 54%, 70%
small CAES	Very small	23+ years	Tested 30000	~75-90%	–
LAES	Small	20-40 years	–	–	55-80+%
	Storage duration	Discharge time	Power capital cost	Energy capital cost	O&M cost
Large CAES	Hours-months	1-24+ hours	~400-1000 $/kW	2-120 $/kWh	0.003 $/kWh
small CAES	Hours-months	Up to ~ 1 hour	~500-1500 $/kW	200-250 $/kWh	Very low
LAES	–	1-12+ hours	~900-2000 $/kW	260-530 $/kWh	–

Table 1 summarizes the important technical and economic characteristics of CAES relevant technologies. Among all the EES technologies, PHS and CAES have lower densities, thus they require large reservoirs for large scale applications. The response time to large-scale CAES is normally up to around 10 minutes [4, 5]. The round-trip efficiency, also named cycle efficiency, is an important index to EES technologies. The round-trip efficiency for large-scale CAES has increased from 42% (in 1978), ~54% (in 1991) to the expected 70% (AA-CAES, ADELE project, in 2011) [4-6, 15].

Two categories of compressors can be used for CAES facilities with different scales: positive displacement (e.g. reciprocating) and dynamic (e.g. axial flow and centrifugal). Reciprocating compressors are more suitable for small-scale CAES due to its low flow rate and high pressure ratio. Dynamic compressors are often used in series for large-scale CAES facilities. For instance, the multi-stage centrifugal compressor has been operated at Huntorf [7].

Similar to PHS, the major barrier to implement the underground CAES plant is the availability of appropriate geographical storage locations. So far, it is possible to build a CAES plant near salt caverns, hard rock and porous rock formations. In practice, the mature experience in constructing large-scale storage reservoirs is only in using mined cavities in salt domes.

6. Application Potentials and Challenges with Future Development of CAES

Table 2. Application potentials of CAES relevant technologies [1, 4, 5, 32-37]

Application area	Characteristics for applications	Suitable or potential CAES related technology
Power quality	~<1MW, response time (~milliseconds), discharge duration (milliseconds to seconds)	Hybrid systems with small-scale CAES and other EES technologies with fast response
Energy management	Multi-scale, response time (minutes), discharge duration (up to days)	Multi-scale CAES and LAES
Renewable back-up power	~100kW-40MW, response time (up to a few minutes), discharge duration (up to days)	CAES, hybrid systems with CAES and others with fast response may need, possible LAES
Time shifting	~1MW-100MW and even more, response time (minutes), discharge duration (~3-12hours)	Multi-scale CAES and LAES
Peak shaving	~100kW-100MW and even more, response time (minutes), discharge duration (~<10hours)	Multi-scale CAES and LAES
Load levelling	up to several hundreds of MW, response time (minutes), discharge duration (up to ~12hours)	Multi-scale CAES, possible LAES
Seasonal energy storage	~30 MW to 500 MW, discharge duration (weeks), response time (minutes)	Possible large-scale CAES and LAES
Black-start	Up to ~40MW, response time (~minutes), discharge duration (seconds to hours)	Multi-scale CAES, possible LAES
Spinning reserve	Up to MW, response time (up to a few seconds), discharge duration (30minutes to a few hours)	Possible the hybrid system with small-scale CAES and other EES technologies with fast response
Uninterruptible power supply	Up to ~5MW, response time (normally up to seconds), discharge duration (up to ~2hours)	hybrid system with small-scale CAES and other EES technologies with fast response
Transmission upgrade deferral	~10-100+ MW, response time (~minutes), storage time at rated capacity (1-6 hours)	Promising multi-scale CAES and LAES

Table 2 summarizes and predicts the power system and grid applications of CAES relevant technologies. Based on its characteristics, CAES technology can be used for grid-scale energy management in supporting load shifting, peak shaving and load levelling. Small-scale CAES can be used as an alternative to replace traditional chemical batteries and mechanical flywheels in back-up power and UPS applications. Also, with the features of moderate responses and good partial load operations, CAES offers strong potential for integration with intermittent renewable energy power generation to provide back-up power. This possibility is being considered to integrate the CAES facilities with wind farms, such as the developing ADELE AA-CAES project in Germany.

A Roadmap for CAES development in Europe was recently completed with the effort from European Association for Storage of Energy (EASE) and European Energy Research Alliance (EERA) [38]. The importance of development of CAES is well recognised in the research community and industrial sectors. However, the challenges associated with the future development of CAES needs to be overcome, which include: technology innovation in air compressors and expanders, urgent need for cooperation of engineers and scientists in different fields, further substantial improvement in efficiency, need for reduction in cost of constructing air reservoirs and the study of the potential environmental impact.

7. Summary

The paper provides an overview of the current development of CAES technology. It is found that small-scale CAES systems can offer a combination of good performance, long lifetime, low net environmental impact and reasonable cost compared to rechargeable batteries. Also, to a certain extent, the costs and performance depend on the scales of CAES. There are huge application potentials for CAES in strengthening the electric power system reliability and grid operations; however, there are challenges and barriers present for the further deployment. Funding support and joint effort from relevant sectors are required to speed up the technology innovation and breakthroughs to demonstrate the role of CAES in supporting power system and grid operations.

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