OVERVIEW OF CURRENT DEVELOPMENT ON COMPRESSED AIR ENERGY STORAGE

TECHNICAL REPORT

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1 INTRODUCTION

Electrical Energy Storage (EES) refers to a technological process, in which electrical energy is converted into different forms of energy suitable for storage and the energy stored can then be converted into electrical energy when needed. The history of EES technology can be dated back to the 19th century. The first rechargeable lead–acid battery was invented in 1859 and the first utility scale pumped hydro storage was installed in the 1890s [1-3]. EES with suitable scales 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 increased renewable power generation. It is well recognized that EES can bring numerous benefits to energy system operation and management. Among all the EES technologies, Pumped Hydroelectric Storage (PHS) is a well-known mature large-scale EES technology and is in commercial operation. Compressed Air Energy Storage (CAES) is another commercialized EES technology in large scale which can provide above 100 MW power output via a single unit.

CAES operates in the way of storing energy in the form of high pressure compressed air during the periods of low electric 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. Any one CAES installation refers to the establishment of a system with integration of different interacting components, devices and processes, such as compressors, turbines/expanders and electrical machines. CAES is often hybrid or combining with alternative energy storage technologies to achieve the required energy capacity, energy density, response time or efficiency. For instance, the combination of CAES with supercapacitor will improve its transition response performance; combining with thermal energy storage will reuse the heat generated from compression process which will improve the round-trip efficiency.

Successful CAES implementation derives from the mid of the 20th century. In 1949, S. Laval obtained the patent on using air to store power inside an underground air-storage cavern, which marked the new era of CAES applications [4]. The world's first utility-scale CAES plant was installed and commissioned to operation by Brown Boveri (today "Asea Brown Boveri (ABB)") at Huntorf, Germany, in 1978 [4]. It has the rated power generation of 290 MW, for providing load following service and meeting the peak demand while maintaining constant capacity factor in the nuclear power industry [4, 5]. As an available approach for peak load shifting in power grid operation and due to its relatively low cost compared to oil and gas prices through the 1980s to 1990s, the CAES technology development and its industrial applications continued staying attractive. In 1991, another large-scale CAES plant commenced operation in McIntosh, Alabama, US [5]. The 110 MW plant, with a storage capacity of 2,700 MWh, 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 [5, 6]. Recently, the interests to small-scale CAES and related hybrid systems are growing and technologies in this area are rapidly developing. It is expected to use CAES as an alternative to chemical batteries in many application areas, such as Uninterruptible Power Supplies (UPS), stand-alone and back-up power systems. For example, in 2009, Energetix Group launched its small-scale compressed air UPS products to the market [7]. Also, Liquid Air Energy Storage (LAES) can be considered as a variant of CAES since many important components needed in building a LAES system are also required by CAES, such as compressors, turbines/expanders, electric motors/generators and sometimes heat exchangers. The UK based Highview Power Storage implemented a pilot LAES facility (300 kW, 2.5 MWh storage capacity) that has been in operation at an 80 MW biomass plant since 2010 [8].

This report will introduce the working principles of CAES, current technology development, typical technical characteristics, existing facilities, application potentials , technological and economic challenges, and issues associated with future development of CAES.

2 WORKING PRINCIPLES OF CAES

The conventional CAES may be rooted from gas turbine technologies. The main feature of the conventional CAES is: it involves combusting fossil fuels via gas turbines and resulting in CO_2 emissions. In the conventional CAES system, the main shaft is used to connect all primary components including the compressors, a reversible electric machine and the turbines with clutches. Both the Huntorf and the McIntosh plants were implemented through the conventional CAES technology.

The working process of a conventional large-scale CAES plant can be considered to have the similarities to that of a gas turbine based power plant except that the process of CAES decouples the compression and expansion cycles of a gas turbine into two separate processes occurring at different time. Fig. 1 shows a schematic diagram for a typical large-scale CAES plant which is composed of six major sections:

- A motor/generator unit combined with clutch mechanisms to provide alternate engagement to the compression or the expansion mode.
- A multi-stage compressor unit operating with intercoolers and after-coolers, which can provide economic air compression operating process.
- A turbine train, containing both high-pressure and low-pressure turbines (the turbine with

the fossil fuel combustion has been used for the commissioned large-scale CAES plant);

- One or more cavities, used for storing a large amount of compressed air. The underground rock caverns can be built by excavating comparatively hard and impervious rock formations, salt caverns from solution.
- A power conditioning system, for converting the electricity to match the requirements of the motor/generator unit or the external power network.
- There are some auxiliaries in a typical large-scale CAES plant, used for control, energy saving, etc., such as fuel storage and heat recuperator units.

As stated above, the generator/motor unit is linked with all compressors and turbines through a common shaft (Fig. 1). A clutch mechanism decides the practical performance of the plant and the operation sequence.

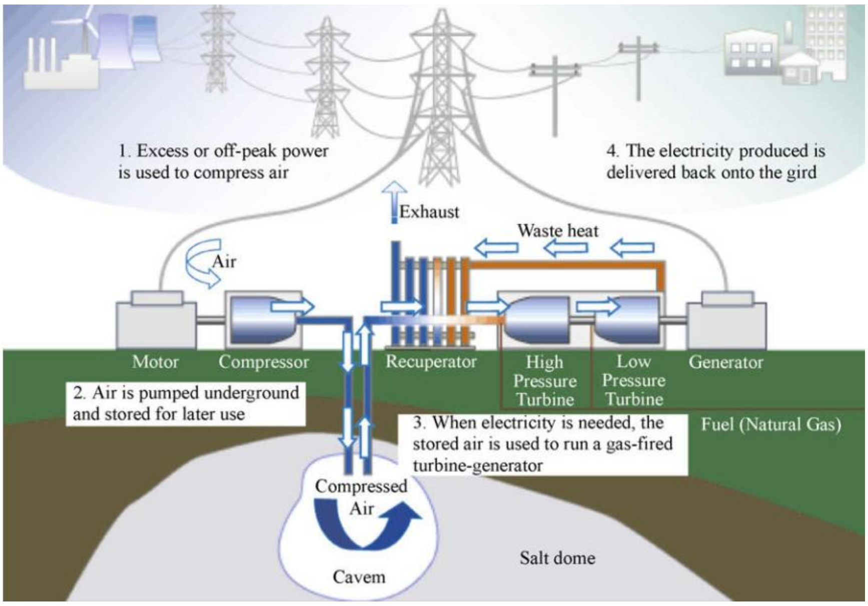


Fig.1 Schematic diagram of a compressed air energy storage system [9]

The compression mode of a typical CAES plant is activated at the time when the low demand presents. 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), and the stored compressed air is at a high pressure (typically 4.0-8.0 MPa) and the temperature of the surrounding formation. Such a compression process can use intercoolers and after-coolers to reduce the working temperature of the injected air thus to improve the compression efficiency and minimising thermal stress on the storage volume walls [5]. When the power generation cannot meet the demand, the expansion mode will be engaged. The stored high pressure compressed air is released from the storage reservoir, heated, and then expanded through a high-pressure turbine which can be a steam turbine or a gas turbine [5, 6, 10, 11]. If a gas turbine is chosen, the combustion process with the mixed compressed air and fuel (typically natural gas) occurs in the combustor of the high-pressure turbine. Then the gas from the outlet of high-pressure turbine mixed with additional fuel is combusted in the combustor of the low-pressure gas turbine. Both the high-pressure and low-pressure turbines are connected to an electrical generator to generate electricity (Fig. 1). The waste heat of the overall system exhaust can be recycled before released to atmosphere; for instance, a heat recuperator unit has been used to recover heat energy from the exhaust gas at McIntosh CAES plant. Also, it is worth noting that the airflow from the reservoir to the turbine must be high enough to meet the system operation requirements. The low temperature obtained from the incomplete or the absence of combustion in the expansion mode would pose a significant risk for turbine blades [5].

With the advancements in the technology of gas turbine systems, some improved designs to large-scale CAES have been proposed. For instance, one design is the CAES with Air Injection (CAES-AI) technology patented by Energy Storage and Power Corporation (ESPC). The concept is based on the injection of the stored and preheated air directly into the compressor discharge plenum to a gas turbine thus providing the gas turbine power increase. Based on the simulation and validation tests by ESPC, a CAES-AI system total power of ~137 MW can be a combination of the combustion turbine power of ~112 MW and the additional CAES power of 25 MW generated due to the air injection into of the additional stored air [12]. Fig. 2 shows the schematic layouts of the above technology. Compared to the conventional CAES systems, the proposed design can bring benefits on eliminating switchover time limitations by decoupling the compression and turbo expander train, improving energy efficiency, etc. Such improved large-scale CAES technology with the optimization design of the gas turbine system is currently still under the research and development.

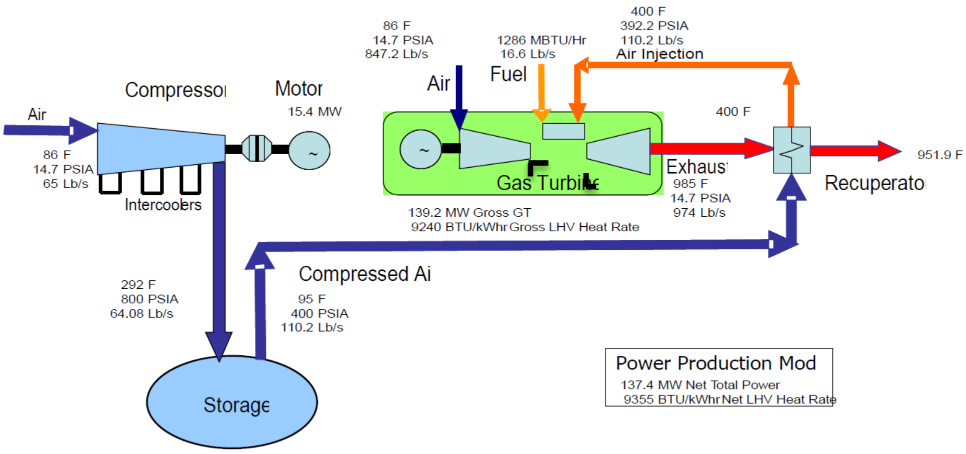


Fig. 2 Schematic layouts for CAES with air injection concept [13, 78]

Among the improved or advanced CAES technological proposals, the most promising CAES scheme is Advanced Adiabatic CAES (AA-CAES. Fig. 3 illustrates a schematic layout of such a CAES system. The air is adiabatically compressed and pumped into a storage reservoir.

When the AA-CAES system is operated at the expansion mode, by integrating a thermal energy storage subsystem, the energy stored in the compressed air is converted into the electrical power output without a combustion process involved. Thus the significant benefit of AA-CAES systems is zero carbon emissions assuming that the required electricity for the compression stage is also from zero carbon energy sources. The key component of such an AA-CAES system is the heat exchanger. The processes of cooling airflow through compressors and the heating of input airflow to each turbine are completed by using the heat exchangers. These heat exchangers absorb heat from the high-temperature compressed air and save the thermal energy for later uses to reheat the air before expansion. However, the heat exchangers and the material for transferring heat energy (Fig. 3, "hot oil" and "cold oil") may increase the cost of the overall system [14]. Thus the compressor and turbine trains associated with the efficiency and cost of the heat exchangers are the main concerns to AA-CAES. Theoretically, the overall roundtrip efficiency of AA-CAES is higher than that of the conventional CAES technology [5, 13]. AA-CAES technology is currently under development and building demonstration plants towards commercialization with different system scales. The technology for small scale AA-CAES is relatively more developed than the one used for large-scale systems. Several practical examples will be introduced in the later sections.

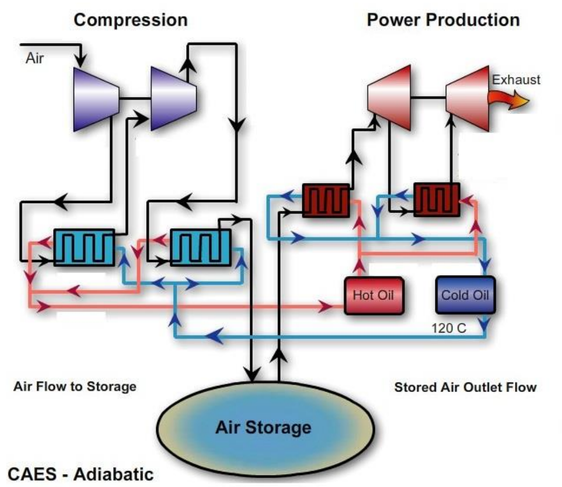


Fig. 3 Schematic layout of an AA-CAES plant [13]

The CAES has recently emerged in building a range of small-scale energy storage products, normally from a few kW level to around 10 MW. With the hybrid connection to capacitors/supercapacitors to bridge the transient responses, small-scale CAES appeared in the market as an alternative to the rechargeable battery for various applications. To the small-scale CAES facility, the storage reservoir can use over-ground cylinders or vessels with suitable dimensions. The stored high-pressure compressed air (the pressure can be much higher than that in underground caverns) can be obtained from on-site compression facility or delivered to the site in the form of pre-filled high-pressure air cylinders through the compressed air product supply chain. 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.

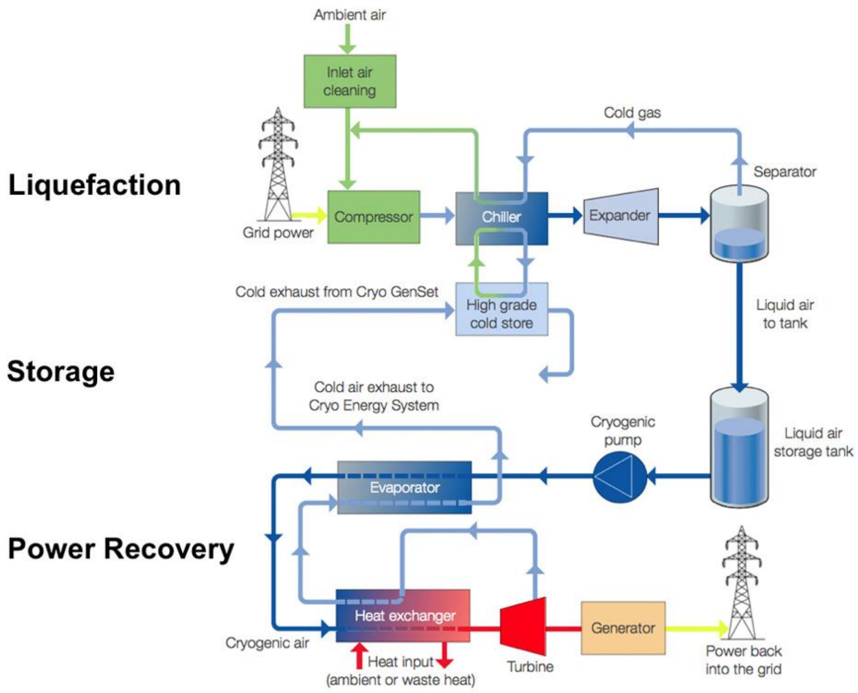


Fig. 4 Schematic layout of a liquid air energy storage plant (Picture courtesy of Highview) [15]

Liquefied air has a high expansion ratio between its liquid state (lower than -196 *ºC*) to, more common, gaseous state, which can expand about 700 times when re-gasified [15]. Thus the energy density of liquid air compares favourably with alternative energy storage of gaseous compressed air. Another advantage of LAES is that it can be bulk stored above ground in low-pressure tanks. Thus, compared to CAES, the main difference is that LAES uses liquefied air stored in a certain volume of tanks at atmospheric pressure. If considering energy storage material temperature, liquid air storage can be classified into cryogenic energy storage which employs cryogen (such as liquid nitrogen or air) to achieve the electrical and thermal energy conversion/storage. Fig. 4 shows a schematic layout of a liquid air storage plant. The working process of LAES is: using an electrical machine drives an air liquefier and then stores the resultant liquid air in an insulated tank at the atmospheric pressure; when electrical energy 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 [15].

3 INTRODUCTION OF COMMERCIALIZED CAES FACILITIES

3.1 THE HUNTORF CAES PLANT

The Huntorf CAES plant, the first commercialized large-scale CAES facility in the world, was built in Germany in 1978 [11]. The plant was designed to provide black-start power to nuclear units located near to the North Sea and also served to level and reduce the prices of the peak power demand. After the Huntorf CAES plant started operation, its mandate was updated to include the support of other facilities, such as back-up for the local power system, filling the energy gap due to the slow response of coal fired power plants, buffering against the intermittence of wind energy production in Northern Germany [5].

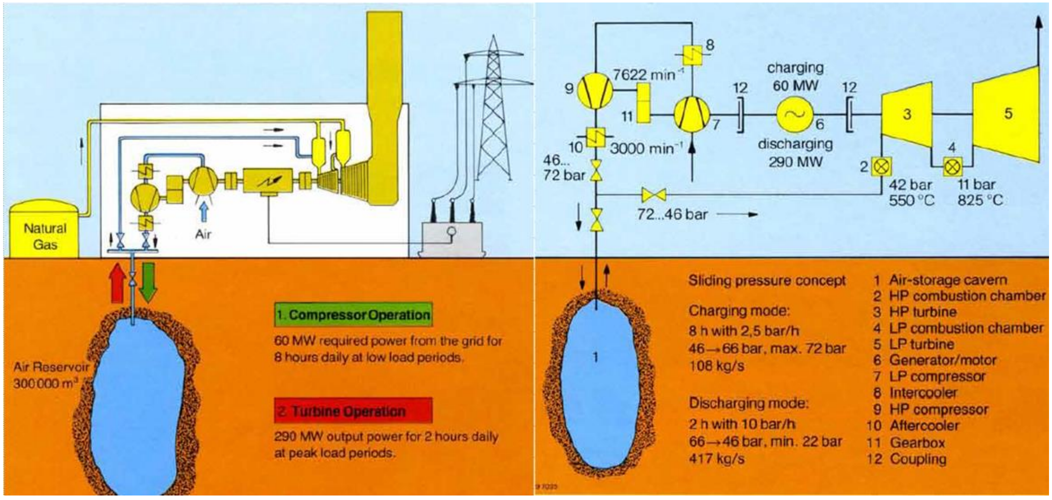


Fig. 5 Schematic layout of the CAES plant at Huntorf, Germany [11]

The Huntorf CAES plant employs two salt dome caverns to store compressed air. The caverns with a total volume of approximately 310,000 m^3, located over 600m below the ground, operated at a high pressure range between 4.8 MPa and 6.6 MPa [5, 6, 11]. The CAES compression unit operates with a maximum pressure output of 10 MPa [5, 11]. Under working condition the plant runs in a daily cycle with eight hours of compressed air charging and two hours of expansion operation at a rated power of 290 MW [6]. The plant has reliably operated over the last 30 years since it was built. It has been reported that the plant has run in good condition and consistently shown excellent performance with 90% availability and also 99% starting reliability respectively [4, 10]. The round-trip (cycle) efficiency of this plant is about 42% [6]. Fig. 5 illustrates the schematic diagram for the Huntorf CAES plant and Fig. 6 shows a view of the power house at the plant. From these figures, it can be seen that, there is a main shaft which is used to connect the compressors, motor/generator and turbines with clutches; the compression and expansion are both composed of low pressure and high pressure stages separately. The centrifugal compressor with at least six stages from low-pressure to high-pressure is used at Huntorf. The compression module is capable of drawing 108 kg/s, while the expansion module is capable of processing 417 kg/s of air [5, 6, 11].

Fig. 6 A view of the power house at the Huntorf CAES plant [17]

3.2 THE MCINTOSH CAES PLANT

Another commercialized large-scale CAES facility started operation in McIntosh, Alabama, U.S. in 1991 [6]. The project was implemented by Dresser-Rand, and the CAES plant was built by Alabama Electric Cooperative [5]. A schematic diagram to illustrate the structural layout of the McIntosh plant is shown in Fig. 7.

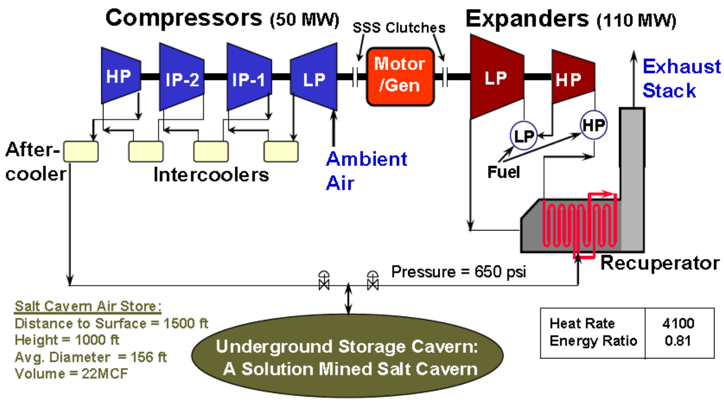


Fig. 7 Schematic layout of CAES plant at McIntosh, Alabama, U.S. [12]

The 110 MW McIntosh CAES plant was designed to be operated for up to 26 hours continuously at its full power. The storage capacity of plant is about 560,000 m^3, utilising a single salt dome cavern, about 450 m under the ground, to store the compressed air in the range of 4.5 MPa to 7.4 MPa [5, 6, 10]. From Fig. 7, it can be seen that the structure of McIntosh CAES plant is similar to that of the Huntorf CAES plant. The major improvement 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%, in comparison with the Huntorf plant [6, 10]. Fig. 8 shows the view of the mechanism inside the McIntosh CAES plant. Under normal operating conditions, the compressed air storage carven is partially recharged during weekday nights and is fully recharged at weekends. 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 [5].

Fig. 8 The compressor, generator/motor and turbine train in the McIntosh CAES plant [16]

3.3 Small-scale CAES Facilities

Small-scale CAES is now attracting the developers' attention and the associated technologies are emerging. A Compressed Air Battery (CAB) system is developed by a UK based company - Energetix Group, with a power rating range between 2 kW and a few MW [7]. Such type of products is currently at its early stage to be recognised by market and consumers. The key factor of success of the CAB product is adaptation of a new scroll expander technology which has led to high expansion efficiency. As the CAB uses pre-prepared compressed air, it only focused on the expansion process without considering the compression process. The hybrid connection to supercapacitor energy storage allows the CAB system to have fast responses matching the speed of chemical batteries, which become a new clean energy technology appeared in the application areas of Uninterruptable Power Supplies (UPS) and back-up power supplies.

The scroll technology has been mainly used in compressors for air conditioners and refrigerators [19, 20]. Recently, the scroll compressor technology has been reinvented to build scroll expanders, that is, expending the air instead of compressing it. The recent research has provided the evidence to explain why the scroll expander has relatively higher energy conversion efficiency compared with its traditional pneumatic counterparts [20-22].

(a) Parallel scroll expanders combined with supercapacitor array for high power applications

(b)

(b) Size from 1 to 50 kW of a single unit of compressed air battery system

Fig. 9 Compressed Air Battery (CAB) systems (courtesy of Energetix Group) [23]

Fig. 9 shows the structure of CAB systems produced from Energetix Group. From the figure, it can be seen that the whole CAB has a very compact structure due to the advantage brought by scroll expanders. Energetix Group 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, lower energy usage in standby mode and outstanding power reliability, which were proven from the experimental tests conducted by Energetix Group [7, 23]. Energetix Group has now produced standardised CAB back-up power systems with capacities of 3, 5, 10, 20, 100 and 200kW [24]. Energetix Group also produces relatively large-scale containerised 1 to 3MW Compressed Air Diesel Rotary UPS Systems which have been implemented for data centre UPS solutions. As launched on 13th August 2012, the Cooperative Bank's Pyramid building in Stockport U.K. has become the first major data centre in the world to use a compressed air electricity generating system made by Energetix Group to provide back-up power (Fig. 10) [25]. The company firmly believes that it can be a direct competitor for relatively large traditional electrical battery and large rotary flywheel solutions. The schematic diagram of an example of containerised compressed air UPS solutions for large-scale applications is shown in Fig. 11. The CAB facilities have been adopted by companies including UK National Grid, U.S. National Grid, Telecom Italia (Italy), Eskom (South Africa), ATK (U.S.) and Harris (U.S.) [7, 23, 24].

Fig. 10 A CAB back-up power system for a Cooperative Bank building in Stockport U.K. (Picture courtesy of Energetix Group) [23]

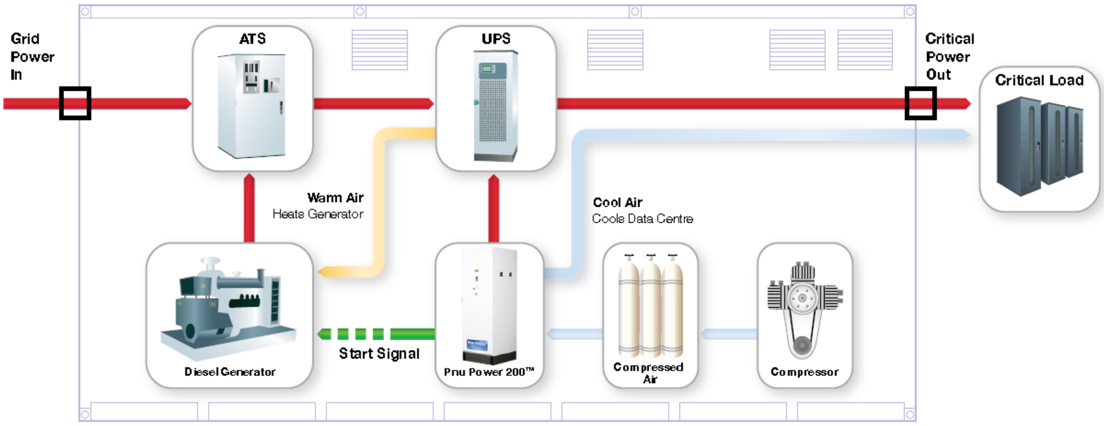


Fig. 11 Schematic diagram of containerised Pnu power UPS solution (Picture courtesy of Energetix Group) [24]

4 Current Research and Development of CAES

4.1 ADELE – Adiabatic Compressed Air Energy Storage Project

RWE Power, General Electric, Züblin and DLR are now working on the world first large-scale AA-CAES demonstration project, named ADELE in Germany (Fig. 12). The feasibility study that the project partners have laid for the ADELE development programme started in 2010 [26]. Some challenging technical difficulties must be overcome in implementing this AA-CAES system. For instance, without using intercooling, the air temperature inside the compressor can exceed 650K with up to 10MPa pressure [27]. This aggressive environment may damage the compressor and other mechanisms. Thus the AA-CAES requires the design of a high pressure and high temperature compressor with considerations of material selection, thermal expansion and thermo stresses, sealing concepts, and thermal limitations for bearings and lubrication [27, 28].

The designed ADELE plant is to compress air at the period of the available renewables - wind power more than demand, to place the resulting heat in an interim heat-storage mechanism and to inject the compressed air into subterranean caverns. When electricity demand rises, the stored compressed air can be used to generate power through a turbine – while recovering the heat [26]. So the ADELE plant can store electrical energy without CO_2 emissions. The site for this demonstration plant is located in Stassfurt, Saxony-Anhalt, Germany, and the plant is planed to have a storage capacity of 360MWh and a power output of 90MW, with the aim of 70% cycle efficiency [26-28]. The ADELE development phase has gained the available funding of €12 million by 2013, which is supported by Germany's Ministry of Economics and Technology (BMWi) with funds from the COORETEC programme [26]. More details to this world first large-scale AA-CAES demonstration plant can be found from the RWE website.

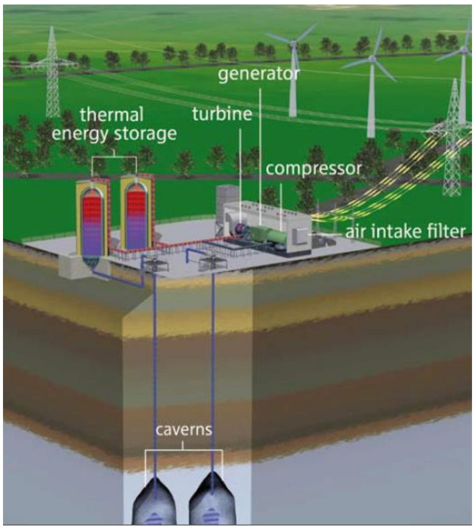


Fig. 12 Schematic diagram of the ADELE AA-CAES demonstration project [26]

4.2 IOWA STORED ENERGY PARK PROJECT – DISCONTINUED

The Iowa Stored Energy Park project was planned by Iowa Association of Municipal Utilities, which is depicted in Fig. 13. The project intension was to build a 270MW CAES plant coupled with 75MW to 100MW of wind capacity, and planned to be operational by 2015 [29，30]. The plant was designed to take surplus electrical energy generated by the wind farm at night and use it to compress air into a deep underground aquifer northwest of Des Moines. When power demand exceeds the power generation from the wind farm, the stored compressed air can be released through turbines in turn to drive electrical generators to fill the gap between generation and demand.

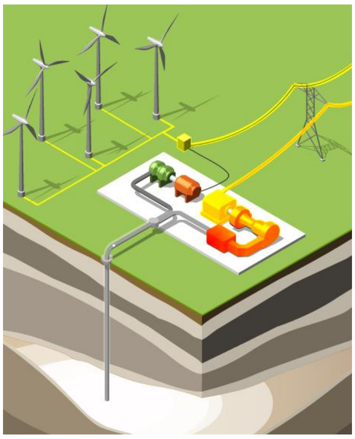


Fig. 13 Schematic diagram of CAES plant with wind farm at Iowa, U.S. [30]

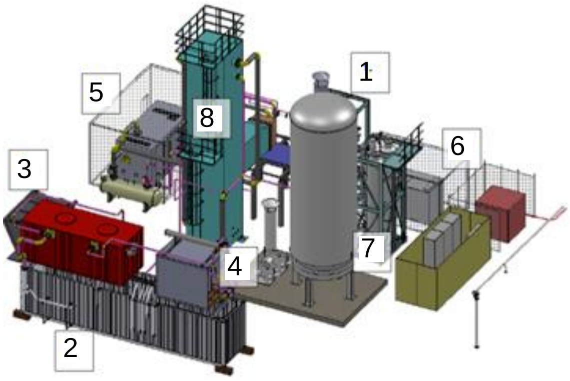
However, the Iowa Stored Energy Park project had to be terminated in 2011 [29, 30]. After years of study, the investors concluded that the porous sandstone aquifers in Iowa are not suitable for CAES; the air stored in such aquifers cannot provide air flow fast enough to satisfy the requirements to form an effective CAES site [29, 30].

Although the project was discontinued, it highlighted some promising economic findings and important lessons for other planned energy storage projects. Some of the legacy of the project include: research for seeking proper CAES reservoirs in challenging geological locations; detailed research into the difficult matter of comparable fund estimation and long-term economics of a CAES facility; insight into the gaps of expertise and engineers for different professional fields [29, 30]. Although the porous sandstone geologic formations have successfully been used for underground natural gas storage for decades, the tests for CAES storage failed from the initial on-site test study [29]. Also from a financial point of view, the budget estimation of the Iowa project was inaccurate. When the project required to raise the capital investment, unfortunately this was not achieved [31]. A detailed study for this discontinued project can be found in the ‘Lessons from Iowa’ Summary Report from U.S. Department of Energy [30].

4.3 HIGHVIEW LIQUID AIR ENERGY STORAGE PILOT PROJECT

The UK based Highview Power Storage designed and assembled the UK first pilot liquid air energy storage facility (300 kW, 2.5 MWh) has been operated at a Scottish and Southern Energy's 80 MW biomass plant since 2010 (Fig. 14) [32]. One London-based company operates the pilot plant. The current obvious drawback is efficiency, lower than 25%; the pilot plant was not built with efficiency in mind, which will be improved up to around 50% for the future demonstrations [32, 33].

(a) A view of the Highview pilot liquid air energy storage facility



1. Cryogen storage
2. Existing Power recovery
3. High grade cold store
4. Cold circulation compressor
5. Recycle compressor
6. Main compressor
7. Air purification unit
8. Main cold box

(b) Structure and main components of the Highview pilot facility

Fig. 14 Highview pilot liquid air energy storage facility at Slough, U.K.

(Picture courtesy of Highview) [15]

Highview claimed that, this technology will be capable of supplying tens or even hundreds of megawatts, and a single 50 tonne tank, a standard piece of kit widely used in the chemical industry, could store enough liquid air to power around 15,000 homes for an hour [15]. The firm has now put forward proposals for two plants that have won competition funding, including its first commercial-scale facility storing energy from the UK National Grid when it is needed, on which construction could start if the plant gets through to the next stage of the competition [33].

4.4 OTHER PROPOSED CAES DEMONSTRATION PROJECTS

The Norton energy storage project by FirstEnergy Generation Corp (FGCO) was announced in 2009. As an initial action, FGCO declared that it purchased a 92-acre site for approximately $35 million to develop a compressed air electric generating plant [10]. The project plans to convert a 600 acre underground idle limestone mine in Norton, Ohio into the storage reservoir for a CAES plant, which can operate within the pressure range from 55 bar to 110 bar [5, 34]. With 9.6 million cubic meters of storage, the Norton Energy Storage project intends to be built in several phases, from about 270 MW to a total capacity of up to 2700 MW [6, 34]. In July 2013, it is reported that FirstEnergy Corp has delayed building the proposed CAES project due to the current market condition including low power prices and insufficient demand [76].

A demonstration project in Dong Sheng, Inner Mongolia, P.R. China, named “advanced large-scale compressed air energy storage system”, with 15-20 MW, has recently been proposed; its corresponding initial test system (1.5 MW, Lang Fang, He Bei) now is under the construction stage and is near completion, which aims to achieve 50-65% cycle efficiency [35, 36].

Ridge Energy Storage & Grid Services L.P. announced to build a 4×135 MW system in Matagorda County, Texas, based on the McIntosh Dresser-Rand design [11]. The proposed system aims to utilize a previously developed brine cavern. The salt dome formations have been used at the existing Huntorf and McIntosh sites. Thus this geological condition has been proven to work well under CAES operations [10]. In 2007, Luminant and Shell-Wind Energy had proposed wind farm projects in Texas and the companies also intended to evaluate the potential for incorporating CAES facilities in conjunction with the wind farm projects [37]. The demonstration plant has planned to make the study of the ability to generate base load power using wind power combined with CAES. After a long wait, in 2013, the project gets underway aiming for hosting 317 MW of CAES underground [75].

The US based LightSail Energy Ltd. now is developing an AA-CAES facility by using a reversible electric motor/generator unit and a reversible reciprocating piston machine [43]. To the designed system, 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 through the initial tests [43].

4.5 CURRENT RESEARCH IN THE AREA OF CAES

CAES is not just a single technology so the research and development efforts need to pay attentions to all the relevant components, devices and system technologies, such as compressors, turbines/ expanders, electrical machines, electric power conditioning, etc. The technology advancement can improve the round-trip (cycle) efficiency of CAES and reduce the capital investment and/or the maintenance cost. Technology development will make CAES technology more competitive compared with other EES technologies. In addition, the research on geologic formations of caverns is currently active which lays the ground in seeking suitable locations for building appropriate storage reservoirs.

The key challenge for incorporating large amounts of wind power into the grid is its inherent intermittency. The research team at from the University of Warwick, U.K., addresses this issue by developing a new hybrid wind turbine system to integrate CAES with wind power generation through its mechanical power transmission [38, 39]. Fig. 15 presents the block diagram of small-scale hybrid wind turbine with CAES. This structure may reduce the cost of the whole system construction and improve the dynamic transmission of the associated wind turbines compared with other published systems ([40]). From Fig. 15, 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 [38, 39]. A test rig under construction in the laboratory is to verify the theoretic development of model. The simulation study has demonstrated that the proposed new hybrid wind turbine system is feasible and has potential for industrial applications.

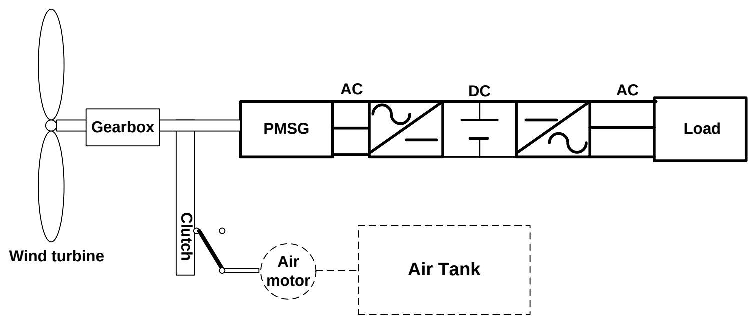


Fig. 15 Schematic diagram of the small-scale hybrid wind turbine system with CAES [38]

One published IEEE journal paper presents the dynamic modelling and the control design of hybrid energy storage system based on CAES and supercapacitors (see Fig. 16) [41]. The designed system converts excess energy from the power supply to stored pneumatic energy by using a compressor. The energy delivered to the power system is controlled through an intermittent operation of the pneumatic converter [41]. In order to smooth the desired output power of the system, a supercapacitors bank is utilized. Power electronics and its control play a significant role in the integration of the whole EES system into the network. The dynamic performance of the proposed systems is evaluated by the simulation study in SimPower Toolbox of MATLAB/Simulink.

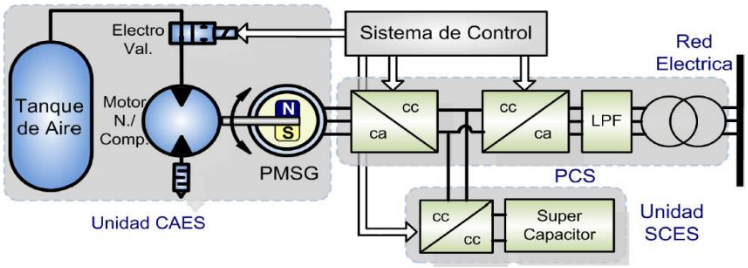


Fig. 16 Structure of the hybrid EES system with CAES and supercapacitors [41]

A system of the renewable energy applications for uninterruptible power supply based on CAES was reported recently (see Fig. 17) [42]. The system is composed of an EES system and an electric power supply system. The energy transferred from the renewable to the CAES system drives the air compressor to produce high-pressure compressed air to be stored in a vessel [42]. The paper focused on the thermodynamic study to analysis the behaviour and performance of the proposed system. To the simulation, the air flow under the variation of wind speed and pressure ratio conditions, the system energy efficiency under varied expansion pressure conditions were studied [42]. The paper concluded that the proposed system can be used for back-up power and peak shaping for energy management applications.

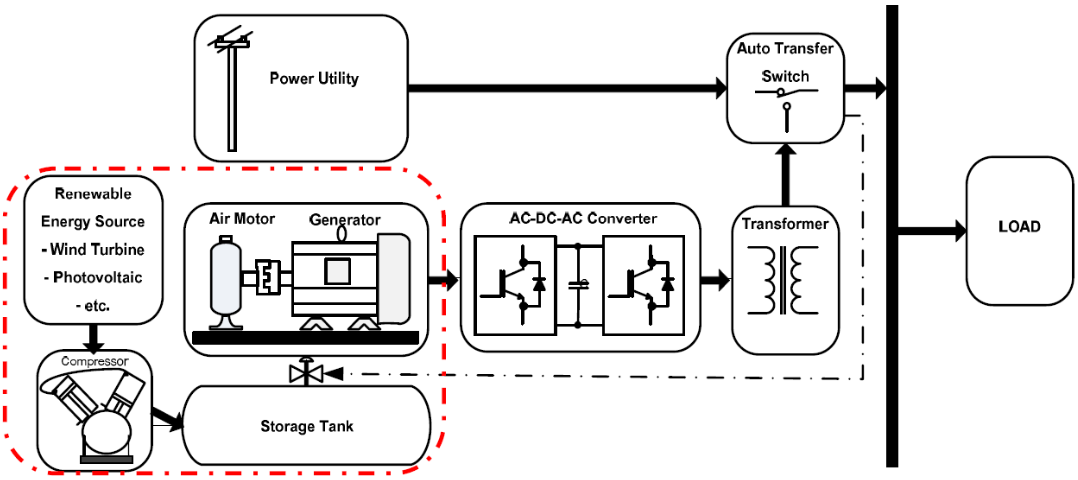


Fig. 17 Simplify diagram of renewable energy applications for UPS based on CAES [42]

5 OVERVIEW OF THE GEOLOGICAL STUDY OF UNDERGROUND CAVERNS FOR CAES

There are three main types of geological structures that are suitable or possibly suitable for CAES storage reservoirs: salt, hard rock and porous rock [5, 44, 45]. The previous research would seem to suggest that vast areas have the geological conditions needed for CASE. An example of this is that over 75% area of the U.S. has one or more of these three geologic conditions [44, 45]. In practice, more detailed studies and evaluations are necessary to verify the suitability and feasibility for compressed air storage of a specific location.

5.1 SALT CAVERN

The salt dome is the most favourable geological structure for solution mining cavities. It can be straightforward to employ and operate this type of solution cavities for compressed air storage. The knowledge acquired from the storage of high-pressure hydrocarbon products, such as liquefied petroleum gas and natural gas, can be easily exploited. Both of the two existing commercialized CAES plants (the Huntorf plant in Germany and the McIntosh plant in U.S.) use cavities mined into salt domes as the compressed air storage reservoirs.

Salt caverns for compressed air storage can be built through the solution mining technique which can provide a low cost and reliable approach. The initial capital cost of such a storage system is about 2-10 $/kWh [5, 46, 77]. Solution mining is the technique of using water or other liquids to dissolve, extract salt from a salt strata, thereby forming a large cavity in the salt with the appropriate size and shape. The elasto-plastic property of salt means that the cavern walls retain their structural integrity even after successive pressurisation cycles, thus salt caverns can make good reservoirs to suffer minimal degradation in long term usage and to pose minimal risk from air leak [47, 48]. The underground salt deposits exist in two forms: salt domes and salt beds. Salt domes are more suited to the design and development of caverns with large volumes for compressed air storage. Fig. 18 shows potential locations for CAES in the EU countries and the US, which are coincided to have the close locations between high wind potential and salt domes. The figure indicates that it could be some prospects for CAES, especially in Europe.

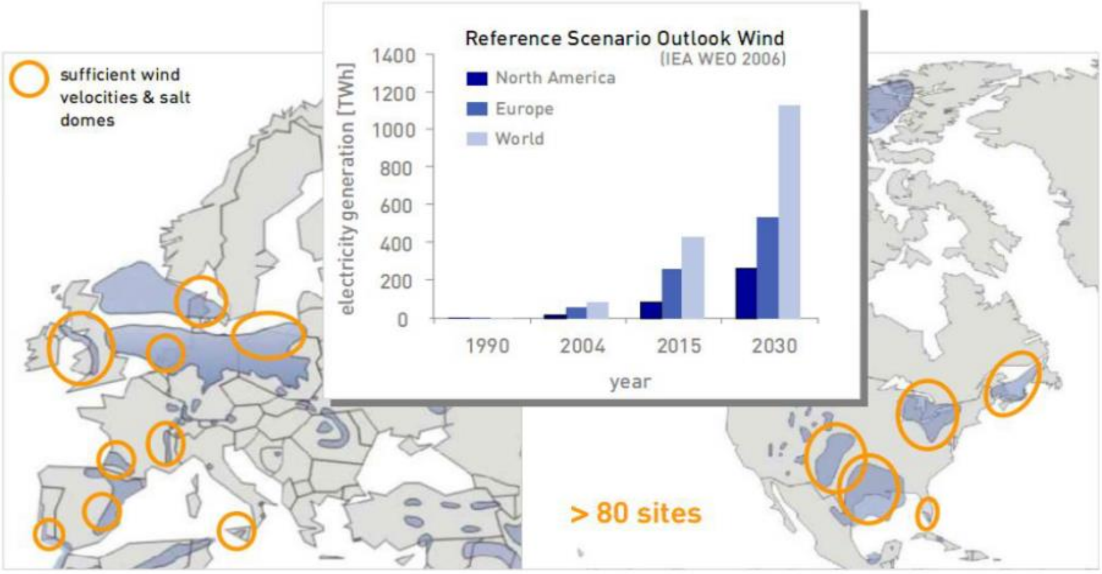


Fig. 18 Potential Locations for CAES in the EU and the US
(Coincidence of High Wind Potential and Salt Domes) [5, 49]

5.2 Hard Rock

Hard rock formations are another option for underground CAES reservoirs. However, the cost of mining a new reservoir is relatively high, typically 30 $/kWh [10, 46]. The available depth for hard rock CAES storage caverns can be within the range of 300 m to 1500 m underground [50, 51]. Several proposed CAES projects plan to use the existing mines (hard rock formations), which can reduce the cost of constructing reservoirs. The Norton energy storage project intends to use an underground cavern that was formerly operated as a limestone mine in Norton, Ohio [5, 34]. A 2MW field test program had used a concrete-lined tunnel in the former Sunagaawa Coal Mine in Japan [46]. Another test facility made by Electric Power Research Institute (EPRI) and the Luxembourg utility Societe Electrique de l'Our SA had employed an excavated hard-rock cavern with water compensation, which had been used for a CAES feasibility study [52]. From the above it can be seen that, although the use of hard rock caverns is one of available approaches for large-scale CAES facility projects, it has restrictions because of the relatively high initial capital cost of their construction when compared to the cost of manufacturing salt caverns and there is only the limited number of suitable existing hard caverns.

5.3 Porous Rock

Porous rock formations may offer one more option for storing compressed air underground in large volumes. The significant advantage of using porous reservoirs is that they offer very low cost characteristic; it was reported that the estimated development cost is approximately 0.10-0.11 $/kWh [5, 46].

Several feasibility study projects of porous rock for CAES had been attempted. Enel, Italy's largest power company, operated a 25 MW porous rock-based CAES research facility plant in Sesta using a porous rock storage that had previously held carbon dioxide near a geothermal region [46]. Although the initial air cyclic testing was successful, additional testing was stopped due to a disturbed geothermal event. Strata Power, EPRI, Nicor, and U.S. Development of Energy (DOE), had tested the porous sandstone caverns in Pittsfield, Illinois to determine the feasibility of using the porous rock formations there for storing compressed air. The test results indicated that compressed air can be stored and cycled successfully in the St. Peter sandstone underneath the Pittsfield site. However, the period for air storage was limited as the stored compressed air would react with local pyrites in the sandstone [53]. The Iowa Stored Energy Park project described above aimed to use porous sandstone aquifers in Iowa. Unfortunately, this project was stopped in 2011, and the main reason for its termination was the lack of geological structures that would allow the compressed air to flow efficiently to match the specifications for building CAES plants [29, 30].

From the above description, although there is a potential for using porous rock formations for underground CAES, it still requires extensive research into the geologic characteristics of the porous rock at the candidate sites to determine their feasibilities.

5.4 Geological Investigation in the UK

The distribution of the possible underground storage sites in the UK are shown in Fig. 19 which sourced from a report by a foresight project looking at the potential sites for natural gas storage. The potential areas mainly lie in parts of England and Northern Ireland [54]. It is seen that there are limited areas suitable for building salt caverns for underground CAES in the UK.

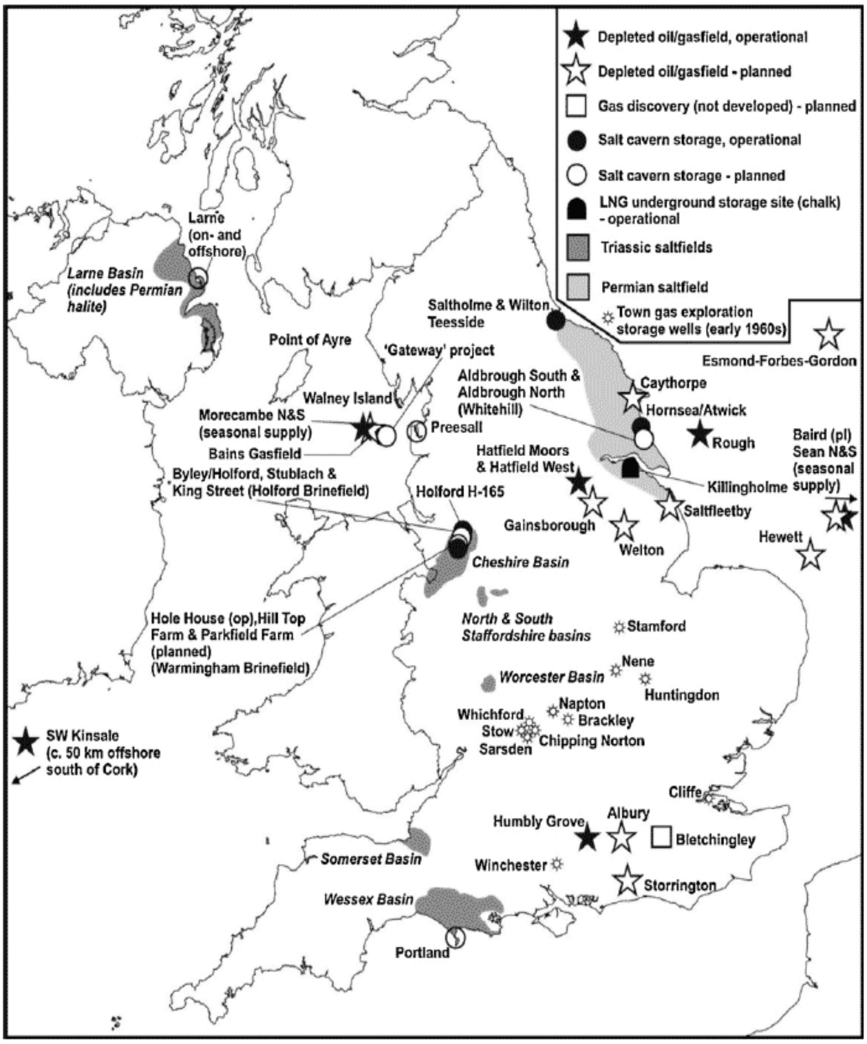


Fig. 19 Locations of operational and proposed UK underground gas storage sites [54]

6 DESCRIPTION OF CAES TECHNOLOGICAL CHARACTERISTICS

The following technological characteristics are important in design and building CAES plants:

- *Rated capacity (or rated energy capacity)*: the total quantity of available energy from the storage system after fully charged. The SI unit of storage capacity is Joule (J). Watt-hour (Wh) and megawatt-hour (MWh) are usually used instead. The currently available CAES plant has the rated capacity up to 2860 MWh; the rated capacity of small-scale CAES is dependent on applications which can vary from a few kWh to around MWh; the existing LAES plant has the rated capacity of 2.5 MWh [5, 6, 8, 15].
- *Specific energy*: the energy per kilogram, in units of the joule per kilogram (J/kg) or the watt-hour per kilogram (Wh/kg). The specific energy of CAES related includes: from 30 to 60 Wh/kg (large-scale CAES); 140 Wh/kg at 300 bar (stored compressed air in cylinders);

214 Wh/kg (LAES) [5, 55].

- *Specific power (or power-to-weight ratio)*: the amount of obtained power per kilogram of a storage medium, in the unit of the watt per kilogram (W/kg). It is an important parameter measuring EES requirements for (hybrid) electric vehicles and other weight limited power sources. There is no available data to specific power of CAES.
- *Energy density*: the amount of energy stored per unit volume in a given system or region of space, in the watt-hour per cubic metre (Wh/m^3); to various types of batteries or liquid fuels, normally in the watt-hour per litre (Wh/L). In EES applications, the energy density relates to the volume of the storage reservoir, e.g. a cylinder or a fuel tank. To the same amount of volume, the higher the energy density of the storage medium is chosen, the more the energy can be stored or transported. The energy density of CAES is 2-6 Wh/L depending on air pressure, and the energy density of LAES is four times than that of CAES [2, 56].
- *Power density*: the amount of power per unit volume, usually expressed in the units of the watt per cubic metre (W/m^3) or the watt per litre (W/L). It is the rate of power on the basis of volume, which can be taken from an energy source. The power density of CAES is within the range from 0.5 to 2 W/L [6].
- *Power rating*: To an EES system, the power rating indicates the maximum rate at which the system can discharge energy, expressed in the units of kilowatt (kW) or megawatt (MW). The power ratings to CAES related are: up to ~1000 MW (large-scale CAES); from a few of kW to a few of MW (small-scale CAES); up to 200 MW (LAES) [7, 57, 58].
- *Part-load operation*: The CAES plant has the high part-load operation ability, which makes it well suited for cooperative work with variable power sources such as wind power generation [5]. The CAES facility output can be controlled by adjusting the airflow rate with inlet temperatures keeping constant at the multi-expansion stage, which leads to better heat utilization and higher efficiency during part-load operation compared to a conventional (gas) turbine system [63].
- *Discharge time duration at power rating*: to an EES system, the amount of time that the system must be able to discharge, at the system power rating, without recharging [57]. The discharge time duration, as a characteristic of system adequacy, is determined by the depth of discharge and operational conditions of the system. To CAES related, the discharge time duration can have: up to ~26 hours (large-scale CAES); up to around 1-2 hour (small-scale CAES); from 1 to 12 hours (LAES) [5, 23, 59].
- *Response time*: The response time of a large-scale CAES plant can be faster than that of an equivalent gas turbine plant. The McIntosh plant can increase or decrease around 18MW per minute, which is about 60% higher than a comparable typical gas turbine facility [27]. The proposed Matagorda Plant is designed to be able to bring its 4×135 MW power train modules to full power in 14 minutes (or 7 minutes for an emergency start) [10]. The

response time of the small-scale CAES can be quicker (from seconds to minutes) than that of large-scale CAES and LAES (minutes).

- *Self-discharge rate*: indicates how long storage system takes to discharge when the system unused. Self-discharge can be caused by the liquid, gas or electromagnetic leakages and the heat dissipation. The self-discharge rates to CAES and LAES are both quite small [5, 7, 59].
- *Heat rate*: The heat rate indicates the fuel consumed per kWh of output for a CAES plant [10]. Heat rates for CAES systems without a heat recovery system are typically 5500-6000 kJ/kWh Lower Heating Value (LHV) and heat rates with a recuperator are typically 4200-4500kJ /kWh LHV [5, 63]. The Huntorf plant, with a rated output of 290 MW over 3 hours and an overall efficiency of 42%, has a heat rate of 5870 kJ/kWh LHV; the McIntosh plant recuperates the turbine exhaust heat, thus improving the overall efficiency to 53%, with a heat rate of 4330 kJ/kWh LHV [5, 64].
- *Recharge rate*: the rate at which power can be pushed for storage, for instance, a battery storage system may take 10 hours to deplete and 14 hours to refill [57]. To a CAES system, the recharge rate can be described as the quantity of compressed air per unit of time that replenishes a reservoir or a cavern.
- *Lifetime*: the service time of a unit or a system. To EES systems, it usually uses the number of year as its unit. It varies with technology and intensity of use. The PHS system has the longest lifetime in EES systems, approximately up to 50 years; the CAES and LAES systems have around from 20 to 40 years of lifetime [5, 57, 59, 60].
- *Cycling times (or cycle life)*: the number of times at which the EES system can be loaded and unloaded, that is, the total number of cycles of completing common charge and discharge cycles [57]. Normally, with the different rates of discharge depth, the cycling times varies. To CAES, the cycling times of large-scale CAES is 8000-12000; also, the small-scale compressed air battery system had been tested, about 30,000 stop/start operations [7, 61].
- *CAES reservoir operation methods*: According to the geological conditions, the operation methods for the compressed air reservoir of a large-scale CAES system mainly consists of two approaches as follows [5, 10, 62, 63]:

(1) Constant volume: the storage volume is fixed and the reservoir is operated over an appropriate pressure range. In this mode, there are two design options to control the reservoir output: a) the output pressure of reservoir is varied and then it can design a proper system to allow the high-pressure turbine inlet pressure to vary following with the reservoir output pressure; b) in the case of the reservoir output pressure varying, it can keep the inlet pressure of the high-pressure turbine constant by throttling the upstream valve to a fixed pressure. Both two existing CAES plants use this method. The Huntorf CAES plant is designed to throttle the air to 46 bar at the high-pressure turbine inlet (with

the cavern operating between 48 to 66 bar) and the McIntosh system similarly throttles the air to 45 bar (with the cavern operating between 45 and 74 bar).

(2) Constant pressure: it may be possible to keep the storage reservoir at constant pressure throughout operation by using a water compensation system by employing an aboveground reservoir (Fig. 20).

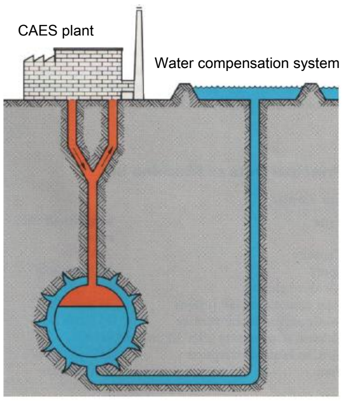


Fig. 20 Schematic diagram of CAES plant with constant-pressure compensation system [65]

- *Energy transfer of CAES plants*:

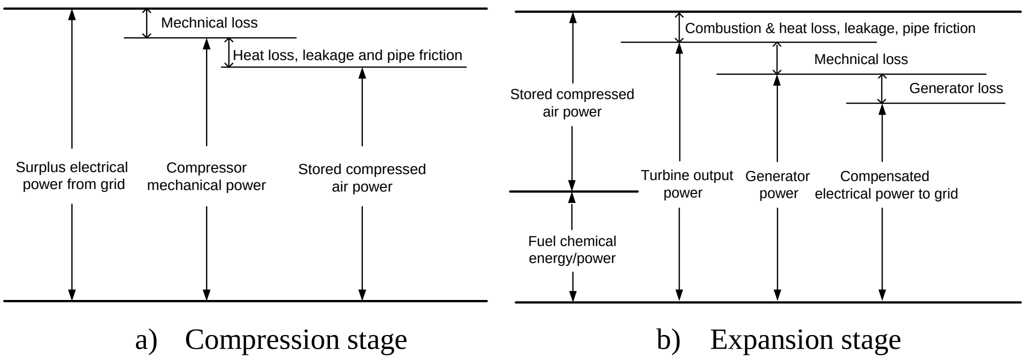


Fig. 21 Energy transmission and conversion in a typical CAES plant

To a traditional CAES plant, the energy transmission and conversion is schematically shown in Fig. 21. During the compression stage, the surplus electrical power from grid or from power generation systems drives the compressor. Thus the input electrical power is converted into the shaft mechanical power of the compressor in turn to the compressed air internal energy. During the expansion stage, the turbine train can restore the energy carried by the compressed air and utilise the fuel chemical power obtained from the combustion process to the shaft mechanical kinetic energy and finally to the compensated electrical power for the grid through driving an electric generator. For such an energy conversion and transmission process, energy losses are inevitable, such as heat losses, combustion losses, mechanical losses due to friction and vibration, etc.

- *Efficiencies*: there are mainly two types of efficiencies which have been considered in energy storage systems. One is energy conversion efficiency, also named energy efficiency. It is defined as the ratio between the useful output of an energy conversion machine from the CASE system and the input in energy terms [60, 61]. The input or useful output could be electric energy, mechanical work, heat energy, chemical energy, etc. [60]. Charge and discharge efficiencies normally contribute to the energy efficiency. Another is round-trip efficiency, also referred to as cycle efficiency [6, 57, 62]. It is the percentage to indicate the amount of energy output from an energy storage system for each unit of energy input [5, 62]. A unit with 70% round-trip efficiency means the energy storage system can return 7 kWh of energy for every 10 kWh put into storage.

  The situation is more complicated for analysing the energy performance of conventional CAES plants due to the presence of two substantial different energy inputs. On the one hand, the input electrical energy is used to drive the compressors; on the other hand, the fuel energy released in the combustion process is used to increase the air internal energy prior to expansion. Thus it is necessary to express both the fuel and compressor electricity on an equivalent energy basis. The roundtrip efficiency for CAES facilities can be: $\eta_{RT} = (energy\ output)/(energy\ input)$ [5, 6, 10]. To the traditional large-scale CAES plants, *energy output* is the output electrical power of generator (E_T) in the CAES plant, and an "effective" energy input is employed for efficiency calculation: $energy\ input = E_{compressor} + \eta_{ng} \times E_{ng}$,where $E_{compressor}$ is the electricity energy consumed by compressors, the second term ($\eta_{ng} \times E_{ng}$) is the amount of electricity that could have been made from the same fuel energy used in the CAES unit (E_{ng}) and the fuel had been used to make electricity in a stand-alone power plant at efficiency (η_{ng}) instead of using the fuel to fire in a CAES unit [5, 10]. To the AA-CAES plants and small-scale CAES facilities, *energy input* is purely the electrical power for driving compressors. From the published literature, the efficiencies related to CAES were reported to have different figures as follows:

  1) the discharge efficiency (i.e., the energy efficiency from the compressed air energy to electric energy) of conventional large-scale CAES is about 70-79% [72]; the discharge efficiency of small-scale CAES can be approximately 75-90% [24].
  2) the two existing commercial CAES plants, the Huntorf plant has an roundtrip efficiency of 42%; the roundtrip efficiency of the McIntosh plant, with the consideration of heat recuperation, is about 53~54% [5, 6, 11, 12, 16];
  3) the system based on the new CAES concept without involving fossil fuel combustion, such as AA-CAES, the roundtrip efficiency can achieve up to around 70%, which can

be similar to PHS [13, 26, 28].

- *Operation switching time*: To the two existing large-scale CAES plants, the turbine normally brings the machinery train to start rotation and speed up until synchronization, and then the turbine is shut down [5]. Thus the turbine needs to be engaged for operation at both the compression and expansion (electricity generation) modes. At the Huntorf CAES facility, the switch from one operating mode to another requires a minimum of 20 minutes [10]. This switching time may affect and limit the CAES plant application for balancing rapid fluctuations. One possible solution is to redesign the overall system structure by separating the compression and turbo expander components rather than linking them through a common shaft via the clutch mechanisms as in the McIntosh and Huntorf plants [5, 10, 11]. This design concept has been considered in the advanced CAES plants.
- *Operational constraints*: relevant to operational or working conditions (e.g. flow rate, temperature and pressure) and/or the safety issues (such as explosions, waste and bursting of a flywheel) [1]. As a function of energy needs, these constraints can influence the selection of a suitable technology used for a specific EES application. The Iowa Stored Energy Park project is a practical example: it had to stop in 2011 due to the airflow rate cannot satisfy the specifications of the proposed CAES plant requirements [30].
- *Compressors*: 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). Fig. 22 shows the pressure ratios versus the airflow rates to different types of compressors. From the comparison, the reciprocating compressors, confining air in a closed space and then reducing the volume to raise pressure, is more suitable for small-scale CAES due to its low flow rate and high pressure ratio. Dynamic compressors impart velocity to a stream of air and then convert the kinetic energy into potential energy (i.e., high pressure) [59]. Dynamic compressors often use in series to provide necessary increase in pressure, for instance, the multi-stage centrifugal compressor is operated at Huntorf [11].

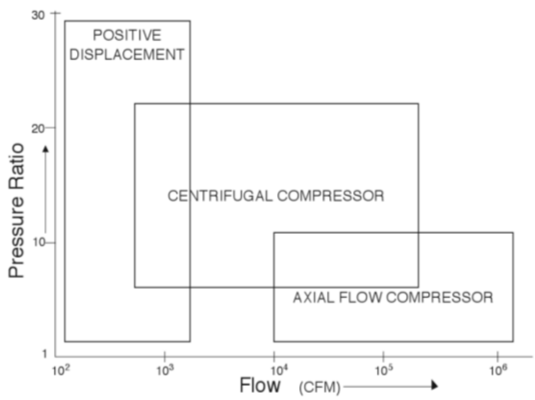


Fig. 22 Pressure ratios and flow rates of different types of compressors [59]

- <u>*Construction constraints*</u>: related to geographic limitations and/or environmental requirements. For instance, the large-scale underground CAES systems require the natural storage reservoir; the solar fuel generation usually need at an area with relatively high solar densities. These constraints can affect the selection of an appropriate EES technology for applications.
- <u>*Environmental aspect*</u>: the environmental issues must be considered as important factor for any new builds. The traditional CAES plants consume the fossil fuels which will definitely lead to CO_2 emissions. AA-CAES, small-scale CAES and LAES cannot employ gas turbines in the expansion mode to make the system environmental friendly. The impact of geological storage to the environment in a long term needs to be closely monitored.
- <u>*Other technical characteristics*</u>: The suitable storage duration for CASE can be from a few hours to several months because its self-discharge is very small. In addition, to the CAES plants, because compression energy is supplied separately at different time, the full output of the turbine can be used to generate electricity during expansion, whereas conventional gas turbines typically use two thirds of the output power from the expansion stage to run the compressor during their working processes [5, 10].
- <u>*Limitations*</u>:

1) Similar to the PHS, the major barrier to implement the underground CAES plant is to seek appropriate geographical storage locations. So far, it is possible to build a CAES plant nearby salt caverns, hard rock and porous rock formations. In practice, the mature experience on constructing large-scale storage reservoirs is only in using mined cavities in salt domes.
2) Traditional large-scale CAES plants require to combust diminishing fossil fuels, which will lead to carbon oxide emissions and environmental pollutions. To avoid the involvement of fossil fuel in CAES, some advanced CAES concepts are under the research and development stage, such as AA-CAES.

7 Economic Analysis Brief

The economic study to an EES technology is important and there has been continuously study reported year by year. The cost of storage technologies is changing with the continuous development of technology and the trend shows that the cost is normally getting cheaper with technology advancement. The paper ([64]) presents the overview of cost data for 25 MW to 220 MW CAES plants but it is outdated (published almost 30 years ago). A complete economic analysis needs to consider not only the capital cost but also the Operating & Maintenance (O&M) costs and the impact of the equipment life. The cost data to CAES related technology is described below.

Energy capital cost and power capital cost: the initial investment costs, usually expressed in the units of dollars per kilowatt-hour ($/kWh) and dollars per kilowatt ($/kW) respectively. The initial cost includes the spending on design, specification, civil works, and installation [1, 59]. Specifically to CAES and LAES, the reported data related to the power capital cost are: 1300-1550 $/kW (small-scale CAES), 400-1000 $/kW (large-scale CAES); 900-2000 $/kW (LAES); the reported data related to the energy capital cost have: 200-250 $/kWh (small-scale CAES), up to 120 $/kWh (large-scale CAES), 260-530 $/kWh (LAES) [6, 58, 66-68]. From the data, it can be seen that the cost relies on the scale. Among the mature and developed EES techniques, PHS and CAES have quite low energy capital costs compared to other technologies. Also it is worth mentioning that, to the underground large-scale CAES, normally 50-60% and even more of the capital cost will be spent on the construction of storage reservoirs [5]. From the above description of geological study, it can be seen that, to different geological formations, the cost can be quite different. In addition, the capital cost to a specific CAES system can be various from the data in cited references here due to, for example, the time of construction, the location of the plant/facility, and the size of the system.

Operating and maintenance cost: the costs in dollars per kilowatt-hour ($/kWh) for periodic inspection, fuelling, maintenance (e.g. adding lubricating oil), mechanical component replacements (such as seals and bearings) and electrical component replacements (such as wires and fuses), recalibration, clearing if need, etc. The operating and maintenance cost of CAES is 19-25$/kW per year [69]. The cost to LAES should be slightly higher than CAES due to its more complex process leading to the more components required.

8 APPLICATION POTENTIALS

From the characteristics of CAES, CAES facilities can be built in multi-scale ranges. The large-scale CAES plant can have the scale of up to 1000MW power rating [6, 7]. Thus CAES 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. The possibility is being considered and has attempted to integrate the CAES facility with the wind farm, such as the developing ADELE AA-CAES project in Germany. Table 1 summarizes and predicts the industry and the power grid applications of CAES.

Table 1 Application potentials of CAES related technology

Application area	Characteristics ([2, 14, 70-74])	Suitable or potential CAES related technology
Power quality	~<1MW, response time (~milliseconds, <1/4 cycle), discharge duration (milliseconds to seconds)	Hybrid systems with small-scale CAES and battery or supercapacitor or other EES technologies with fast response
Energy management	Large-scale (>100MW), medium/small-scale (<100MW), response time (minutes), discharge duration (up to days)	Large-scale energy management (large-scale CAES); Small-scale energy management (small-scale CAES, LAES)
Renewable back-up power	~100kW-40MW, response time (seconds to minutes), discharge duration (up to days)	Multi-scale CAES, hybrid systems with CAES and capacitor or others with fast response may need, possible LAES
Emergency back-up power	Up to ~1MW, response time (milliseconds to minutes), discharge duration (up to ~24hours)	Possible small-scale CAES, hybrid systems with small-scale CAES and other technologies with fast response
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 (hour level, ~<10hours)	Multi-scale CAES and LAES
Load levelling	up to several hundreds of MW, response time (minutes), discharge duration (up to ~12hours and even more)	Multi-scale CAES, possible LAES
Seasonal energy storage	Energy management, ~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 level, response time (normally up to a few seconds), discharge duration (30minutes to a few hours)	Possible the hybrid system with small-scale CAES and capacitor or other EES technologies with fast response
Uninterruptible power supply	Up to ~5MW, response time (normally up to seconds), discharge duration (~10minutes to 2hours)	hybrid system with small-scale CAES and supercapacitor or other EES technologies with fast response, e.g., Pnu power
Standing reserve	Around 1-100 MW, response time (<10 minutes), storage time at rated capacity (~1-5 hours)	Promising multi-scale CAES and LAES
Transmission upgrade deferral	~10-100+ MW, response time (~minutes), storage time at rated capacity (1-6 hours)	Promising multi-scale CAES and LAES

9 Challenges and Emergent Needs on Development of CAES

Roadmap for CAES development in Europe was completed with the effort from EERA. The importance of development of CAES is well recognised in the research community and industrial sectors. However, the challenges present and questions are not yet answered:

- What technical performance can be achievable by CAES by 2020/30/40/50?
- What cost levels are achievable for CAES systems in the long-term?
- What developments are required to achieve the above performance and costs?
- Over what time-scale might the technical breakthroughs happen and what will they cost?
- How to clarify the economic benefits from CAES and the related quantitative analysis?
- What are needed for stimulating and supporting innovation in CAES technology development?

Need for cooperation: Development of a complete CAES system especially to large-scale CAES is very challenging for any one company to tackle. The mechanism is urgently required to accommodate cooperation between complementary companies. Some obviously complementary areas are: compression/expansion machines, thermal storage & heat transfer, high pressure air storage and electromechanical power-conversion and grid interfacing. Also, it is necessary to galvanise some of the European world-leading turbo-machinery companies into developing products to address CAES market and thereby prepare to become world market leaders in this area.

Needs for new technologies in air compressors/expanders: Pnu-Power has shown an excellent example for the importance of new technology development. Without adopting the advanced efficient scroll air expander technology, it is impossible to have the market acceptable product – Compressed Air Battery. Technical innovations and technology breakthrough are essential, especially for compressor and turbine technology, such as developing improved sealing methods for compression & expansion machinery to suppress internal leakage and discovering approaches to minimise losses associated with secondary flows in compressors and turbines.

Need substantial improvement in efficiency: Compressed air is traditionally famous for its low efficiencies, which will no doubt affect its competitiveness and feasibility. The Huntorf plant has a cycle efficiency of 42%; the cycle efficiency of the McIntosh plant is about 53~54% [5, 6]. The low efficiencies of CAES result from the heat losses in the compression and expansion modes, the air leakage throughout the whole CAES system, the internal energy losses due to the air compressibility, etc. AA-CAES combined with thermal energy storage, which can reduce the heat losses, expects to achieve up to 70% of cycle efficiency. Effective turnaround efficiencies of >70% are certainly achievable by 2020. Values up to 80% will be achievable before 2030.

Need for the software tools for complete system analysis and integration with grid operation: A modelling tool for complete system simulation will help understand the whole system dynamics, efficiency improvement, operation optimisation. While a CAES system is connected with the grid or is imposed into the framework of smart grid operation, the tool will assist to design optimised control and operation strategy.

Need for reduction in cost of constructing air reservoirs: Reducing the construction cost of building large-scale underground cavities or over-ground reservoirs is challenging. Normally, more than 60% of the capital cost invested on building a CAES plant comes from the construction of the air reservoir.

Need for a clear map of underground storage resources: The large-scale CAES plant needs to seek appropriate geographical storage locations. It is important to conduct research and survey to gain a clearer picture of natural resources suitable for CAES and mapping the locations of storage and renewable energy sources. Currently, the mature experience on constructing large-scale storage reservoirs is only in using mined cavities in salt domes. The research is required to identify alternative suitable geologic structure for CAES and to develop lower-cost methods for building cavern formations.

Need for study of the potential environmental impact: The long term impact of underground storage to the environment should be assessed. It might cause competition with natural gas or CO2 storage while the limited storage resources are used for CAES as well. Also, current operating large-scale CAES plants require to combust diminishing fossil fuels, which will lead to carbon oxide emissions and environmental pollutions. AA-CAES and small-scale CAES normally have not this issue.

10 CONCLUDING REMARKS

This report provides an overview of the state-of-the-art of CAES technology development. It is found that the costs and performance largely depend on the scales; in general, with the same types of components in a CAES systems, large scale results in more efficient performance and lower cost. Small scale CAES systems offer a combination of good performance, long lifetime, low net environmental impact and reasonable cost compared to rechargeable batteries. There are huge application potentials for CAES in strengthening various aspects of electric power system reliable operations, however, the enormous challenges and barriers present for further deployment. Funding support and joint effort from academic and industrial sectors are required to speed up the technology innovation and breakthrough to realize the great potential of CAES and demonstrate its role in supporting power system operation.

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