Compressed Air Energy Storage

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Additional information is available at the end of the chapter

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1. Introduction

Electrical Energy Storage (EES) refers to a process of converting electrical energy from a power network into a form that can be stored for converting back to electrical energy when needed [1-3]. Such a process enables electricity to be produced at times of either low demand, low generation cost or from intermittent energy sources and to be used at times of high demand, high generation cost or when no other generation is available[1-9].The history of EES dates back to the turn of 20th century, when power stations often shut down for overnight, with lead-acid accumulators supplying the residual loads on the then direct current (DC) networks [2-4]. Utility companies eventually recognised the importance of the flexibility that energy storage provides in networks and the first central station energy storage, a Pumped Hydroelectric Storage (PHS), was in use in 1929[2][10-15]. Up to 2011, a total of more than 128 GW of EES has been installed all over the world [9-12]. EES systems is currently enjoying somewhat of a renaissance, for a variety of reasons including changes in the worldwide utility regulatory environment, an ever-increasing reliance on electricity in industry, commerce and the home, power quality/quality-of-supply issues, the growth of renewable energy as a major new source of electricity supply, and all combined with ever more stringent environmental requirements[3-4][6]. These factors, combined with the rapidly accelerating rate of technological development in many of the emerging electrical energy storage systems, with anticipated unit cost reductions, now make their practical applications look very attractive on future timescales of only years. The anticipated storage level will boost to 10~15% of delivered inventory for USA and European countries, and even higher for Japan in the near future[4][10].

There are numerous EES technologies including Pumped Hydroelectric Storage (PHS)[11-12][17], Compressed Air Energy Storage system (CAES)[18-22], Battery[23-27], Flow Battery[3-4][6][13], Fuel Cell[24][28], Solar Fuel[4][29], Superconducting Magnetic Energy Storage system (SMES)[30-32], Flywheel[13][16][33-34] and Capacitor and Supercapacitor[4][16]. However, only two kinds of EES technologies are credible for energy storage in large scale (above 100MW in single unit) i.e. PHS and CAES. PHS is the most widely implemented large-scale form of EES. Its principle is to store hydraulic potential energy by pumping water from a lower reservoir to an elevated reservoir. PHS is a mature technology with large volume, long storage period, high efficiency and relatively low capital cost per unit energy. However, it has a major drawback of the scarcity of available sites for two large reservoirs and one or two dams. A long lead time (typically ~10 years) and a large amount of cost (typically hundreds to thousands million US dollars) for construction and environmental issues (e.g. removing trees and vegetation from the large amounts of land prior to the reservoir being flooded) are the other three major constrains in the deployment of PHS. These drawbacks or constrains of PHS make CAES an attracting alternative for large scale energy storage. CAES is the only other commercially available technology (besides the PHS) able to provide the very-large system energy storage deliverability (above 100MW in single unit) to use for commodity storage or other large-scale storage.

The chapter aims to review research and application state-of-arts of CAES including principle, function and deployments. The chapter is structured in the following manner. Section 2 will give the principle of CAES. Technical characteristics of the CAES will be described in Section 3 in terms of power rating and discharge time, storage duration, energy efficiency, energy density, cycle life and life time, capital cost etc. Functions and deployments will be given in Sections 4 and 5. And research and development of new CAES technologies will be discussed in Section 6. Finally, concluding remarks will be made in Section 7.

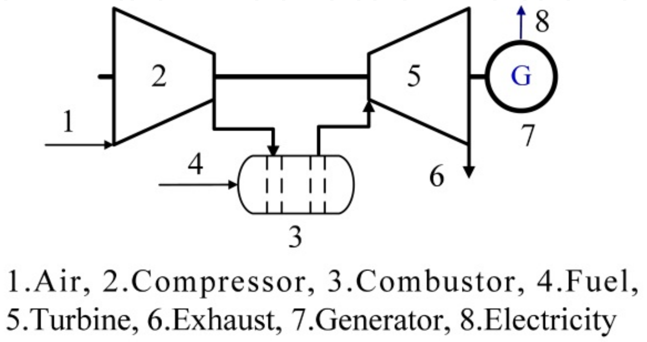
2. Principle

The concept of CAES can be dated back to 1949 when Stal Laval filed the first patent of CAES which used an underground cavern to store the compressed air[9]. Its principle is on the basis of conventional gas turbine generation. As shown in Figure 1, CAES decouples the compression and expansion cycle of a conventional gas turbine into two separated processes and stores the energy in the form of the elastic potential energy of compressed air. In low demand period, energy is stored by compressing air in an air tight space (typically 4.0~8.0 MPa) such as underground storage cavern. To extract the stored energy, compressed air is drawn from the storage vessel, mixed with fuel and combusted, and then expanded through a turbine. And the turbine is connected to a generator to produce electricity. The waste heat of the exhaust can be captured through a recuperator before being released to the atmosphere (figure 2).

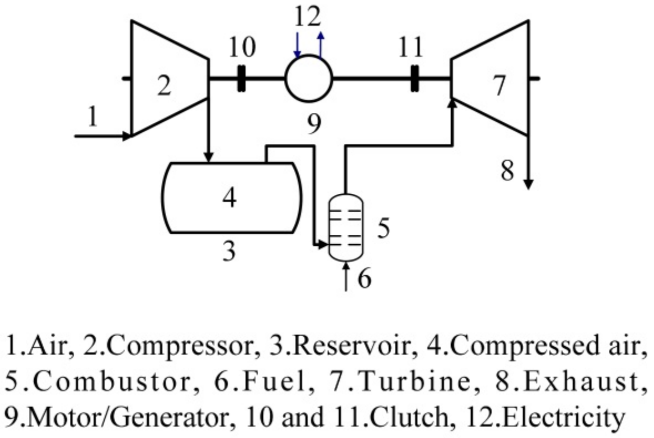
As shown in Figure 2, a CAES system is made of above-ground and below-ground components that combine man-made technology and natural geological formations to accept, store, and dispatch energy. There are six major components in a basic CAES installation including five above-ground and one under-ground components:

1. The motor/generator that employs clutches to provide for alternate engagement to the compressor or turbine trains.
2. The air compressor that may require two or more stages, intercoolers and after-coolers, to achieve economy of compression and reduce the moisture content of the compressed air.

3. The turbine train, containing both high- and low pressure turbines.
4. Equipment controls for operating the combustion turbine, compressor, and auxiliaries and to regulate and control changeover from generation mode to storage mode.
5. Auxiliary equipment consisting of fuel storage and handling, and mechanical and electrical systems for various heat exchangers required to support the operation of the facility.
6. The under-ground component is mainly the cavity used for the storage of the compressed air.



(a) Schematic diagram of GT system



(b) Schematic diagram of GT system

Figure 1. Schematic diagram of gas turbine and CAES system

The storage cavity can potentially be developed in three different categories of geologic formations: underground rock caverns created by excavating comparatively hard and impervious rock formations; salt caverns created by solution- or dry-mining of salt formations; and porous media reservoirs made by water-bearing aquifers or depleted gas or oil fields (for example, sandstone, fissured lime). Aquifers in particular can be very attractive as storage media because the compressed air will displace water, setting up a constant pressure storage system while the pressure in the alternative systems will vary when adding or releasing air.

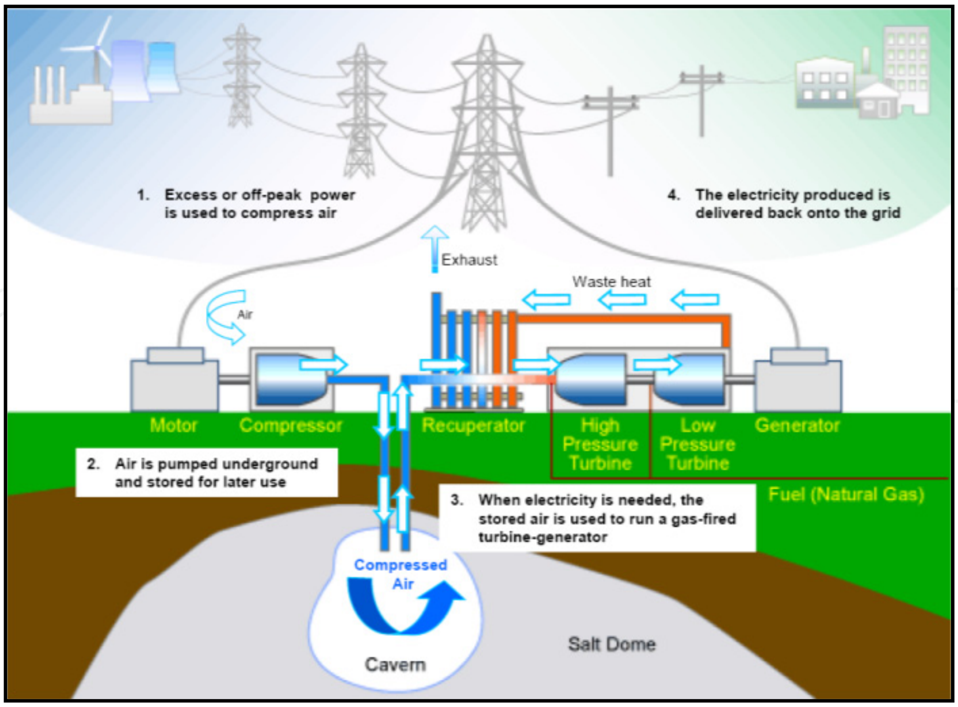


Figure 2. Components of CAES[35]

3. Technical characteristics

Figure 3 shows the comparison of technical characteristics between CAES and other EES technologies. One can see that CAES has a long storage period, low capital costs but relatively low efficiency. The typical ratings for a CAES system are in the range 50 to 300 MW and currently manufacturers can create CAES machinery for facilities ranging from 5 to 350 MW. The rating is much higher than for other storage technologies other than pumped hydro. The storage period is also longer than other storage methods since the losses are very small; actually a CAES system can be used to store energy for more than a year. The typical value of storage efficiency of CAES is in the range of 60-80%. Capital costs for CAES facilities vary depending on the type of underground storage but are typically in the range from \$400 to \$800 per kW. The typical specific energy density is 3-6 Wh/litre or 0.5-2 W/litre and the typical life time is 20-40 years.

Similar to PHS, the major barrier to implementation of CAES is also the reliance on favourable geography such as caverns hence is only economically feasible for power plants that have nearby rock mines, salt caverns, aquifers or depleted gas fields. In addition, in comparison with PHS and other currently available energy storage systems, CAES is not an independent system and requires to be associated the gas turbine plant. It cannot be used in other types of power plants such as coal-fired, nuclear, wind turbine or solar photovoltaic plants. More importantly, the combustion of fossil fuel leads to emission of contaminates such as nitrogen oxides and carbon oxide which render the CAES less attractive[19][36,37]. Many improved CAES are proposed or under investigation, for example Small Scale CAES with fabricated small vessels and **A**dvanced **A**diabatic CAES (AACAES) with TES[19][21], which will be discussed in Section 6.

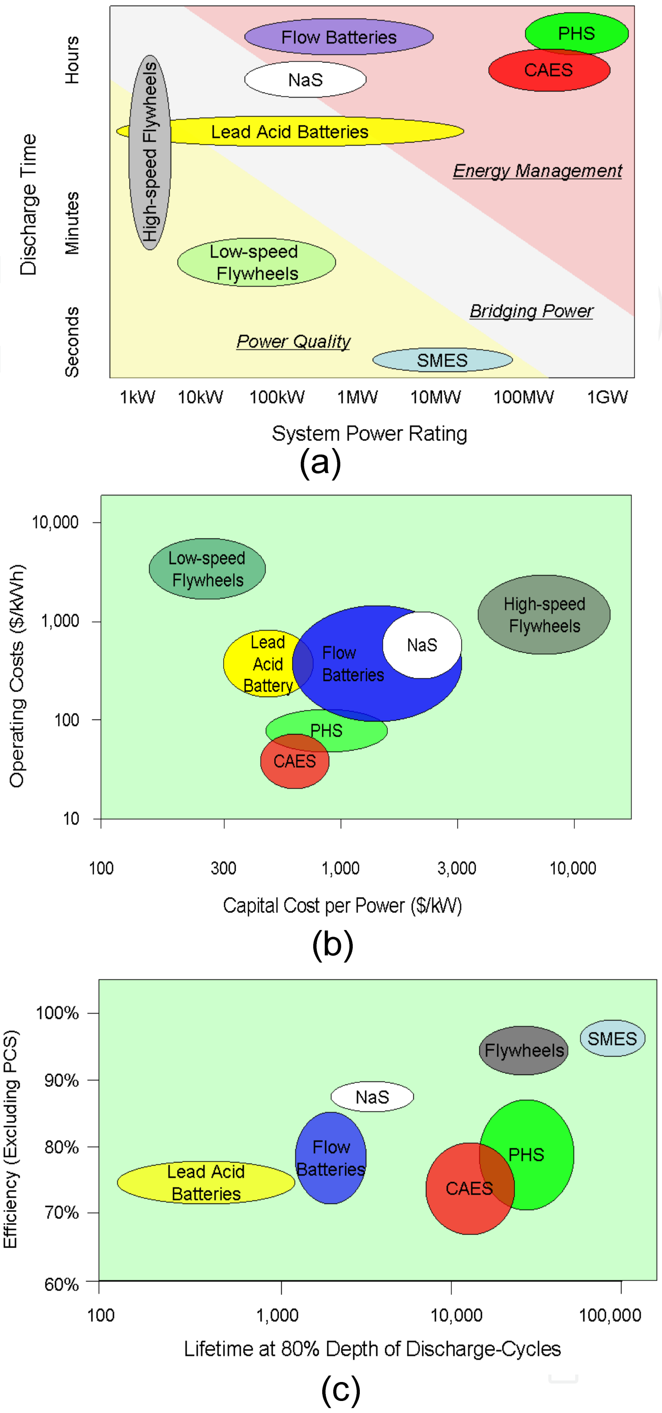


Figure 3. Technical characteristics of CAES

4. Function

CAES systems are designed to cycle on a daily basis and to operate efficiently during partial load conditions. This design approach allows CAES units to swing quickly from generation to compression modes. CAES plant can start without extra power input and take minutes to work at full power. As a result, CAES has following functions

1. Peak shaving: Utility systems that benefit from the CAES include those with load varying significantly during the daily cycle and with costs varying significantly with the generation level or time of day. It is economically important that storing and moving low-cost power into higher price markets, reducing peak power prices.
2. Load leveling: CAES plants can respond to load changes to provide load following because they are designed to sustain frequent start-up/shut-down cycles.
3. Energy Management: CAES allows customers to peak shave by shifting energy demand from one time of the day to another. This is primarily used to reduce their time-of-use (demand) charges.
4. Renewable energy: Linking CAES systems to intermittent renewable resources, it can increase the capacity credit and improve environmental characteristics.
5. Standby power: CAES could also replace conventional battery system as a standby power which decreases the construction and operation time and cost.

5. Deployment

Although CAES is a mature, commercially available energy storage technology, there are only two CAES operated all over the world. One is in Huntorf in Germany, another is in Mclntosh, Alabama in USA. The CAES plant in Huntorf, Germany is the oldest operating CAES system. It has been in operation for about 30 years since 1978. The Huntorf CAES system is a 290 MW, 50Hz unit, owned and operated by the Nordwestdeutche Krafiwerke, AG. The size of the cavern, which is located in a solution mined salt dome about 600m underground, is approximately 310,000 m^3. It runs on a daily cycle with eight hours of charging required to fill the cavern. Operating flexibility, however, is greatly limited by the small cavern size. Compression is achieved through the use of electrically driven 60 MW compressors up to a maximum pressure of 10 MPa. At full load the plant can generate 290 MW for two hours. Since its installation, the plant has showed high operation ability e.g. 90% availability and 99% starting reliability.

The second commercial CAES plant, owned by the Alabama Energy Cooperative (AEC) in McIntosh, Alabama, has been in operation for more than 15 years since 1991. The CAES system stores compressed air with a pressure of up to 7.5 MPa in an underground cavern located in a solution mined salt dome 450m below the surface. The storage capacity is over 500,000 m^3 with a generating capacity of 110 MW. Natural gas heats the air released from the cavern, which is then expanded through a turbine to generate electricity. It can provide 26 hours of generation. The McIntosh CAES system utilizes a recuperator to reuse heat energy from the gas turbine, which reduces fuel consumption by 25% compared with the Huntorf CAES plant.

There are several planed or under development CAES projects:

1. The third commercial CAES is a 2700 MW plant that is planned for construction in the United States at Norton, Ohio developed by Haddington Ventures Inc.. This 9-unit plant will compress air to ~10 MPa in an existing limestone mine dome 670m under ground. The volume of the storage cavern is about 120,000,000 m^3.

2. Project Markham, Texas: This 540 MW project developed jointly by Ridege Energy Services and EI Paso Energy will consist of four 135 MW CAES units with separate low pressure and high pressure motor driven compression trains. A salt dome is used as the storage vessel.
3. Iowa stored energy project: This project under development by Iowa Association of Municipal Utilities, promises to be exciting and innovative. The compressed air will be stored in an underground aquifer, and wind energy will be used to compress air, in addition to available off-peak power. The plant configuration is for 200MW of CAES generating capacity, with 100MW of wind energy. CAES will expand the role of wind energy in the region generation mix, and will operate to follow loads and provide capacity when other generation is unavailable or non-economic. The underground aquifer near Fort Dodge has the ideal dome structure allowing large volumes of air storage at 3.6 MPa pressure.
4. Japan Chubu project: Chubu Electric of Japan is surveying its service territory for appropriate CAES sites. Chubu is Japan's third largest electric utility with 14 thermal and two nuclear power plants that generate 21,380 MWh of electicity annually. Japanese utilities recognize the value of storing off-peak power in a nation where peak electricity costs can reach $0.53/kWh.
5. Eskom project: Eskom of South Africa has expressed interest in exploring the economic benefits of CAES in one of its integrated energy plans[10].

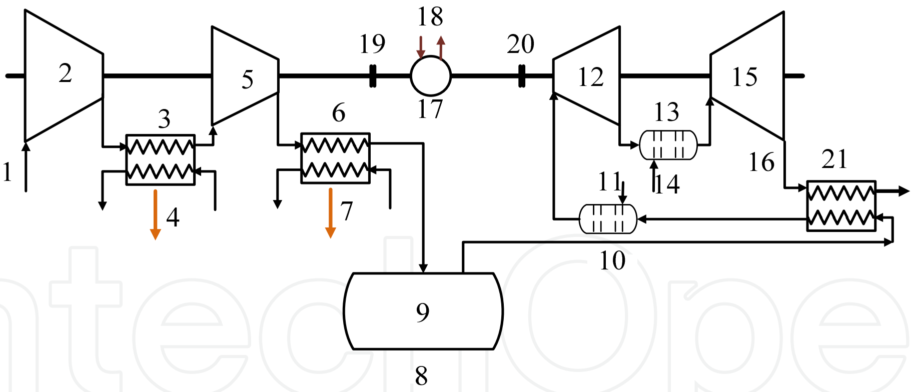
6. Research and development

As mentioned in Section 3, there are two major barriers to implementation of CAES: the reliance on favourable caverns and the reliance on fossil fuel. To alleviate the barriers, many improved CAES systems are proposed or under research and development, typical examples are improved conventional CAES, **A**dvanced **A**diabatic CAES (AACAES) with TES[19][21] and Small Scale CAES with fabricated small vessels.

6.1. Improved conventional CAES system

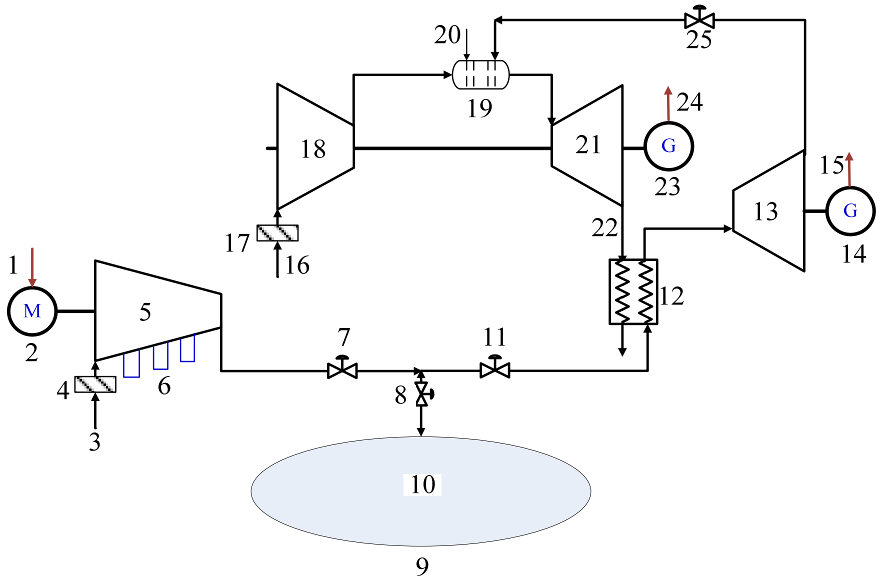
Figure 4 shows the principle of the improved conventional CAES system, which is similar to Figure 3. In figure 4, there are intercoolers and aftercooler in the compression process; reheater is installed between turbine stages; and regenerator is used to preheat the compressed air by the exhausted gas. McIntosh plant can reduce fuel consumption by 25% using the improved cycle shown in figure 4.

Another improved conventional CAES system combined with a gas turbine is shown in figure 5[38-41]. When the electricity is in low-demand, the compressed air is produced and stored in underground cavity or above ground reservoir. During the high-demand period, the CAES is charging the grid simultaneously with the GT power system. The compressed air is heated by the GT exhaustion and the heated compression air expands in the high pressure (HP) turbine and then ejects to the GT turbine combustor to join GT working fluid. The CAES system shown in figure 4 can recover almost 70% of compression energy.



1.Air, 2 and 5.Compressor, 3 and 6.Heat Exchanger, 4 and 7. Heat, 8.Reservoir, 9.Compressed Air, 10 and13.Combustor, 11 and 14.Fuel, 12 and 15.Turbine, 16.Exhaust, 17.Motor/Generator, 18.Electricity, 19 and 20.Clutch, 21.Recuperator

Figure 4. Schematic diagrams of improved conventional CAES system

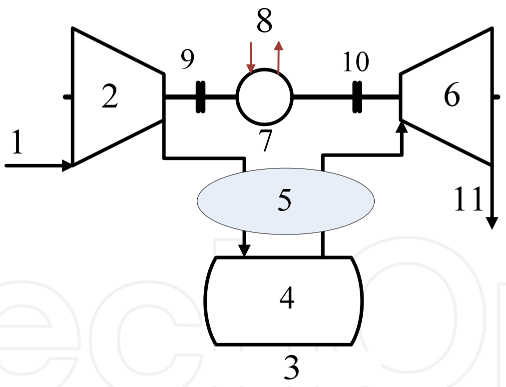


1 15 and 24.Electricity, 2.Motor, 3 and 16.Air, 4 and 17.FIltEr, 5 and 18.Compressor, 6.Intercooler, 7 8 11 And 25.Valve, 9.Underground Cavern, 10.Compressed Air, 12.Recuperator, 13 and 21 Turbine, 14 and 23 Generator, 19.Combustor, 20.Fuel, 22.Exhaust

Figure 5. CAES combined with GT system

6.2. Advanced Adiabatic CAES system

The so called Advanced Adiabatic CAES (AA-CAES) stores the potential and thermal energy of compressed air separately, and recover them during expansion (as shown in figure 6). Although the cost is about 20~30% higher than the conventional power plant, this system eliminates the combustor and is a fossil free system. IAA-CAES may be commercially viable due to the improvements of thermal energy storage (TES), compressor and turbine technologies. A project "AA-CAES" (Advanced Adiabatic – Compressed Air Energy Storage: EC DGXII contract ENK6 CT-2002-00611) committed to developing this technology to meet the current requirements of energy storage.

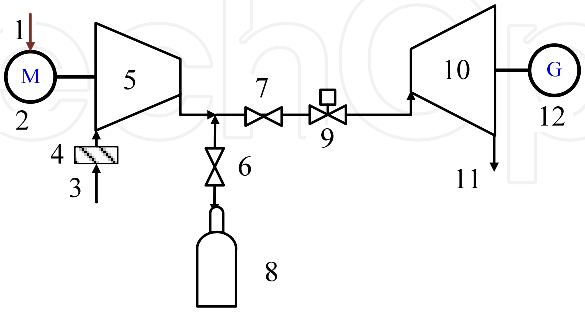


1.Air, 2.Compressor, 3.Storage Reservoir,
4.Compressed Air, 5.Thermal Energy Storage,
6.Turbine, 7.Motor/Generator, 8.Electricity, 9 and
10.Clutch, 11.Exhaust

Figure 6. Schematic diagram of AA-CAES system

6.3. Small-scale CAES System

Small-scale CAES system (<~10MW) with man-made vessels is a more adaptable solution, without need of caverns, especially for distributed generation that could be widely applicable to future power networks. Figure 7 shows a small-scale CAES used for standby power system[42]. It can replace battery with technical simplicity, low degradation of components, high reliability, low maintenance and lower life cycle cost characteristics. For a 2kW power application, CAES can work 20 years, while vented lead acid batteries (VLAB) 12 years; the installation and commissioning durations are 8 hours, respectively, while 16 and 64 hours for VLAB; with 300bar, 24,000L compressed air in cylinders, the CAES can work as a standby power for one year by charging four times. In general, there is no heat recovery/storage component in the small-scale CAES system, therefore its efficiency is lower than that of VLAB system.



1.Electricity, 2.Motor, 3.Air, 4.Filter,
5.Compressor, 6 7 and 9.Valve, 8.Air
Reservoir, 10.Expander, 11.Exhaust,
12.Generator,

Figure 7. Schematic diagram of the CAES system as a standby power supply

7. Concluding remarks

Research and application state-of-arts of compressed air energy storage system are discussed in this chapter including principle, function, deployment and R&D status. CAES is the only other commercially available technology (besides the PHS) able to provide the very-large system energy storage deliverability (above 100MW in single unit). It has a long storage period, low capital costs but relatively low efficiency in comparison with other energy storage technologies. CAES can be used for peak shaving, load leveling, energy management, renewable energy and standby power. However, there are two major barriers to implementation of CAES: the reliance on favourable caverns and the reliance on fossil fuel. To alleviate the barriers, many improved CAES systems are under research and development such as improved conventional CAES, AACAES and Small Scale CAES.

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