Current research and development trend of compressed air energy storage

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ABSTRACT
Power generation from renewable energy has become more important due to the increase of electricity demand and pressure on tough emission reduction target. This has brought great impact on grid reliable operation. Wind curtailment often happens when grid can not accommodate more wind power. Various solutions are under investigation and energy storage (ES) is one of the recognized potential ways forward. Among all the ES technologies, Compressed Air Energy Storage (CAES) has demonstrated its unique merit in terms of scale, sustainability, low maintenance and long life time. The paper is to provide an overview of the current research trends in CAES and also update the technology development. The paper has also given a comprehensive review to the work conducted by the researchers in China.

1. Introduction
With energy strategy reform of the world, there is a rapid increase of wind and solar power integrated to the power grid in recent years, which has caused big issues in frequency control and power network stability, such as enlarged peak-valley demand gap and insufficient system peak demand regulation capacity. As the major load balance regulation is currently performed by thermal power plants, large-scale thermal power generation is becoming low efficient and costly due to frequent start-up and shut-down to meet the demand variation and renewable energy intermittence. In addition to thermal power plants, pumped hydro energy storage has also been a regulatory mechanism in many cases but it has no sufficient capacity. In the future, grid connection of more distributed and renewable energy is inevitable. It is essential to develop feasible solutions to accommodate the changes in energy sources to maintain reliable and stable power supply. Energy storage has been recognized as an important enabling technology for solving the problems. So the service value of energy storage is increasingly considered by industry and there is rapid growth in energy storage market around the world.

There are a number of different ways of storing electrical energy, including flywheel energy storage, electrochemical energy storage, pumped hydro energy storage and compressed air energy storage (CAES). Among all the technologies, pumped hydro and CAES are standing out due to their grid scale and lower cost. This paper will focus on the development status of CAES and overview the current research progress in CAES. China is the major energy consumer of the world; the rational and efficient use of its energy will have big impact on the world energy and economic development. The research works conducted by Chinese researchers has been given a particular attention in this paper.

2. Brief description of CAES systems and current development
A CAES system mainly includes compressors, driving motors, generators, air reservoir(s) (underground cavern), turbines and other components. The structure of a typical CAES system is illustrated in Figure 1 (Luo, Wang, Dooner, & Clarke, 2015). When the grid load demand is low, the compressor will be driven by renewable energy or surplus electricity from the grid to produce compressed air which is then stored in an air reservoir. In the compression process, the working temperature of the compressed air can be reduced by inter-cooler to improve the compression process efficiency. When the grid load demand is high, the compressed air can be released to drive the turbine and the associated generator for electricity generation. The potential energy stores in the compressed air can be converted to electrical energy to provide supplement electricity to the power grid. The pressurized air can be
preheated by a combustion chamber, and the efficiency of the turbine is improved.

From the current development of CAES technology, CAES is classified into three types, which is dependent on the management of the thermal energy in the CAES process:

1. **Adiabatic**: There is heat exchange linked to the air after compression and before expansion. The heat generated by the compression process is stored, which is then used for pre-heating the compressed air or supply the heat for users; The cold energy generated by the expansion of the compressed air is used for inter-stage pre-cooling of the compressor or other cooling process in order to improve the efficiency of the system. With this adiabatic process, the dependence on fossil fuels is eliminated and greenhouse gas emission is reduced.

2. **Diabatic**: The system does not have intermediate heat exchange links and the heat generated through the compression is released to the atmosphere. To avoid the turbine inlet air temperature being too low and affecting system efficiency, a combustion chamber is added in front of the turbine to heat the compressed air through the combustion of natural gas.

3. **Isothermal**: The process aims to maintain a constant temperature or near to a constant temperature, allowing the air to be compressed to a higher pressure without temperature variations and the expansion can deliver energy without requirement for natural gas combustion.

In view of the future development of CAES technologies, various attempts for efficiency and structure improvement have been reported. From the study conducted by Liu (2016), CAES has obvious advantages in terms of energy density, life cycle, safety, construction investment and working environment requirements through a variety of energy storage comparison. Cryogenic liquefied CAES system compared with the traditional CAES has a higher energy density, but it has a higher complex requirement for equipment, and the investment cost is also higher. At the present, CAES is mainly used for electricity peak load shifting, smoothing renewable energy, preparation of emergency power supply and power generation in the isolated areas such as desert, islands and other places. Low stored energy density and compression heat losses are the key issues to be addressed in the technology development (Mei, Xue, & Chen, 2016).

Gulagi, Aghahosseini, Bogdanov, and Breyer (2016) evaluated the energy system based on 100% renewable power generation in Southeast Asia, the Pacific Rim and Eurasia in 2030. The study showed that the market share of other energy storage methods will be reduced by the integration of A-CAES. It also studied the effect of Adiabatic compressed air energy storage (A-CAES) operation on an hourly resolution for the duration of one year. Gao (2016) analysed several major energy storage opportunities in China and pointed out that building large-scale CAES systems is limited by the geographical conditions. Alami et al. (Sciakovelli et al., 2017) presented a construction and test of a modular low pressure CAES. It provided a great option for energy storage in remote locations that
Wang from Shanghai Institute of Electrical and Mechanical (Wang, Wang, Huang, & Lv, 2016) suggested that the development should focus on developing new CAES system technologies, such as isothermal CAES system, ground CAES system, liquid air energy storage system, Advanced adiabatic compressed air energy storage (AA-CAES) system and air-steam combined cycle CAES system. At the same time, it was imperative to promote the industrialization and technical verification of new technologies, mainly including: thermal storage of CAES technology, liquid air energy storage technology, supercritical air energy storage technology, combined with gas and steam cycle of CAES technology, and the CAES technology coupled with renewable energy. Meanwhile, multi-level high load centripetal turbine technology, advanced composite compressor technology, compact large capacity cold/ heat storage. Mazloum, Sayah, and Nemer (2017) discussed an innovative Isobaric Adiabatic Compressed Air Energy Storage (IA-CAES) system and its dynamic process modelling using ‘Dymola’. The system provides a potential solution to reduce the impact of the intermittence from the renewable energy sources onto the grid. Liu, Xu, Chen, Zhang, and Chen (2014) presented that the over ground gas storage device comparing with the underground gas storage CAES can avoid the constraints of geological conditions, and the application prospect is broader. Liu’s study identified the pressure and temperature characteristics of CAES by analysis of Gas Storage Characteristics. The performance of the storage device can be improved by increasing storage pressure; the storage and the inlet of the expander pressure difference should not be too large, so as not to the performance of CAES system was reduced. Underwater compressed air energy storage (UWCAES) attracted a great attention because of its unique characteristics compared with the ground and underground energy storage systems. Isobaric compression can be achieved through the use of water pressure, especially for offshore wind energy and other renewable energy storage. Current research carried out on UWCAES system is mainly around its gas storage package. Gas storage package was divided into rigid gas storage and flexible gas storage package. Wang, Xiong, and Wang (2015) presented an overview of UWCAES system and pointed out that the key technologies for UWCAES are structure design, ballasting, layout, recovery, failure processing, Heat storage methods and deep water high-pressure test study of the energy storage package. Krawczyk, Szablowski, Karellas, Kakaras, and Badyda (2017) presented a thermodynamic analysis of selected CAES and LAES systems. The LAES cycle was a combination of an air liquefaction cycle and a gas turbine power generation cycle. CAES and LAES systems were simulated using Aspen HYSYS software. One clear advantage of the LAES over the CAES is the significantly lower volume demanded for energy storage. For the considered LAES system, the liquid air tank volume is around 5000 m³, while for the CAES the cavern volume is approximately 3,10,000 m³. As shown in Table 1 (Wang et al., 2015) the economic analysis is relatively brief, and the cost of construction and profitability need to be calculated in the future.

### 3. Research progress in CAES and the associated performance analysis

#### 3.1. Study on thermodynamic properties

It is well known that the energy efficiency of a CAES system is highly influenced by the heat losses from compression process. A lot of studies can be found by Chinese scholars. This subsection will give an overview of the research in performance improvement via better understanding to the process thermodynamic behaviours. A comprehensive thermodynamic model was developed to investigate the thermal performance of AA-CAES by Mozayeni, Negnevitsky, Wang, Cao, and Peng (2017). It was found that the storage pressure has a significant effect on the amount of energy stored in the AA-CAES and power generated by the expander. The results also showed that the overall energy conversion efficiency is dominated by the efficiency of the compressor and turbine. The temperature distribution in a gas storage tank under different storage pressures were obtained by Fluent modelling analysis (Li, Yang, & Zhang, 2015). In order to study the influences of the parameters of the high-pressure storage tank on the performance of the energy storage system four sets of energy storage schemes were designed by Guo, Deng, Fan, and Chen (2014) of Zhejiang

| Technology          | Storage capacity/MW | Specific energy/(Wh/kg) | Duration/h | Life/year | Efficiency/% | Maturity      |
|---------------------|---------------------|-------------------------|------------|-----------|--------------|---------------|
| LAES                | 10–200              | 214                     | 12         | 25        | 55–90        | comparatively mature |
| CAES                | 3–15 (small)        | 140 (small, 30000)      | 3 (small)  | 20–40 (small) | 50 (small)   | Mature(sm)    |
| Pumped Hydro storage| 5–400 (large)       | 30–60 (large)           | 10 (large) | 20–40 (large) | 70–89 (large) | Mature(lg)    |
| Sodium sulfur cell  | 0.05–8              | 150–240                 | 3          | 10–15     | 80–90        | mature        |
Table 2. Parameter values of the first run for CAES with different configurations (Li et al., 2015).

| Pressure/MpA | Release time/min | System heat consumption/(kJ/kW·h) | System efficiency/% | Total output power/kW·h |
|--------------|------------------|------------------------------------|---------------------|------------------------|
| 2.8          | 132              | 4106.88                            | 54.89               | 2510.16                |
| 1.6          | 155              | 4171.97                            | 56.33               | 2612.11                |
| Poor heat transfer of the storage tank | 2.8 | 115 | 4106.88 | 52.30 | 2186.88 |

University, as shown in Table 2 (Li et al., 2015) The results showed that the capacity of the high pressure storage tank is highly influenced by the heat transfer. And the energy release time and the total output power of the system are affected directly by the capacity of the compressed air storage tank. The study can be used for guiding the parameters selection of high-pressure tanks.

Han, Liu, Zhou, and Pang (2016) proposed a constant wall temperature storage model using the first law of thermodynamic and the ideal gas equation of state. The effects of the storage pressure ratio, convective heat transfer coefficient, storage and release time interval on system efficiency influences were analysed. Wang, Zhang, Yang, Zhou, and Wang (2016) conducted an experimental study on CAES system with thermal energy storage unit integrated in, and the factors of influencing its efficiency were analysed. The study showed that the effect of unstable operation on the efficiency should be avoided for achieving higher efficiency and the efficiency of the axial flow turbine insulation and the heat preservation effect are important factors, which need to be improved. Sciacovelli et al. (2017) investigated the dynamic performance of a specific A-CAES plant with packed bed thermal energy storage. A plant model that blends together algebraic and differential equation sub-models detailing the transient features of the thermal storage, the cavern, and the compression/expansion stages was developed for the first time. He, Liu, Zhang, Cai, and Liu (2015) from the North China Electric Power University established a complete set of energy consumption analysis model of CAES system, the irreversibility of the heat transfer temperature difference was considered in the conventional exergy analysis of regenerator. The unit energy consumption of the improved CAES system of McIntosh Power Plant in the United States was analysed. It was found that the additional unit consumption of compression process, expansion process and combustion process was higher and the regenerative process was lower. The study proposed the key strategy for system reform in increase efficiency, namely, the compression, expansion and combustion process. But the model is not sufficient to capture CAES complex feature and characteristics. According to the characters of symmetry of CAES mass flow, and the correspondence of process points, Guo, Xu, Liu, and Chen (2015) of the Institute of Engineering Thermophysics, Chinese Academy of Sciences proposed a corresponding point analysis method to establish the mathematical model of corresponding point efficiency, corresponding equipment analysis and restitution coefficient, which corresponded the compression process to the expansion process and reflected the overall and local recovery capabilities, corresponding equipment performance, and system optimization direction. The reliability of the method needs to be further proved. Kaiser et al. (Friederike, 2016) proposed a new method to define the equivalent energy efficiency of CAES. But the method is lack of wide acceptance and controversies of the current definition of efficiency in CAES. With this method, the overall efficiency depending on the process efficiency, thermal efficiency, and market conditions can be used for evaluate the system of the non-dimensional gains to achieve economic comparison of different energy-saving procedures. He, Liu, Zhang, Cai, and Liu (2016) studied the exergy efficiency of the CAES system by orthogonal design and numerical simulation method. The experimental design and numerical simulation were carried out on the six parameters including compressor insulation efficiency, turbo-adiabatic efficiency and combustor efficiency, as shown in Table 3 (Friederike, 2016) The number of tests required to obtain the reliable results was greatly reduced by using this method, and the results had high reliability. Kosi et al. (2017), (Barbour, Mignard, Ding, & Li, 2015) developed a numerical model of an A-CAES system with packed beds and it is validated against

Table 3. Factor level in orthogonal experiments (Friederike, 2016).

| Factors | Compressor efficiency/% | Interstage cooling temperature/K | Minimum working pressure of storage chamber/MpA | Degree of heat recovery | Adiabatic efficiency of expander/% | Combustion chamber efficiency/% |
|---------|-------------------------|---------------------------------|-----------------------------------------------|------------------------|---------------------------------|-------------------------------|
| A       | 80                      | 298                             | 5.00                                          | 0.60                   | 75                              | 85                            |
| B       | 85                      | 308                             | 5.50                                          | 0.75                   | 80                              | 90                            |
| C       | 90                      | 318                             | 6.00                                          | 0.90                   | 85                              | 95                            |
analytical solutions. The results suggested that an efficiency in excess of 70% should be achievable, and the main losses occurred in the compressors and expanders rather than in the packed beds, and the build-up of left-over heat from previous cycles in the packed beds leads to a small reduction ( < 0.5%) in efficiency for continuous operation.

Sun (2015) studied the working characteristics of adiabatic, multistage and multivariable working conditions, and the effects of constant capacity and constant pressure energy storage on system efficiency. It was found that the storage pressure, gas storage mode and expansion process all have an influence on the performance of the CAES system. The corresponding optimization measures were proposed. Coney, Wazni, and Schulte (2016) proposed a CAES system that had two-stage compression and two-stage expansion. The system also had two types of thermal fluid: water was used for heating transfer and molten salts were used for storing heat. The high thermal efficiency was achieved by maintaining a constant pressure of compressed air in storage chamber using a hydraulic machine and maintaining a small temperature difference between the hot fluid and the air. Han and others (2016) proposed a non-equal compression ratio structure of the energy storage system. Four specific system structure schemes were proposed. The thermodynamic analysis showed that the non-equal compression energy storage system can reach an higher temperature and an higher the energy storage density. The storage heat and the irreversible loss of the system can be reduced by using two types of heat storage medium to store compression heat in various stages to improve the heat storage efficiency of the whole system. Jia and Cui (2016) established a dynamic model of an AA-CAES system using a lumped parameter method. The mathematical model for the energy storage compressing stage was established and the simulation study in Matlab was conducted for obtaining the pressure ratio and the outlet pressure of the compressor, the influencing factors of the power consumption, the change trend of the inlet and outlet temperature and the influencing factors of the outlet water temperature of the heat exchangers. The mathematical model of the system was greatly simplified by this mathematical modelling method.

Wu, Hu, Wang, and Dai (2016) proposed a new type of trans-critical CO₂ energy storage system concept, aiming to solve the bag flaw of supercritical compressed air storage in low temperature storage, energy exchange, and component separation. The results of thermodynamic analysis showed that the smaller heat exchange temperature difference between the regenerator and the intermediate heat exchanger is the key to improve the energy storage efficiency of the system. Using Genetic Algorithm for multi-objective optimization, the optimal solution of the system was obtained. In order to further optimize the system and reduce cost, the development of efficient CO₂ special turbine machinery need to be considered in next step of the study. Wang, Gao, Cao, and Dai (2016) designed a cogeneration-type humid air turbine cycle CAES system to improve the generation power and energy efficiency of conventional CAES systems. As showed in Figure 2 (Wu et al., 2016) water as heat storage medium, wet air and water as the working fluid, the power and heat were respectively output. The simulation results showed that the designed system had higher power and efficiency than the traditional CAES system, and its actual effect needs to be proved by experiment.

The efficiency of the UWCAES is decreased due to the fluctuation and intermittent of renewable energy. Wang, Ting, Carriveau, Xiong, and Wang (2016) proposed a multi-level CAES system integrated with battery and thermal energy storage. The thermodynamic analysis showed that the efficiency of the designed system was between 62% and 81%. Yao, Wang, Wang, Xi, and François (2016) proposed a small-scale CAES combined with cold, heat and electric power to solve the problem that the heat energy of the diabatic CAES system cannot be effectively recovered and the intake air temperature of the A-CAES system was low. And the actual design efficiency of the system can achieve up to 51%. But the system requires fuel to boost heat supply and the environmental contamination can not be avoided.

### 3.2. Integration of CAES system and renewable energy

It is noticed that CAES operation on its own is difficult to demonstrate its merits. However, it will bring the unlimited benefits to power generation, distribution, transmission, renewable energy integration, consumers and grid operation while it is integrated with those systems and operate in a coordinate manner. Some Chinese scholars considered the local situation and put forward the corresponding system. CAES coupling with renewable energy can greatly reduce the volatility of power generation from renewable energy sources and support peak load shifting, to meet the needs of power system operation, which has attracted a wide range attention from industrial sectors and research community.

While the wind power generation increase, the power system may not be able to accommodate the power from wind while maintaining the system stability and reliability, for example, 50% of the wind power may cause the phenomenon of wind curtailment. Cleary, Duffy, O’Connor, and Conlon (2015) used PLEXOS software conducted some simulation study and the results showed
that a 270 MW CAES system with 75% maximum instantaneous wind capacity combined, the amount of wind curtailment can be reduced to 2.6%, and the local government tax will increase €10 million. But the impact on the individual economy needs to be further considered. He, Liu, and Liu (2016) proposed to use the exergy flow ratio coefficient and exergy cost factor of wind energy to evaluate the wind power storage system energy consumption and economic characteristics, for the complexity of the performance evaluation and multiple inputs of wind power-compressed air combined operation system. Some theoretical guide for the policy formulation of energy storage was provided by the method. Zhou, Zhang, and Zhao (2015) also conducted the study on the combined system for direct energy conversion from wind power to CAES. The key feature was that wind power generation is directly converted to the internal energy of compressed air while it was not transmitted or distributed via power network. The feasibility of the scheme was assessed by simulation study using the software programme in Matlab. Compared with the traditional wind energy to electrical power and then power to CAES, the scheme of CAES integration with wind power can improve the efficiency of the system. Krupke, Wang, Clark, and Luo (2016) used an energy separation device to divide the wind into two parts. As showed in Figure 3 (Zhou et al., 2015) when the wind power is large, some of the wind power is directly used for generating electricity, and the remaining part energy is stored through compressed air. The results from mathematical modelling, simulation and experimental study showed that the designed structure can restrain the fluctuation of wind power generation through. The design structure compared to the study of Zhou et al. is more economical. Chen, Santos, and Izadian (2016) proposed to couple the CAES with the hydraulic wind power generation system.
And the performance of this designed system was verified by mathematical modelling and simulation study. The results showed that the power generation shortfalls can be compensated by CAES, when the cylinder pressure within the operable range. The power can be maintained at a constant frequency, which will improve the stability of the power network.

Krupke, Wang, Clarke, and Luo (2015) proposed a hybrid CAES system connection with wind turbines for reducing the impact brought onto the grid operation from wind power fluctuations; in order to improve the flexibility of the rigid coupling between the turbine shaft and the scroll air motor, a planetary gearbox was designed as the power separation device, and the maximum power point tracking can be realized in the mechanism. The simulation results showed that the power factor of the turbine is affected by the input power of the vortex air motor. The hybrid system can lead to more stable wind power, and the impact on turbine shaft was reduced. The experimental system was a small scale turbine and CAES, so the actual results for scale-up need to be further verified, and the performances of gas storage and compression process need to be studied.

In addition to the coupling of CAES system with wind power generation, Hao and Li (2016) proposed a scheme combining the cold energy of LNG with the supercritical CAES system. Compressed air absorbed the cold energy of LNG and liquefied. The shortcomings of the scheme are obvious: natural gas combustion heating was needed by liquefied air expansion power generation; the greenhouse gas emissions were increased; the system was more complex and the control was more difficult. Taking into account the differences of LNG filling stations and supercritical CAES system location, the difficulty of the implementation of the scheme is increased. Yao, Wang, and Xi (2016) connected a CAES system with the internal combustion engine technology to achieve trigeneration. The results from the analysis showed that the turbo-expander, internal combustion engine and heat exchanger are the key equipment in determining the system efficiency and the power generation efficiency of the internal combustion engine has the major influence on the system.

Simpson, Garvey, Pimm, and Garvey (2016) proposed a scheme that solar energy was stored as thermal energy in CAES inter-stage heat exchangers for renewable energy sources. The heat was used for preheating compressed air before expansion. The preliminary modelling results showed that the storage pressure was greatly improved. The next research is to establish the exergy loss thermodynamic model of the exothermic process and make a technical and economic evaluation of the cost and value of the storage and generation. Simpore, Garde, David, Marc, and Castaing-Lasvignottes (2016) also proposed a combined photovoltaic power generation with the CAES system to solve the volatility problem of photovoltaic power generation in Reunion, France, which can not be connected to the grid because of its geographical location. A system model was established to analyse the system reliability. Sensitivity analysis and simulation study of the key parameters of the system showed that it is essential to optimize system parameters to order to achieve high efficiency and high coverage. Arabkoohsar (2015) introduced a dynamic model of the CAES system for a large-scale PV grid-connected power plant in Brazil. For this power generation system, a 50 MW CAES system can effectively stabilize the power generation volatility and minimize the penalty paid due to fluctuations. By combining the city gate station (CGS) with the power generation system, not only the energy and efficiency of the power plant can be considerably increased, the capacity of the CAES system was reduced and the power sales policy of the power plant was greatly improved. The feasibility assessment of the system was studied through the meteorological data of Natal region in 2012, and the comprehensive energy and economic analysis were carried out (Arabkoohsar, Machado, & Koury, 2016). The internal rate of return method as an authentic economic assessment was used for comparing the economic factor of the system, which indicated that the system designed is more efficient and more recommendable.

### 3.3. Research on key equipment of thermal energy storage

It is the current trend to develop new CAES technologies without using any fossil fuel. Therefore, it is important to develop the essential efficient and cost effective system components to achieve the overall system implementation.

Han, Liu, Zhou, and Pang (2016) proposed to use water instead of mineral oil for storing heat. The stored heat was added to the original structure of the expander to reduce the temperature and achieved cogeneration. However, due to the characteristics of compressed air storage system, the heating and cooling energy can not be constantly produced. So the system needs to be improved to meet the continuous heating / cooling requirements of users. Yang, Chen, Wang, Sheng, and Lv (2016) studied the impact of thermal storage on supercritical air energy storage system. It was found that the system efficiency was closely relevant to the change of the storage water flow rate. The efficiency increased at first and then decreased with the increase of the storage water flow rate, and the optimal value exists. Xue, Chen, Mei, Chen,
and Lin (2016) of Tsinghua University used molten salt as the traditional storage medium. Low electric power, discarding wind power, and discarded photoelectricity was used for heating the molten salt through electric heaters for heating the turbine inlet air. High-temperature heat storage was achieved, which avoids the dependence on high-temperature compressor. However, there are certain difficulties in the heat recovery of the compression process compared with using the mineral oil as the storage medium. A certain degree of energy was wasted. Velraj and Thenmozhi (2015) suggested that the uplift failure of the overlying rock mass may have a significant effect on the gas storage chamber, considering that the pressure of the storage chamber is reach up to 10–30 MPa. It was emphasized that the safety of the gas storage chamber mainly depends on rock strength, depth cover, horizontal stress and cave type. Carranza-Torres, Fosnacht, and Hudak (2017) addressed the fundamental problem in establishing the stability conditions of shallow cylindrical or spherical openings excavated caverns in cohesive ground, and subjected to either decreasing or increasing internal pressure, associated with the process of contraction or expansion of the cavities during operation of a CAES system. Guo, Zhang, and Li (2016) utilized UGH2-EOS3/MP simulator for simulating a CAES system for analysing the pressure, gas saturation and cycle number of the underground aquifer storage system. It was confirmed that the aquifer could be used as the gas storage of CAES system. By comparing the diurnal cycle and the weekly cycle, it was found that the pressure variation range of the weekly cycle was bigger and the requirement to the system equipment was also more restrict. It is necessary to study the influences of different parameters of the aquifer storage on the performance of the whole system before the aquifer can be used in practice. The authors also simulated compressed air storage of the aquifer and cave by using the Huntorf power station parameters and observed data (Guo et al., 2016). The gas storage performance of aquifer is comparable to or even better than the salt cavern energy storage. CAES system analysis showed that more attention should be paid to heat storage, reservoir properties and the characteristics of two-phase flow processes. The chemical and safety issues need to be studied further. Mas and Rezola (2016) proposed a tubular bag for storing compressed air in a large Under Water CAES (UWCAES) system in the deep sea. And the mathematical modelling and simulation of 1GWh energy storage system, 1000 m deep sea was carried out to verify its feasibility. It is still unclear for the impact of the flow velocity of water brought onto the energy storage package and the dynamics of the energy storage package need to be studied.

In order to study the influence of compressor on the performance of the whole AA-CAES system, a compressor model was built on the basis of a traditional AA-CAES model by Pang and Han (2016). The performance curves of the compressor were plotted by polynomial fitting, and the relationship of energy storage efficiency, energy storage density and thermal efficiency of the heat storage system between heat exchanger efficiency, the maximum pressure ratio of the gas storage chamber was obtained. The influence of the compressor on the system performance was clarified which provides the evidence to support the system optimization. Perazzelli and Anagnostou (2016) proposed a geometrical description of the vortex air motor, derived the calculation formula of the vortex drive torque, established the dynamic working process of the vortex air motor and verified it through experiment. Li et al. (Saadat & Li, 2016) combined a liquid piston with a solid piston, which was driven by a hydraulic booster, to substantially reduce the volume of the pump/motor. The case analysis showed that the pump/motor volume were reduced by 85%; the ratio of the maximum the minimum displacement was reduced by 70%; and the average efficiency was increased by 2.4 times with an optimal intensifier ratio. It was reported that the Institute of Engineering Thermophysics, Chinese Academy of Sciences (China energy Storage Network News Center) has selected and processed the core components required for a 10MW turbo expander. And the mechanical transmission and control system, which was the core of the expander drive, have also been tested. Yang (2014) designed a scroll-type compression / expansion machine with integrated compression and expansion functions. With the operating mode switching mechanism, the tongue-type exhaust valve at the bottom of the fixed scroll can be rotated at an angle and the exhaust vent would be plugged in or open to achieve compression or expansion functions. Xue (2014) studied the thermodynamic characteristics of the single-valve expander, the internal flow field of the expander, Variation of the state parameter of the expansion cylinder with the crank angle and the influence of different operating parameters on the overall performance of the expander by the numerical simulation and experimental method. Li, Yang, and Zhang (2013) obtained the optimal combination of AA-CAES system compressor and expander by calculating the work efficiency and exergy efficiency of different stage compression-expansion of the CAES. The compression had two stages and the expansion had three stages.

### 3.4. Control of CAES systems

CAES is a complex system with mixed components and processes from mechanical, electrical and thermal
engineering. The individual component optimization does not imply the process optimization so the system level control and optimization strategy is very important. Various effort has been made from both industry and academia, which are to be reported in the section. The control model reported in Chinese is mainly focused on the key components of the system.

Li and Wang (2014) proposed a method optimizing the system piping, installing high-efficiency variable frequency control system, increasing the capacity of the system gas storage, stabilizing the system gas pressure and installing alarm system to improve system operating efficiency. Benefit analysis showed that the energy-saving rate increased by 20% through the technological transformation. This technology is very important to promoting the sustainable development of economy and society. Mazloum, Sayah, and Nemer (2016) developed a static model of A-CAES without considering the inertia of the system and also a dynamic model with consideration of the inertia. The simulation results showed that the system can not follow the response to the power system demand. There was a 5-minute delay between producing the energy required to meet the grid demand. When the CAES system is involved in the power system scheduling, sometimes the system can be regarded as generators or the load. Kokaew, Sharkh, and Torbati (2015) studied the performance of a real-time maximum power point tracking algorithm for interference observations of CAES systems, which employed a novel hybrid perturb and observe approach using coarse and fine speed steps to improve the convergence and accuracy of the MPPT. It was found that the method using the rate of change of the power with respect to the speed is better than using the rate of change of the power with respect to the duty cycle of the dc–dc converter.

Ghalelou, Fakhri, Nojavan, Majidi, and Hatami (2016) proposed a random self-scheduling model of renewable energy considering CAES in the presence of a demand response programme. The objective function of the model was to minimize thermodynamic units and the operating costs of CAES. The proposed model was solved by the general algorithm model system optimization package combined with a mixed integer linear programming model. Four programmes were proposed to evaluate the demand response procedure and the role of CAES in the self-scheduling problem, which verified the designed model. Li, Miao, Luo, and Wang (2016) proposed a scheduling model for a power system combined with CAES and wind power generation. By using the operation data from Huntrof power plant, the simulation results from model prediction showed that the scheduling profit. The wind power generation schedule in the model is based on the forecast data of the previous day.

Hybrid gas compression energy storage system is composed of the combination the CAES with large energy capacity and super capacitor energy storage with high power density. Zhang, Luo, and An (2016) studied the motor control strategy of hybrid gas compression energy storage system and proposed the hybrid maximum efficiency point tracking and maximum power point tracking control strategy. The maximum efficiency point tracking algorithm was used for the early stage of system control to make the system work at a higher efficiency point. When the system pressure is high, the maximum power point tracking algorithm is switched on to limit power and speed of the system. The feasibility of the strategy was verified by MATLAB simulation and experiment. The flaws that the insecurity of the maximum efficiency point tracking and the low efficiency of the maximum power point tracking were overcome by this strategy. Zan and Zhu (2015) applied a switched reluctance motor to a CAES system instead of a motor and generator. A sliding mode PI control strategy was used for controlling the working process of the motor and the fuzzy PI control strategy was used for the generator. The error between the actual speed and the tracking speed was decreased rapidly by the sliding mode control, and the PI control was adopted to avoid the vibration caused by small errors. The error between the actual and tracking voltage was reduced rapidly by the fuzzy control, and the static error of fuzzy control was reduced by PI control. The system has good stability and robustness.

Jiang, Zhao, and Chao (2015) linearized the model of the gas storage chamber by direct feedback linearization control, which was suitable for a multi-input and multi-output coupled nonlinear system, and the gas temperature and pressure of the gas storage chamber were controlled by the multi-drop configuration method. The method showed good effect on the temperature and pressure control of the gas storage chamber, which can make the closed loop design of the system reach the optimal pole configuration and was easy to be realized in practice. In the actual design of a CAES system, the efficiency is usually improved by increasing the efficiency of the regenerative system. Heat exchanger as the most critical equipment in the regenerative system, its precise control in improving the efficiency of heat recovery has a great role. Zheng, Li, and Liu (2016) developed a mathematical model of heat exchanger by using system identification method, and a fuzzy PID controller was designed for the heat exchanger. Compared with the conventional control method this control achieved the smaller overshoot and steady state error and shorter regulating time.
3.5. Miniature CAES

Compared with large-scale compressed air energy storage systems, micro-compressed air energy storage system with its high flexibility and adaptability characteristics has attracted interest in research. Miniature CAES system is generally refers the CAES with the power rating less than 10MW and the restriction from air energy storage chamber. It can be used in the production of spare batteries, urban peak shaving, is the future development trend of a power grid. The research work conducted by Chinese researchers is mainly used in urban communities and rarely in rural areas.

Duan, Li, and Wu (2015) applied the AA-CAES system to the micro-grid, and established an AA-CAES model and micro-grid model using STAR-90 simulation platform. The analysis showed that the transmission and consumption ratio of micro-grids with AA-CAES system was far lower than that of micro-grid without it. The transmission and consumption ratio of micro-network cluster was significantly lower than that of single micro-network, and has good independence and autonomy. The economy and safety of power grid operation can be greatly improved and the influences of new energy output fluctuation and randomness was reduced by the addition of AA-CAES system. Ciocan, Tazerout, Prisecaru, and Durastanti (2015) established a small CAES system to store renewable energy and to provide electricity for district, villas and farms. The thermodynamic modelling and simulation was performed to obtain the optimum configuration. As shown in Figure 4 (Ciocan et al., 2015) Xue, Liu, Wang, Chen, and Mei (2016) proposed a cooling-heating-power supply system for the urban community, which was based on the non-supplemented compressed air energy storage. The power supply pressure of the large power grid can be eased and the energy utilization rate of the system can be improved by the combination of electric energy, cold energy, heat energy and user demand, which allows the diversified energy supply to be provided for users. The community micro-energy architecture design for the future micro-grid construction provides a reference, but its multi-objective optimization configuration should be explored. Priyadi et al. (Setiawan, Priyadi, Pujiantara, & Purnomo, 2015) proposed a method of coupling the CAES system with solar power generation in order to solve the problem that the life of the battery in the domestic solar energy system was relatively short compared with that of the photovoltaic module and the battery repair was difficult in the rural area. The mathematical modelling and Matlab simulation results showed that the tank size depends on the load and operation time. The system efficiency can be improved by selecting the appropriate regulator and initial pressure. Zhao, Liang, and Yang (2016) established a miniature CAES system for the community, which was

Figure 4. Scheme of small AA-CAES system (Ciocan et al., 2015).
coupled with wind, solar and biomass energy. The CAES system was equivalent to battery energy storage calculated by the HOMER simulation software. According to local actual load, wind energy resource, solar energy resource and biomass resource, the optimal configuration was obtained by simulation analysis, which satisfied the load requirement. A fundamental knowledge for the working state and power of CAES was provided by the research. Two small scale second-generation compressed air energy storage (CAES) systems have been investigated by Salvini (2017). Both plants were based on a 4600 kW Mercury recuperated gas turbine (GT) and on an artificial air storage system. In CAES air injection (CAES AI) plant, the stored compressed air was mixed with the air flow exiting the GT compressor and fed after a recuperative heating to the GT combustion chamber. A topping air expander was included in the CAES air injection/expander (CAES AI/E) plant scheme. CAES AI plant allowed a 30% maximum extra power delivery (some 1500 kW) in respect to the nominal design of GT power. The introduction of the topping air expander in CAES AI/E plant allowed an additional power production of some 300 kW. Both plants have shown storage efficiency improvements by reducing the discharge period duration. Satisfactory values around 70% have been found in the best operating conditions. He also presented the design and off-design analysis of a compression and storage system for small size Compressed Air Energy Storage (CAES) plants. A methodology for preliminary sizing and off-design modelling has been developed. The proposed approach allows the instant-by-instant evaluation of minimum and maximum absorbable electric power. The developed tool gives useful information to appropriately size the compression system and to manage it in the most effective way (Salvini, Mariotti, & Giovannelli, 2017).

Xue et al. (2014) of the Institute of Engineering Thermophysics, Chinese Academy of Sciences, designed a miniature compressor air energy system with a single-valve piston compressor using the characteristics that the single-valve piston expander has simple structure, high pressure ratio and easy adjustment and control. A thermodynamic analysis results of the system’s main parameters showed that in order to obtain the best potential energy efficiency, the following measures can be taken into consideration: (1) When the inlet pressure of the expander is lower than the rated pressure, it will be sent directly to the expander without throttling. Until the stage indicates that the power is less than single-stage cylinder friction power, the gas is sent to the next stage expander to complete the same process; (2) when the expander inlet pressure is higher than the rated pressure, it is throttled to the inlet pressure.

### 3.6. Economic analysis

To improve economic benefits of compressed air energy storage and give full play to the advantages of CAES, the economic analysis is an indispensable part in the study of CAES. From the review, the study conducted in this area in China is much less than those did by the researchers from other countries.

Herrmann, Kahler, Wuerth, and Sliethoff (2017) combined a compressed air energy storage with a combined cycle power plant. The new cycle was based on the basis of a GE LM6000 gas turbine model, an adiabatic compressor model, an air expander and a conventional dual pressure HRSG configuration. The thermodynamic and economic performance was compared to a conventional LM6000 combined cycle. The net present value of the novel cycle was higher than that of the combined cycle. Liu, Xu, Hu, and Chen (2015) developed a technical and economic model of CAES system. The economic analyses of AA-CAES system with and without government subsidy were carried out by using financial, sensitivity, profit and loss analysis. The results showed that the economic indicators of the power station have shown a good income effect, and a good level of responses to the expected risk. The government support had an important role on the improvement of financial income level and anti-risk capability of in developing compressed air storage power. A price model was set up by Hammann, Madlener, and Hilgers (2017) to produce, in combination with the application of a Monte Carlo simulation, possible future price paths for power, natural gas and demand rate for minute reserve. Based on these price paths, costs and revenues for different CAES applications are calculated. For the economic evaluation three different configurations are considered for both diabatic and adiabatic CAES. Investment in a diabatic CAES used for load-levelling purposes is found to be the most economical option. Shafiee, Zareipour, Knight, and Amjady (2016) proposed a risk-constrained bidding / selling strategy based on the information gap determinism for commercial CAES equipment, with taking into account price uncertainty. If future price declines in the robust region, the proposed strategy would guarantee a minimum critical profit. Opportunistic behaviour could ensure that manufacturers benefit from the preferential price deviation and might earn higher profits. In the case of robust scheduling, the optimization method based on the determinism of information gap can find the worst case of price separation and give the corresponding optimal scheduling to guarantee profit. This method regarded the self-scheduling efficiency parameter of CAES as a fixed value; in fact, the parameter sometimes depends on the operating conditions.
conditions and did not consider the variable efficiency parameter. Shamshirgaran, Ameri, Khalaji, and Ahmadi (2016) used the Thermoflex software to perform cyclic modelling and design calculations on the CAES system. The cost-benefit function as a target function was maximized using Genetic Algorithm. The results of sensitivity analysis showed that the net annual return and CAES discharge time decrease with the increase of the fuel price. The optimal heat exchanger efficiency increased with the fuel price, but there was a maximum ceiling. As a result, different fuel prices should be taken into account by the future design and the existing plant operating strategies.

Keatley, Lytvyn, Huang, and Hewitt (2015) conducted a feasibility study on the establishment of a compressed air reservoir on a salt bed in northeastern Ireland. The market conditions for the development of CAES in Ireland were evaluated and the obstacles to its development were indicated. The payment mechanism and tax were considered to be the factors that restrict the potential investors of the project; investors were lack incentives to balance the cost and make profit.They suggested the value of the project and the role of CAES systems in reducing use of fossil fuel should be clearly stated and policy incentives for CAES systems should be adequately given. Amoli and Meliopoulos (2015) used CAES for the renewable energy grid to address uncertain grid loads due to the inherent volatility of renewable energy sources, which allowed the power system to be more flexible to accommodate a large variety of different types of renewable energy. The uncertainties associated with the wind energy and payload prediction errors were addressed by establishing a random programming market clearing model. The test results showed that the wind curtailment and system operating costs could be effectively reduced and the flexibility of operation could be enhanced by the involving CAES in system operation.

4. Challenges and future prospect of CAES

CAES technology will play an important role in the construction of smart energy system in the future and enhancement of the regulation ability of power systems. Renewable energy utilization will be greatly promoted by involving CAES operation. The abandonment of the wind, the phenomenon of electricity and other occurrences will be reduced by integrating CAES with renewable energy such as wind power, photovoltaic and biomass power generation.

In the past year, CAES technology research focused on the thermodynamic analysis, especially the energy storage phase, as well as the coupling with a variety of renewable energy, the development of key equipment, system operation control strategy, miniature CAES system and the economic analysis of the system. As can be seen from the literature review, the future development of CAES technology is mainly restricted by the compressor, expander efficiency and cooling capacity and heat recovery efficiency. Therefore, the advanced multi-stage high load to the heart of the turbine, advanced composite compressors and heat transfer technology should be vigorously developed in the future. The development of CAES technology also is constrained by the high cost of investment in CAES system, the lack of clear participation mechanism and settlement methods and the difficulty in correctly measuring the energy storage value. In addition, the energy storage system installed in the scenery base is operated by wind power station in some areas at this stage so energy storage resources can not be scheduled by grid from view of the global optimization point and the advantages of CAES can not be fully visualized. In view of this problem, the concept of constructing independent storage power station in the centralized wind power station area was put forward by a company. The current cost of energy storage power plant value can be maximized by the concept to help solve the problem of renewable energy consumption. This independent energy storage station can be directly dispatched by the power grid and provide various services such as peak regulation, frequency modulation, reserve, tracking power generation plan, smooth wind power output and so on. As it can operate independently, the regulation of electricity and measurement of service types is easy to be obtained by statistic methods. To a certain extent, the operation of energy storage power station is simplified in this way. Independent storage power station and power generation are completely separated so the difficulty of investment assessment is correspondingly reduced. In addition, it is easier to assess the value of energy storage itself and policy subsidies have a more pertinence.

Achieving a breakthrough in the development and utilization of renewable energy, especially new energy grid technology and energy storage, micro-network technology, the fully construct ‘Internet +’ smart energy network, enhancing power system regulation, increasing new energy consumption capacity, developing advanced energy-efficient technology and seizing the commanding heights of energy technology competition are the trend for future renewable energy development. Therefore, the future of CAES technology needs to pay more attention to the research on integration with the renewable energy system, and the combination of micro-CAES system with micro-grid. Furthermore, the improvement of the energy density of CAES system and the development of supercritical and liquefied CAES system are also play an important role in to improving energy storage efficiency. In terms of
policy, in-depth reform of the energy market and increase of government subsidies could give strong support to promote the development of CAES technology.

5. Concluding remarks and discussion

The current development of CAES technology is reviewed in this paper, which covers the thermodynamic characteristics of the energy storage system, the coupling CAES with renewable energy, the research progress about the key equipment/components of the thermal storage and system integration, control strategies, progress in developing miniature CAES systems, and the economic analysis. It can be seen that CAES research is very active in recent years and substantial progress has been made. All the progress will lead to the major technology breakthrough in the near future. There are two large scale compressed air storage plants are in operation and their success encourages the technology development. A number of pilot projects in building new generation of CAES are on-going. All the projects have demonstrated the difficulties in financial investment. Therefore, the reform of energy market and policies are required which is gradually happening. China has announced the electricity market reform already and will make progress step by step. It is clear that CAES has great potential to become a key part of the future smart energy network. Its merits in clean, sustainability, low maintenance, low cost, variable scales and low self-discharge for long time storage will be highlighted in future energy storage technology selection.

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