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Compressed Air Energy Storage and Future Development

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Compressed Air Energy Storage and Future Development

Jingyue Guo[1, †], Ruiman Ma[2*, †], Huiyan Zou[3, †]

[1] Environmental engineering, Hubei University, Wuhan 430061, China

[2] Environmental and energy engineering, The University of Sheffield, Sheffield S10 2TN, the UK

[3] Changzhou No.1 High School International Division, Changzhou 213004, China

[*]Corresponding author's e-mail: rma21@sheffield.ac.uk

[†]These authors contributed equally.

Abstract. Power generation around the world is changing dramatically as a consequence of the demand to lower greenhouse gas releases and present a mix of power supplies. Energy storage technology is considered to be the fundamental technology to address these challenges and has great potential. This paper presents the current development and feasibilities of compressed air energy storage (CAES) and provides implications for upcoming technology advancement. The paper introduces various primary categories of CAES (Advanced Adiabatic-CAES, Liquid Air Energy Storage and Supercritical CAES). Compared with other energy storage technologies, CAES is considered a fresh and green energy storage with the distinctive superiorities of high capacity, high power rating, and long-term storage, and shortcomings of low power density, high transportation losses, and geological restriction. CAES is regarded as a promising technology that is able to be applied in renewable energy production, cogeneration, and distributed energy and microgrid systems. It's also considered to be integrated with other technologies, such as renewable energy, gas turbine, solid oxide fuel cells, and other systems in the future.

1. Introduction

The world relies heavily on traditional power supplies to generate electricity. As a result, two significant relevant problems are brought about, namely depleting fossil fuels, which are expected to be exhausted within ten decades[1], and the emissions of greenhouse gases (GHGs) and other contaminants with adverse effects on environment facilities and individual wellbeing[2]. Renewable energy is a prominent energy supply that can significantly reduce greenhouse gas emissions and meet global energy needs[3]. However, the inclusion of renewable energy into the grid presents upcoming issues[4]. Demand response (DR) and electric energy storage (EES) applications holds great promise[5]. EESs can absorb changes in renewable energy[6], and allow renewable energy to be allocated[7]. Energy storage technique is exerting vital impacts on the grid over the past few decades[8]. Another crucial facet associated with the adoption of storage technologies is represented by the air-quality concerns[9], minimizing the use of hydrocarbons for electricity transportation and circulation[10].

There are several suggested ways to classify the various EES technologies, for example, according to their functionality, response time, and appropriate storage time. A broadly used means is in the light of the accumulated in the device in the form of energy[11]. One thorough explanation and analysis of each class of EES technology will be offered later[12]. Among these energy storage technologies, CAES is considered a fresh and green energy storage with the distinctive superiorities of high capacity.

CAES represents the power stored as high-pressure compressed air and converted into diverse forms of energy consumption. This is a physical energy storage method with a large scale and can expand the utilization rate of sustainable energy[13]. When the demand is less than the output, the excess energy generated by renewable energy can be stored by compressed air energy storage technology[14]. The paper introduces three main types of CAES, including their operating principles, unique advantages, and developments. Then, the paper concludes the general advantages and disadvantages of CAES and its possible application, which has not been done systematically by others.

2. Overview and types of CAES

2.1. Overview

For maintaining the robustness and reliability of the energy devices, CAES has a significant comparative advantage, and has become the most promising large-capacity of power storage machineries. The gas turbine device uses air and gas as the working medium. The compressed air and fuel are mixed to form high-temperature and high-pressure gas in the burning space to drive the turbine, which then runs the generator. Since the CAES device is composed of two different operating stages, compression and expansion, and these two stages run at different times, the efficiency of air compression energy storage technology is higher than that of traditional gas turbine systems[15]. Hitherto, tremendous different concepts of compressed air energy storage technology are developed to adapt to the application requirements of different scenarios[16].

2.2. Types of CAES

2.2.1. Advanced Adiabatic-CAES (AA-CAES). In recent years, advanced AA-CAES has attracted people's attention because of its advantages: no fossil fuel employment, low cost, high start-up speed, and large partial load capacity[17]. In a traditional CAES system, high temperature produced by compression is discarded during charging and must be replaced by heat generated by combustion during power generation, which means that heat cannot be reused and limits storage efficiency[18]. However, in AA-CAES systems, as shown in Figure 1, the heat is released from the compression phase and can then be stored and reused in an adiabatic vessel during the expansion phase. Heat can be stored before the air enters the tank[19]. Therefore, through heat storage, the fossil fuel can be reduced by the heat of compression to reheat the air gas turbine increase and improve device efficiency. In conclusion, AA-CAES systems have the potential to improve efficiencies and emit fewer greenhouse gasses[20]. AA-CAES is regarded as a great choice to deliver extra services with reduced prices. Currently, several AA-CAES demonstration plants have been developed to some extent or in its infancy globally [17, 18].

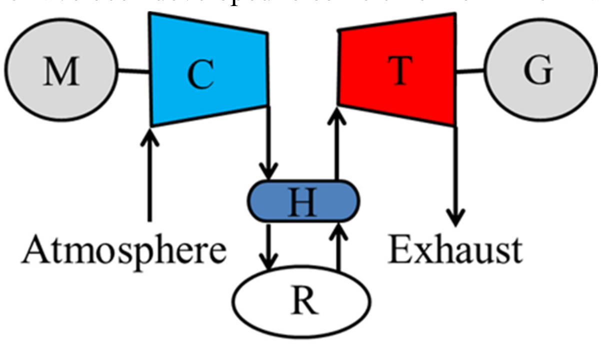

Figure 1. Scheme of AA-CAES system[19]

2.2.2. Liquid Air Energy Storage (LAES). LAES aims to increase the power storage density. Figure 2 reveals the typical scheme of AA-CAES system[21]. When operating LAES, both heated and cold thermal streams are generated, respectively, during charge-discharge process[22].

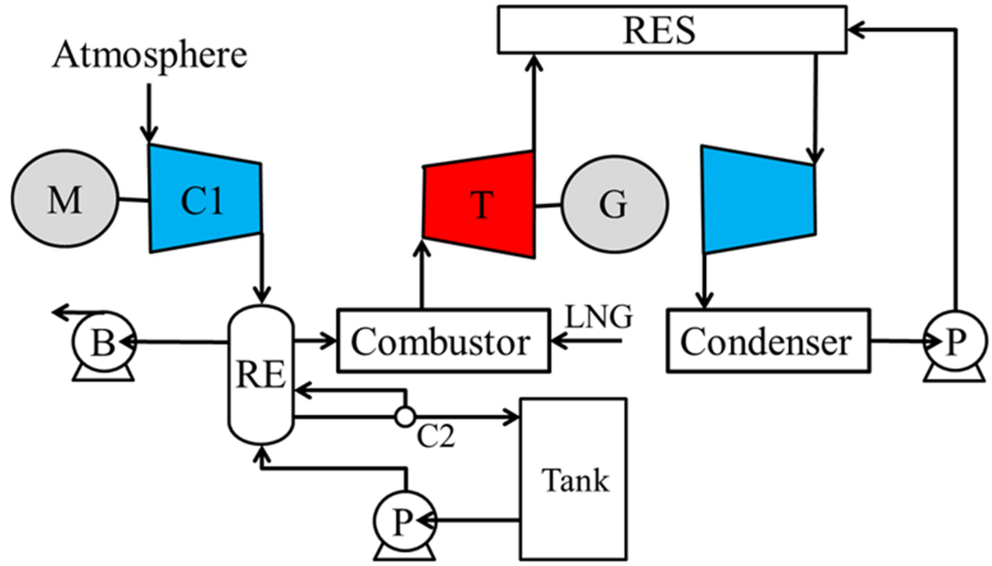

Figure 2. Schematic diagram of LAES system[19]

LAES is a promising class of sustainable power technique[23], whose components are strong with decent conservation constraints, and can be compatible with plant scale at scales ranging from dozens to hundreds of megawatts. The foremost components of a LAES device are likely to be individually sized and designed according to the specific presentation requirements[24].

2.2.3. Supercritical CAES (SC-CAES). The SC-CAES incorporates the benefits of AA-CAES and LAES. Figure 3 indicates the scheme of one typical SC-CAES system. According to Guo, Xu, Chen, Zhou's research[25], the energy densities are approximately 18 times higher than that of conventional CAES with round-trip efficiency of 67.41%.

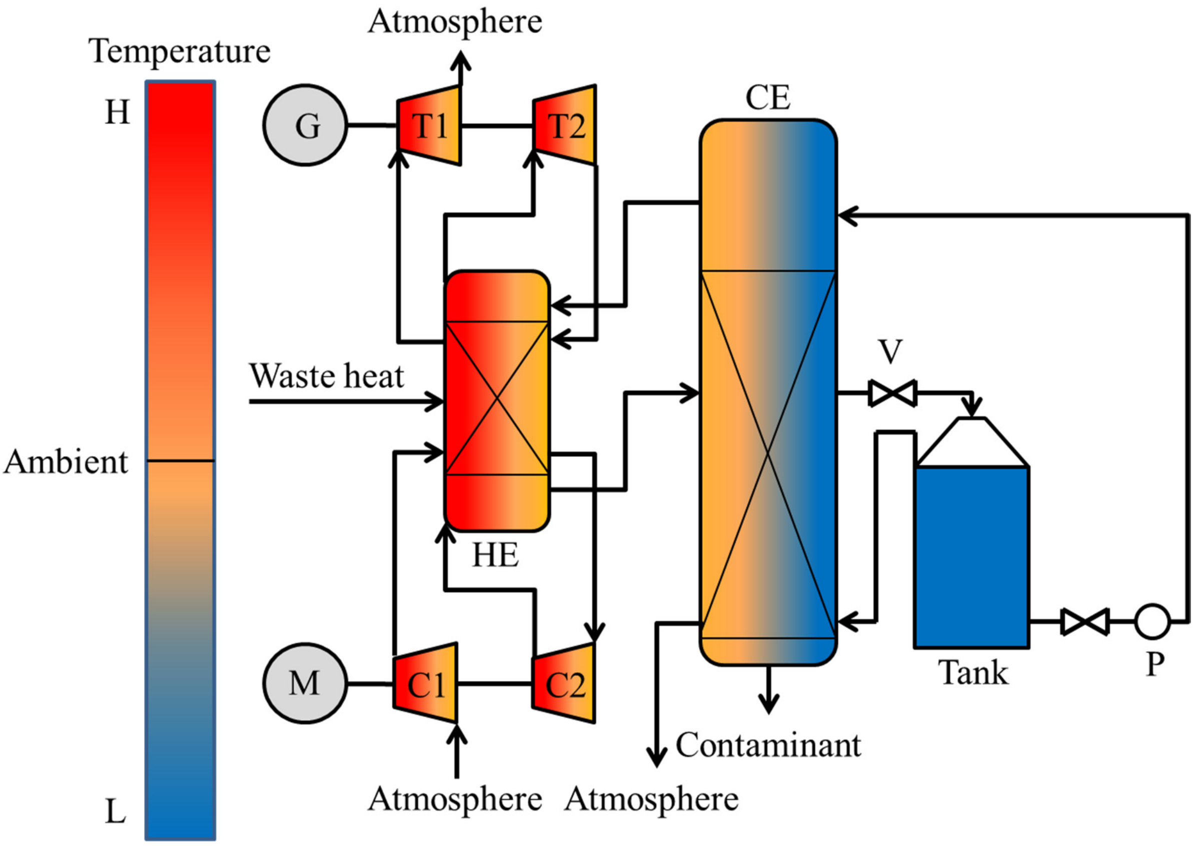

Figure 3. Scheme of SC-CAES system[19]

2.3. Merits and limitations

2.3.1. Merits. CAES possess the scales from small to large with wide storage stability and exceptional part-load properties[26]. Compared with all the technologies listed in table 1 below, the power rating of CAES is one of the highest technologies. Also, the table shows that its suitable storage duration is longer than most of the technologies such as the flywheel, capacitor, Superconductor Magnetic Energy Storage, Solar fuel, and so on. Instead of too long or too short, its lifetime is also relatively moderate. Besides, the table indicates that CAES is relatively mature, meaning that scientists have already had a lot of experience with it.

Table 1. Technological traits of electrical energy tools[26]

Technology	Energy Density (Wh/L)	Power Rating (MW)	Suitable Storage Duration	Lifetime (years)	Discharge Time	Cycling Times (cycles)	Maturity
PHS	0.5-2	30--5000	H-Mon	40-60	1--24 H+	10,000--30,000	Mature
Flywheel	20-80	0.1--20	Sec-Min	15--20	Sec-15 Min	20,000	Early Com
CAES	2--6	≧300	H-Mon	20--40	1--24 H+	8000--12,000	Early Com
Capacitor	2--6	0--0.05	Sec-H	1--10	Millis-1 H	50,000+	Com
SMES	0.2--6	0.1-10	Millis-H	20--30	≧30 Min	10,000+	Demo/Early Com

TES	80--500	0.1-300	Min-Days	5--30	1--24H+	-	Demo/Early Com
Solar fuel	500--10,000	0-10	H-Mon	-	1--24 H+	-	Developing
Hydrogen	500--3000	0-50	H-mon	5--20	Sec-24 H+	1000+	Developing /Demo
fuel cell Li-ion	150--500	0-100	Min-Days	5--20	Min-H	1000--10,000	Demo
Lead-acid	50--90	40	Min-Days	5--15	Sec-H	500--10,000	Mature

Abbreviations: SMES, Superconducting magnetic energy storage; TES, Thermal energy storage.

2.3.2. Limitations. Compared with gas, heat, and electricity, CAES's power density is lower and transportation losses are higher[19]. Table 2 also shows that its discharge time is comparatively long and its cycling time is shorter than some of the other technologies. Besides, compressed air energy storage is also restricted by the size and the availability of suitable geological locations[27, 28].

3. Applications

3.1. Cogeneration system
The combined heat and power system is also called the combined cooling, heat and power (CCHP) system. The main feature of this system is that it can reduce primary energy consumption and reduce the emission of pollutants. However, it still has difficulties integrating renewable energy into the grid, and as a result of the high volatility and instability of green power, the quality of the generated power cannot be guaranteed. In order to control the frequency, guarantee the grid robustness, and adjust the load, the system needs to be started and shut down frequently, which makes the cost higher. The air-storage compression use in the combined heat and power system can effectively improve the above-mentioned problems, storing excess energy during off-peak intervals to supply the requirement during peak intervals sooner or later. Thereby improving and stabilizing energy efficiency, reducing costs, etc.[29].

3.3. Distributed energy and microgrid systems
Distributed energy systems and microgrid systems are one of the main development trends of high-efficiency, low-carbon, and high-safety energy systems in the future. However, compared with large power grids, distributed energy systems have disadvantages such as large load fluctuations, poor system regulation capabilities, and high failure rates. air-storage compression can be used as a load-balancing device and a backup power source to effectively solve the above problems, improve the dependability and durability of the system's power supply, and realize black start and isolated grid operation. Due to the heat produced in compressed air energy storage technology, it could be merged with refrigeration and heating systems to realize the combined cooling, heating and power generation of distributed energy systems, which has a good application prospect[30].

4. Future development of CAES

From the perspective of technology itself, CAES is promising and is being considered to be integrated with other technologies, such as renewable energy, gas turbine, solid oxide fuel cells, and other systems[19]. For instance, the developing ADELE AA-CAES project in Germany[26] utilizes the CAES technology together with the wind farm. Also, CAES has a lot of space to develop and problems to overcome, including the urgent need for cooperation of engineers and scientists in various fields, technology innovation in air compressors and expanders, further substantial improvement in efficiency, necessity for lowering the cost of manufacturing air reservoirs and the study of the potential environmental impact[26]. From the perspective of economics, it is found that CAES investment can have good investment potential in the future since CAES operates both on the spot market and the controlling energy market, suggesting prospective practicability[31]. The better the technology develops, the less the operation will depend on higher price fluctuations[32]. From the perspective of the whole energy system and the whole society, the need for flexible technologies to maintain electricity balance is continuously increasing. In this way, it will have a well political and financial condition, which contributes to its better development.

5. Conclusion

The need for energy storage has been increasing rapidly recently and CAES plays a dominant role to address this. This paper has presented the current development of CAES according to its principles and advantages and the future development as one of the most encouraging energy storage technologies is also predicted. The advantages of CAES include high capacity, high power rating and long-duration storage. However, it has the disadvantages of low power density, high transportation losses, and restriction by the size and the availability of suitable geological locations. This study has identified three potential applications for CAES, including Renewable power generation, cogeneration system and distributed energy and microgrid systems. CAES is a mature technology that scientists have already had a lot of experience on and have more clear goals. It’s also promising and is considered to be integrated with other technologies, such as renewable energy, gas turbine, solid oxide fuel cells, and other systems in the future. Finally, on the other hand, based on the summary of the status, the future research directions of CAES are prospected like further substantial improvement in efficiency, need for reduction in the cost of constructing air reservoirs, and the study of the potential environmental impact.

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