Advances in
Geo-Energy Research

Vol. 2, No. 2, p. 135-147, 2018
www.astp-agr.com

Original article

# Compressed air energy storage: characteristics, basic principles, and geological considerations

Li Li[1], Weiguo Liang[2], Haojie Lian[2], Jianfeng Yang[2], Maurice Dusseault[1]*

[1]*Civil and Environmental Engineering, University of Waterloo, Waterloo N2L 3G1, Canada*

[2]*College of Mining Engineering, Taiyuan University of Technology, Taiyuan 030024, P. R. China*

(Received February 23, 2018; revised March 10, 2018; accepted March 11, 2018; available online March 15, 2018)

**Citation:**
Li, L., Liang, W., Lian, H., Yang, J., Dusseault, M. Compressed air energy storage: characteristics, basic principles, and geological considerations. *Advances in Geo-Energy Research*, 2018, 2(2): 135-147, doi: 10.26804/ager.2018.02.03.

**Corresponding author:**
*E-mail: mauriced@uwaterloo.ca

**Keywords:**
Energy storage
CAES
salt rock
geological considerations

**Abstract:**
With increasing global energy demand and increasing energy production from renewable resources, energy storage has been considered crucial in conducting energy management and ensuring the stability and reliability of the power network. By comparing different possible technologies for energy storage, Compressed Air Energy Storage (CAES) is recognized as one of the most effective and economical technologies to conduct long-term, large-scale energy storage. In terms of choosing underground formations for constructing CAES reservoirs, salt rock formations are the most suitable for building caverns to conduct long-term and large-scale energy storage. The existing CAES plants and those under planning have demonstrated the importance of CAES technology development. In both Canada and China, CAES plants are needed to conduct renewable energy storage and electricity management in particular areas. Although further research still needs to be conducted, it is feasible and economical to develop salt caverns for CAES in Canada and China.

## 1. Introduction

The increase of energy consumed by households and industries has exerted tremendous pressure on energy grids all around the world. Meanwhile, the existing energy production is facing increasing restrictions, due to international treaties on controlling pollution and global warming. Many countries are gradually abandoning coal-fired power plants and are looking for renewable energy sources, for example, solar power and wind power (Clayton et al., 2014).

These renewable energy resources present new challenges. The reliable operation of electric facilities can be threatened by the intermittency of wind power and solar power (Daim et al., 2012). The amount of energy produced by these kinds of sources, especially wind power, can fluctuate and may not match the power requirements, as shown in Fig. 1. The electricity demands are highest in the summer, but at that time the wind resources produce less power. The solar resources match the energy demands closely, but in the winter, there is a considerable gap between energy demand and solar generation. To resolve these issues, energy storage technology is required. Energy storage refers to a process of converting one type of energy, which is hard to store, into another form that can be easily stored and converted back to its original form when needed (Mclarnon and Cairns, 1989). This technology enables energy that is produced when demand and generation costs are low or when energy sources are intermittent, to be then used when energy demand and generation cost are high or when there are no alternative means for power generation, especially for electricity (Walawalkar, 2007).

Since the 1970s, Compressed Air Energy Storage (CAES) has attracted attention as one way to store cheap power during off-peak periods and used for periods when power is more valuable (Succar and Williams, 2008). It is also considered as one of the best options for storing energy with the highest economic feasibility (Lund and Salgi, 2009) and is shown to be an effective technology for handling the fluctuation of renewable energy (Xu et al., 2012).

In this work, an overview and comparison of different energy storage methods that are available or under development is carried out to show the superiority of CAES. In addition, the operation principles of CAES and the main components of a CAES plant are introduced, as well as the potential underground formations which can be used to develop CAES reservoir. The first two CAES plants under

https://doi.org/10.26804/ager.2018.02.03.

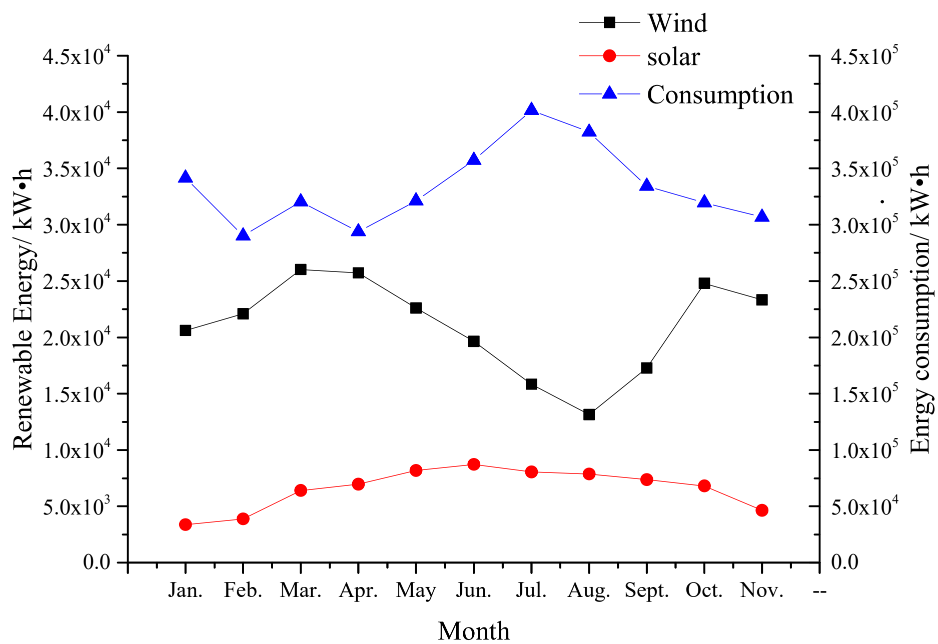


**Fig. 1.** Change of renewable energy generation and energy usage with months (IEA, 2018).

**Table 1.** Technical characteristics of energy storage (Chen et al., 2009).

| | Technology Parameters | Power Rating | Self-discharge per day | Expected Life Time (years) | Energy Density (Wh/L) | Power Density (W/L) |
|---|---|---|---|---|---|---|
| Mechanical energy storage | PHS | 100-500 MW | Very small | 40-60 | 0.5-1.5 | - |
| | CAES | 5-300 MW | Small | 20-40 | 3-6 | 0.5-2.0 |
| | FES | 0-250 kW | 100% | ∼15 | 20-80 | 1k-2k |
| Chemical Energy Storage | Conventional Battery | 0-40 MW | 0.1-0.6% | 5-20 | 50-500 | 0-400 |
| | Molten Salt Battery | 0-8 MW | 15%-20% | 10-15 | 150-250 | 0-300 |
| | Flow Battery | 30 kW-15 MW | small | 5-15 | 16-60 | - |
| Electric Storage | ECC | 0-300 kW | 20-40% | 20 | - | 100k |
| | CAP | 0-50 kW | 40% | ∼5 | 2-10 | 100k |
| | SEMS | 100 kW- 10 MW | 10-15% | 20-30 | 0.2-2.5 | 1k-4k |
| Heat Storage | LHS | 0-5 MW | 0.5-1.0% | 10-40 | 80-200 | - |
| | HHS | 0-60 MW | 0.05-1.0% | 5-15 | 120-500 | - |

commercial operation in the world are presented. Finally, geological considerations for CAES in Canada and China are discussed to indicate the necessity and challenges of CAES in salt formations in these two countries.

## 2. Energy storage technology

The energy storage methods can be categorized into four different types: mechanical energy storage, chemical energy storage, electric storage, heat storage, and biological storage. The mechanical energy storage includes Pumped Hydroelectric Storage (PHS), CAES, and Flywheel Energy Storage (FES) (Chen et al., 2009). The chemical energy storage can be divided into three major types: conventional, molten salt, and flow battery (Chen et al., 2009). Electric energy storage is a technology that can store energy, charge, and return power in electronic form; it contains Electrochemical Capacitors (super-capacitors) (ECC), Electrostatic Capacitors (CAP), and Superconducting Magnetic Energy Storage (SMES) (Dincer and Rosen, 2002). The heat storage system uses heat as energy to be stored, and covers a broad temperature range that can be classified into Low-temperature Heat Storage (LHS) and High-temperature Heat Storage (HHS) (Fernandes et al., 2012).

The technical characteristics of the different energy storage systems are compared in Table 1. The PHS, CAES, conventional battery, flow battery, SEMS, and HHS can be conducted in large-scale energy storage, which is described as a method that can store energy ranging from 10's to 100's MW (Hameer and van Niekerk, 2015). Molten Salt Battery and LHS can undertake medium-scale energy storage (1's - 10's

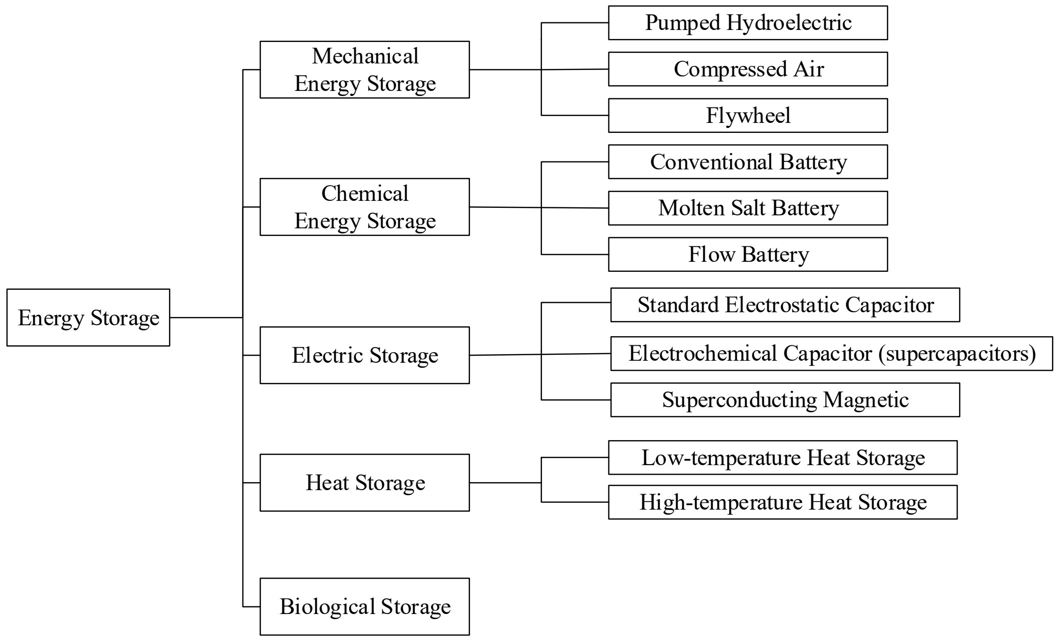


**Fig. 2.** Energy storage classification (Dincer and Rosen, 2002; Fernandes et al., 2012).

MW), and FES, ECC, and CAP are suitable for small-scale energy storage (0 - 1's MW). Regarding self-discharge per day for energy storage methods, PHS, CAES, and flow battery are suitable for long-term storage, because they have a very small self-discharge ratio. Conventional battery, LHS, and HHS have a relatively small self-discharge ratio and the suitable storage period of these methods is no more than tens of days. The self-discharging ratio of molten salt battery, ECC, CPA, and SEMS are higher, which ranges from 10 to 40% per day. These kinds of energy storage methods can only be implemented in short cycles of up to a few hours. If the storage period is greater than a day, the flywheels will run out of energy due to self-discharge (Suzuki, 2005). So, the suitable storage period of Flywheel is from minutes to hours (Amiryar and Pullen, 2017). The expected lifetime of PHS, CAES, SEMS, and LHS is longer than other energy storage systems. In terms of energy quality, the chemical energy storage system and the electric storage system are better than the ones of mechanical and thermal energy storage. The energy density is the energy stored divided by the whole volume of energy storage system, and the power density is the parameter calculated as output power divided by the volume (Kondoh et al., 2000). It can be concluded that the energy density of the conventional battery, molten salt battery, LHS, and HHS is higher than other technologies and can reach hundreds of Watts per hour. The energy density of CAES, FES, flown battery and CAP are among the medium level. PHS and SEMS have the lowest energy density. ECC and CAP have an extremely high-power density up to 100 kW/L. The power density of CAES is the lowest among energy storage systems.

Capital energy cost and capital power cost are important factors aside from technical characteristics. The capital energy cost and capital power cost of different energy storage systems are shown in Fig. 3. It should be mentioned that all the data

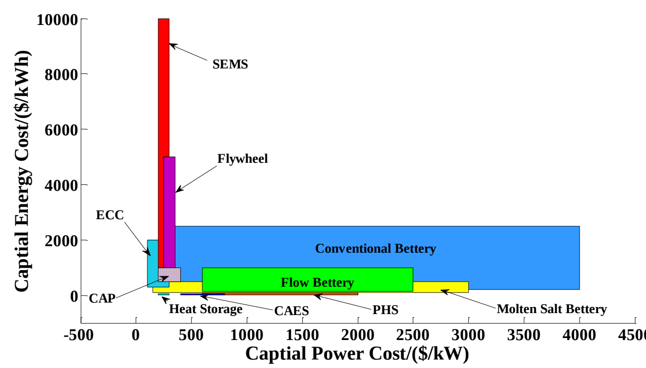


**Fig. 3.** Capital energy cost vs. capital power cost (Chen et al., 2009).

in the figure are the cost per useful energy, which means that all the costs per unit are divided by the storage efficiency. Heat storage system, CAES, PHS and molten salt battery are in the low range of capital energy cost, but the self-discharge per day of the molten salt battery is higher than other technologies. Regarding capital power energy cost, heat storage, CAES, ECC, CAP, SEMS, and Flywheel are among the low range. However, the self-discharge of ECC, CAP, SEMS, and Flywheel is high, so these technologies are suitable for high power but short-term energy storage. The capital energy cost of SEMS and Flywheel can be higher than other technologies.

The cycle efficiency of an energy storage system can be obtained by the equation below:

$$\gamma = \frac{E_o}{E_i}$$

where $\gamma$ is the cycle efficiency of the energy storage system,

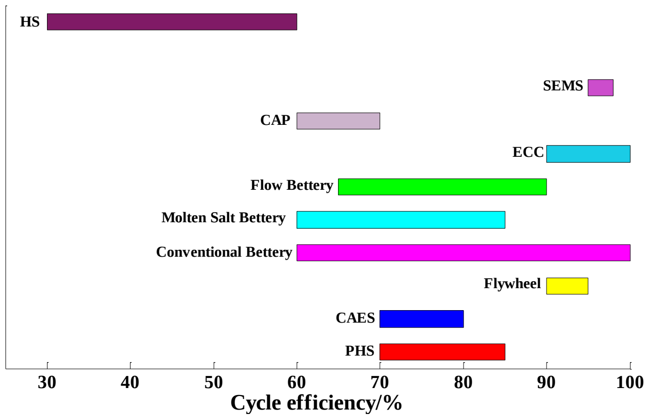


**Fig. 4.** Cycle efficiency of energy storage systems (Ibrahim et al., 2008).

$E_i$ is the input energy to energy storage system during a single cycle, $E_o$ is the output energy of a single cycle.

The cycle efficiency of different energy storage systems is elucidated in Fig. 4. The cycle efficiency of SEMS, ECC, and Flywheel can be above 90%. The CAES and PHS cycle efficiency is above 70%. It is also shown that the usage of compressed air for energy storage is less efficient than pumping and draining water with PHS. This is because gas is heated up during compression and increases the pressure, which contributes to more energy consumed to conduct further compression. The cycle efficiency of conventional, molten and flow battery cover a broad range, from 60% to 100%. The heat storage technology has the lowest cycle efficiency.

Storage technologies such as PHS, CAES, conventional battery, flow battery, SEMS, and HHS can be used to conduct large-scale energy storage. However, SEMS has high self-discharge per day, and this limits its ability to store energy for a long time. The expected lifetime of the conventional battery and flow battery is shorter than PHS, CAES, and HHS. In terms of capital cost, the capital energy cost of PHS, CAES and HHS are similar, but the capital power cost of PHS is much more than CAES and HHS. The cycle efficiency of CAES is above 70% while the one of HS is below 60%. In summary, CAES is one of the best options for long-term, large-scale energy storage.

## 3. CAES

The fundamental idea of using compressed air as a medium to perform energy storage dates back to the 1940s (Kalhammer and Schneider, 1976), but it wasnt until the 1960s that this technology was conducted in the industry. The development of nuclear power, lignite coal-fired power plant and other kinds of plants in the 1960s made adequate electricity, but it also caused a series of problems. A significant amount of cheap off-peak power was wasted, and an increasing amount of power was needed during peak time. The price difference of electricity between peak and off-peak periods motivated CAES research. CAES is a technology which uses compressed air as a medium to store energy and generate energy when it is needed (Hadjipaschalis et al., 2009). In terms of electrical energy, CAES means using electricity to drive the air compressor to compress air at a higher pressure and store the electricity in the form of internal energy in reservoirs when the electricity system load is low. Then the high-pressure air in reservoirs is released to drive the turbine generator to generate electricity to meet the electricity demand when the load of electricity is high (Chen et al., 2014; Yao et al., 2016), as shown in Fig. 5.

The schematic diagram of a more detailed CAES system is illustrated in Fig. 6. The figure demonstrates that usually a whole CAES system is made up of 5 components: a compressor, a reservoir, a turbine, a motor/generator and a thermal storage system. These five components can be divided into two categories. The first one is the machinery, which includes a compressor, a turbine, a motor/generator and a thermal storage system. The performance of machinery is essential to the efficiency of the CAES system. The compressor and turbine are the core components of the first part. The designed storage pressure is a significant factor for the compressor and turbine selection. To get high efficiency, a large CAES power station often adopts axial-flow and centrifugal compressors to conduct multi-stage compression, and the expanders which can conduct multi-stage expansion are used to drive generators to generate energy (Chen et al., 2013). During the energy-producing stage, a small amount of natural gas is used to preheat the air before it enters to the turbine. Although this technology is capable of producing three times more electricity than conventional gas turbine for the same amount of fuel (Connolly,2009), fuel is also being used, and carbon footprint is still produced. In order to reduce the usage of fuel and carbon dioxide emission, thermal energy storage devices are utilized to absorb and store the heat generated by compression and heat is reused to heat the air before expansion (Grazzini and Milazzo, 2012). This CAES system is recognized as advance adiabatic CAES (AA-CAES) (Jakiel et al., 2007; Li et al., 2013). The application of thermal storage system can increase the efficiency of CAES (Tessier et al., 2016; Sciacovelli et al., 2017), but further research needs to be conducted to solve the problems related to the energy storage system, such as large energy waste when the air temperature is too high (Liu and Wang, 2016). The second one is the reservoir. Due to the low power and energy density of CAES, a large volume of reservoirs or high-pressure air is needed to conduct large-scale CAES energy storage. Although some types of steel pressure vessels and gas pipes can bear the gas pressure up to tens of megapascals, high-pressure containers on the ground cannot meet the demand for large-scale CAES energy storage due to their capacity and manufacturing costs. Also, the storage security is a significant problem for high-pressure tanks on the ground. For large-scale energy storage, the cost of underground storage is only one fifth the cost of above ground gas tanks. The underground formations prove to be the most economical options (Eckroad and Gyuk, 2003).

## 4. CAES in underground formations

The most prominent challenge to conduct underground

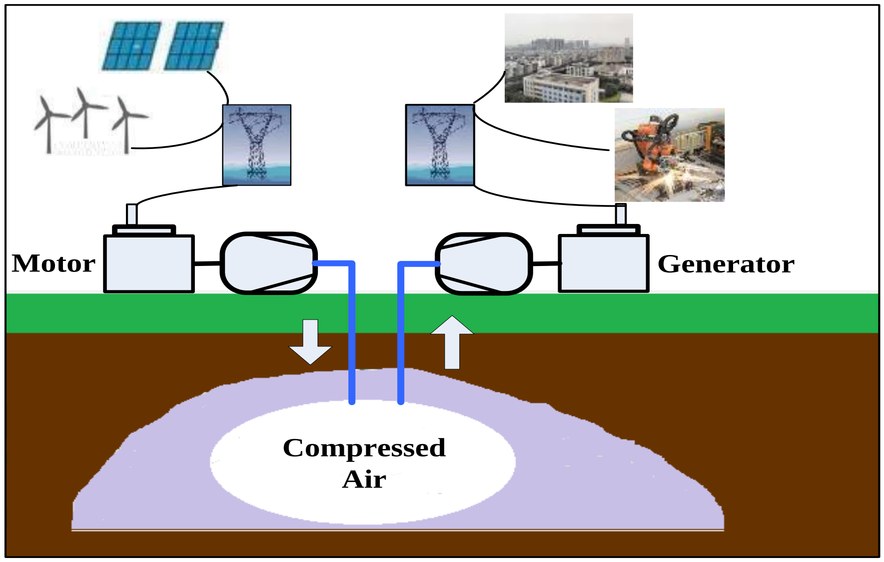


**Fig. 5.** Sketch of the process of compressed air energy storage (Wang et al., 2017).

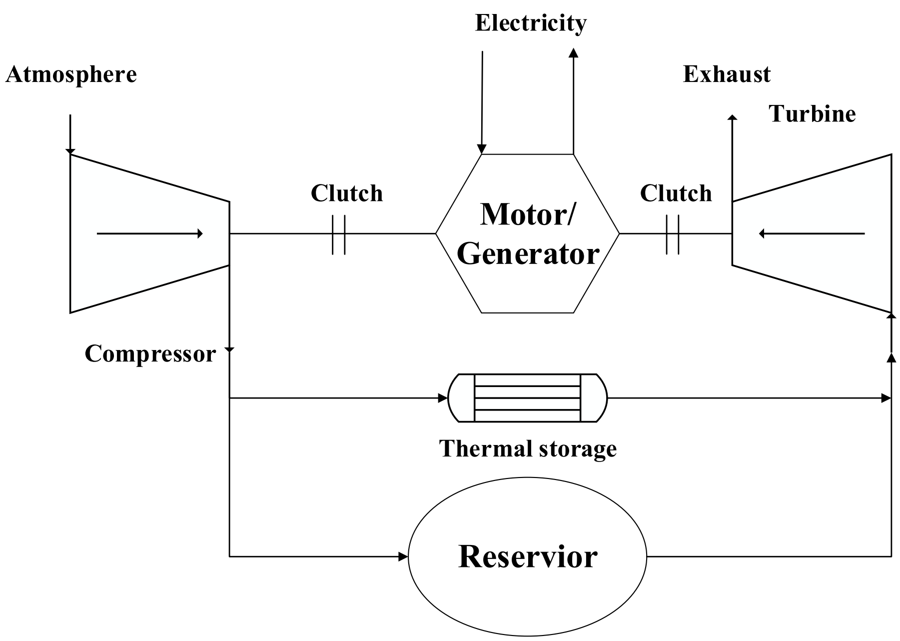


**Fig. 6.** Compressed air storage system.

CAES is to find geographical formations, which are tight enough to prevent the high-pressure air stored in the formations from escaping under cyclic operations. Additionally, the formations should be deep enough to conduct operations safely under the demanded air pressure. Thus far, salt caverns, hard rock caverns, saline aquifers and subsurface porous formations are promising options (Luo et al., 2014).

Salt caverns are considered one of the best options to store energy, with at least four advantages (Wang et al., 2013). Salt is easily dissolved in water, which means a salt cavern can be developed by solution mining (Reda and Russo, 1986) and that the shape of the cavern can be controlled (Connolly, 2009). The excellent self-healing capability of salt rock can guarantee the safe operation of CAES regular gas-pressure changes and eliminate air leakage. The permeability of the salt rock is low ( $10^{-24}$-$10^{-21}$ $m^2$), which can ensure that pressured air will not leak from the salt cavern. In addition, the resource of salt rock is abundant all around the world, so it is not too challenging to develop salt caverns near renewable-energy production and power-consumption area, and large mined cavities can be reused to conduct large-scale energy storage. The feasibility of reusage of old caverns for air storage has been proven by

**Table 2.** Cost for different CAES storage media (Mahlia et al., 2014).

| Reservoir | Size (MW) | Power-related plant components cost ($/kW) | Energy storage components cost ($/kW·h) | Storage typical hours (h) | Total cost ($/kW) |
|---|---|---|---|---|---|
| Salt | 200 | 350 | 1 | 10 | 360 |
| Hard rock | 200 | 350 | 30 | 10 | 650 |
| Porous formation | 200 | 350 | 0.1 | 10 | 351 |

**Table 3.** CAES projects all around the world (Zhuang et al., 2014; Réveillère and Londe, 2017).

| Name | Country | Power Capacity (MW) | Geological Formation | Depth (m) | Cavern Volume ($m^3$) | Operation Pressure (MPa) | Status |
|---|---|---|---|---|---|---|---|
| Huntorf | Germany | 290 | Salt Rock | 650 | 310,000 | 4.3-7.0 | Operation |
| McIntosh | USA | 110 | Salt Rock | 442 | 580,000 | 4.5-7.4 | Operation |
| Norton | USA | 2700 | Hard Rock | 670 | 9,600,000 | 5.5-11.0 | Construction |
| Iowa Energy Park | USA | 270 | Porous Formation | 914 | - | - | Construction |
| ADELE | Germany | 300 | Salt Rock | - | - | - | Planning |
| Matagorga | USA | 540 | Salt Rock | - | - | - | Planning |
| Seneca | USA | 150-270 | Salt Rock | 760 | 150,000 | 8.0-11.0 | Planning |
| PG&E | USA | 300 | Porous Formation | - | - | - | Planning |
| Datang CAES | China | 300 | Porous Formation | 500 | 900,000 | 5.0-8.0 | Planning |

Swift and Reddish (2005). The first two CAES plants in the world both used salt caverns developed by solution mining, and details will be described later.

Hard rock formations have been used to conduct hydrocarbon storage, e.g., natural gas, for decades due to their excellent air tightness and commercially available excavation technologies (Kim et al., 2012; Zhu et al., 2015). Although the output power of CAES system built in hard rock is higher than salt rocks, the excavation of new hard rock caverns can be costly (Succar and Williams, 2008), as shown in Table 2. To maximize the hard rock CAES system, hydraulic compensation is used. During the discharging operation, water is injected into the hard rock from surface reservoirs to displace the stored air. Thus, the air in the hard caverns can stay at a constant pressure to drive the turbine in the CAES plant. During the charging operation, high-pressure gas is injected to displace the water in the cavern. By adopting this approach, only one-fifth of the volume of the salt cavern is needed to achieve the same capability of energy storage (Schainker and Nakhamkin, 1985).

Since 1915, porous formations, such as aquifer formations, have been used to conduct natural gas storage. Currently, more than 95% of natural gas in natural gas storage systems is stored in the porous formation, and the technology of gas storage in porous formations has been fully developed. Although some of the physical and chemical characteristics and storage cycles of natural gas are different than those of CAES, most technologies and methodologies used in natural gas storage can be directly applied to CAES, such as reservisors site selection and development, gas compression-system operation, stability analysis of the reservoirs and system, and so on (Buschbach and Bond, 1973; Greenblatt, et al., 2007; Ibrahim et al., 2008; Barnes and Levine, 2011; Evans, 2017). Among the three promising options for underground CAES, reservoirs in porous formations have the potential to be the lowest cost storage option. However, the conduction of CAES has strict requirements on the porous formation. The formations must be porous enough to ensure that there is enough space to store high-pressure air, and the reservoirs need to have sufficient permeability so that the airflow rate in the reservoirs can be ensured during charging and discharging operation. Additionally, the structures of the overlying rock layers and adjacent formations must be impermeable, which means that they must have structural integrity, to prevent air from leaking and escaping to the ground (Eckroad and Gyuk, 2003). Besides, some minerals in the porous formation may react with the oxygen in the air and produce oxidation products such as gypsum ($CaSO_4 \cdot 2H_2O$), which can reduce the porosity of reservoir rocks, and affect the performance of the CAES system (Bui et al., 1990).

## 5. CAES facilities

The CAES facilities all around the world are listed in Table 3. It indicates half of the CAES projects are constructed or planned to be constructed in Salt Rock, which shows that Salt Rock has ideal formations to conduct underground CAES. The two projects that are now in commercial operation are Huntorf and McIntosh.

The first CAES facility, Huntorf plant, as shown in Fig.

**Fig. 7.** The Huntorf CAES Plant (Source: DOE Global Energy Storage Database).

**Fig. 8.** The McIntosh CAES Plant (Source: DOE Global Energy Storage Database).

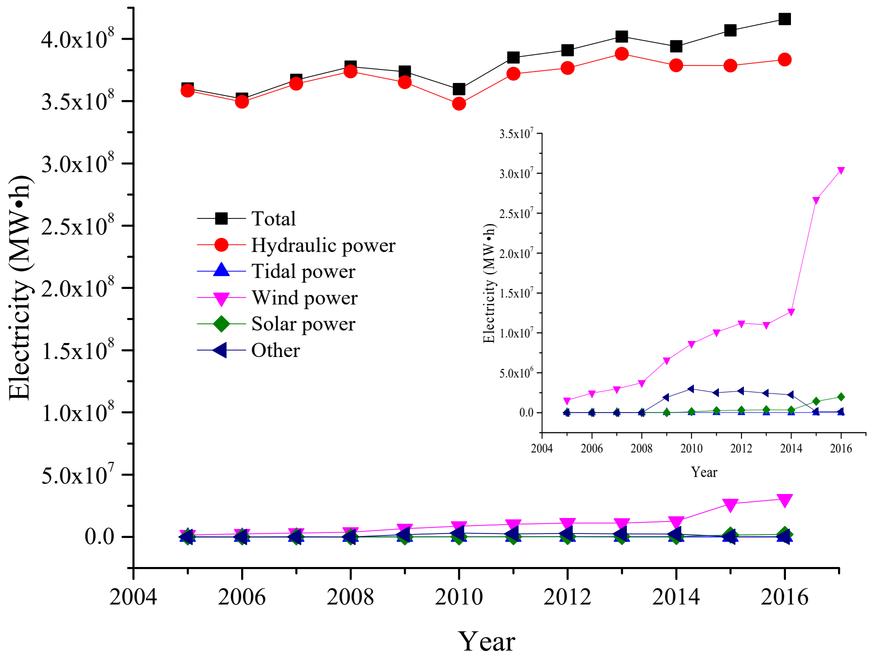


**Fig. 9.** Renewable energy in Canada (Statistics Canada, 2017).

7, was built near Bremen, Germany in 1978 (Crotogino et al., 2001), and has been successfully operating for more than 30 years. Until now, the plant is still running in excellent condition with 99% starting reliability and 90% ability (Luo and Wang, 2013). The CAES plant was initially designed and built to provide the nearby nuclear power units with black-start services and cheap peak power. However, the cavern volume is relatively small (310,000 $m^3$) and can only offer two hours rated output. Now the plant has been operationally modified to conduct wind output balance and can offer power for up to three hours (van der Linden, 2006). In the Huntorf CAES plant, two caverns were built in salt formation over 600 m under the ground to store compressed air ranging from 4.8 MPa to 7.0 MPa, creating a total volume of about 310,000 $m^3$. Under the working condition of a daily cycle, 290 MW rated power is provided for two hours after charging for eight hours by injecting compressed air into the salt carven.

About a decade later, Alabama Electric Cooperative built another CAES plant in southwestern Alabama on the McIntosh salt dome, as shown in Fig. 8. It is the first CAES facility in the United States and started operating commercially since 1991. This plant employs a single cavern, which is 442 m under the ground, to store compressed air (4.5-7.4 MPa) with a total cavern volume of 560,000 $m^3$. The plant was designed to provide power continuously for up to 26 hours. The design of McIntosh is similar to that of the Huntorf CAES plant, but the McIntosh CAES plant improves the design by using a heat recuperator to store the heat from the exhaust. The heat stored is then used to reheat the air released from salt cavern to approximately 320°C. This improvement contributes to reducing about 22% fuel consumption at full load output and improves the cycle efficiency by 15% (Luo and Wang, 2013). In the early operations, significant outages occurred, but these problems were solved by modifying the mounting of the high-pressure combustor and redesigning the low-pressure combustor (Biasi, 1998). Over ten years of operations (1998 - 2008), the McIntosh CAES plant maintained high average starting reliabilities from 91.2% to 92.1%. The average running reliability for generation and compression cycle is 96.8% and 99.5% respectively.

## 6. Geological considerations for CAES in Canada and China

### 6.1 Geological considerations for CAES in Canada

The increasing demands of energy in Canada have presented challenges for the traditional resource industries and motivated the progress towards renewable energy. In 2015, 18% of the total energy supply in Canada was obtained from renewable sources (IEA, 2017). Fig. 9 indicates that hydraulic power is the major part of the renewable energy, but it has increased slowly since 2004. In contrast, wind power has had an 18-fold increase since 2004. As mentioned previously, wind power fluctuates monthly and even hourly, and failure to store it will lead to a huge waste of wind energy. This can be seen especially in Ontario, where 40% of Canada's energy is produced (Statistics Canada, 2017). Compressed air energy storage can be one of the best options to store wind energy. When discussing the co-development of wind energy production and CAES operation, choosing suitable underground formations is critical.

In the Salina Formation of the Silurian age in southwest Ontario, a large number of salt deposits were found. The maximum occurrence thickness of the salt beds is 200 m, making it possible to build salt caverns in this area for large-scale energy

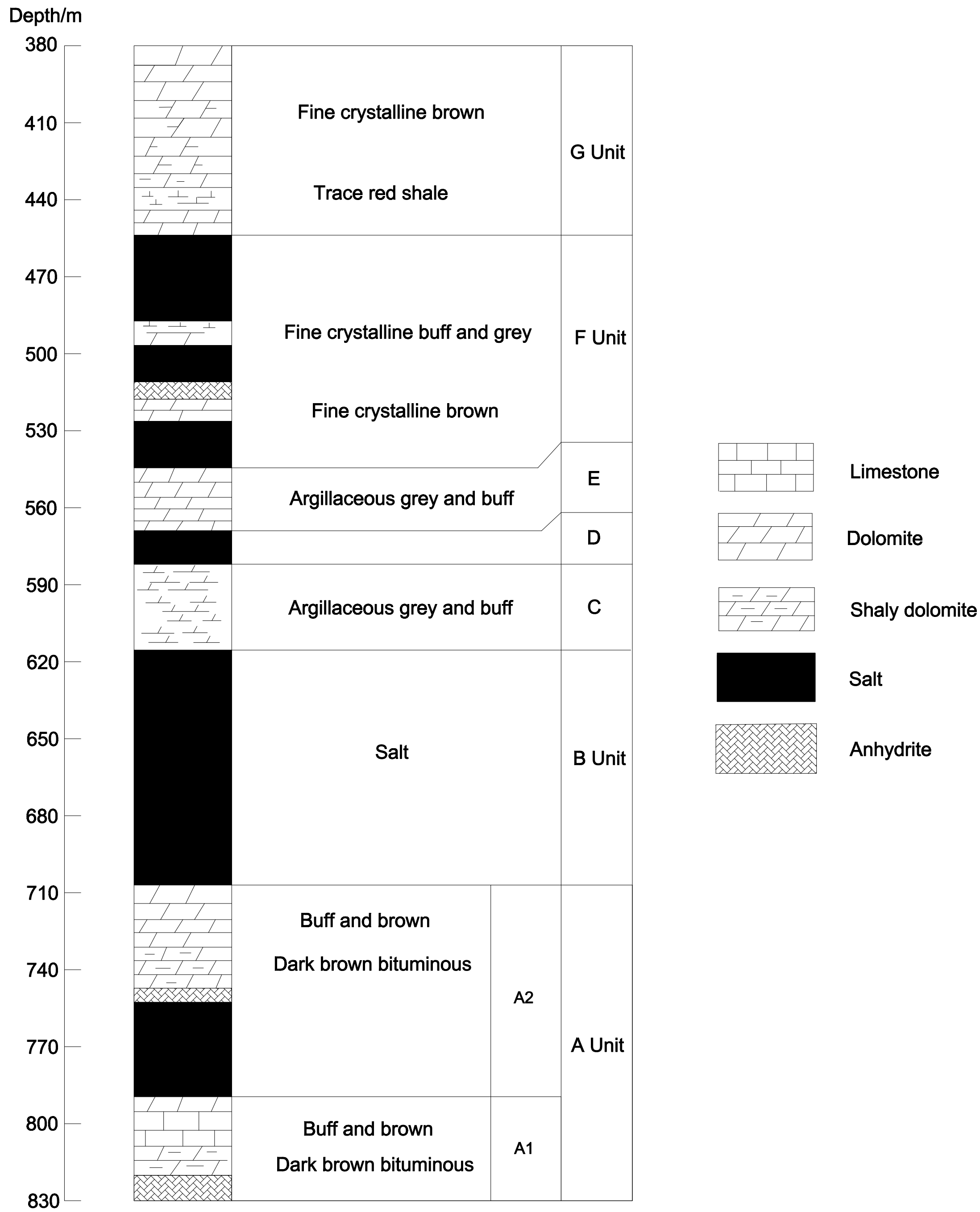


**Fig. 10.** The Salina Formation Subdivision (Frizzell et al., 2011).

storage. In addition, solution-mining operations have been in this area for decades; the first brine operation can be traced back to 1960. The existing salt caverns developed by solution mining of salt provide a more economically attractive option for building CAES facilities (Konrad et al., 2012). However, the number of the existing caverns may not be enough to meet the demand. The soluble component in Ontario's salt rock is up to 98%, which means new salt caverns can be built by solution mining efficiently. Although the development of new caverns by solution mining can be costly, time-consuming, and involve tedious brine disposal, it provides the salt caverns designer with the opportunity to control the shape and size of the caverns to ensure the stability and reliability of them.

The main Salina formation in Ontario can be divided into two main formations: upper Salina and lower Salina respectively (Hewitt, 1962), as shown in Fig. 10. The units containing salt in upper Salina are F, D, and B. Although the rock salt is pure, there are some interbedded layers of the salt rocks. In the F unit, the beds of shale appear between the layers of the salt in addition to the shaly dolomite and fine

**Fig. 11.** Undissolved interlayers in salt rock (Li et al., 2014).

crystalline buff. The salt in D unit is nearly pure, but divided by a thin layer of buff dolomite. B unit is the main salt unit in upper Salina. It is the thickest salt layer among the four units with a thickness of about 90 m, but also including some thin dolomite layers. Unit A2 is the only unit containing salt in the lower Salina. The thickness of the salt layer in A2 is about 45 m. It is interbedded with several kinds of dolomite.

The construction of vertical salt caverns like Huntorf and McIntosh can be complicated in the Ontario Salina formation because the vertical salt caverns should cross the units of E and C as well as some thin insoluble layers in the salt. The construction of horizontal salt caverns in the thin salt bed can avoid crossing the large insoluble interlayers (Russo, 1967). Han et al. (2007) built a model and studied the influence of cavern geometries, overburden stiffness and interface properties on the salt cavern in single bedded salt formations under cyclic pressure operations. He determined that the cavern can be more stable when its size is smaller. Horizontal salt caverns can be unstable with a large roof span, so more research is required, and measures should be taken to control the volume of horizontal salt caverns during dissolution progress.

### 6.2 Geological considerations for CAES in China

The explored reserves of the salt rock in Yulin, Shannxi province, is $8.9\times10^{11}$ t, accounting for 70% of the total resource in China. The salt formations are buried between 2000 m to 2500 m, and the average thickness of the salt deposit is above 120 m. In addition, 12 ore districts of salt have been ascertained in Sichuan province, amounting to about $2.2\times10^{11}$ t of salt rock (Mei et al., 2017). Meanwhile, renewable energy is mainly distributed in northwest, northeast, and southwest of China. However, due to the limitation of power transmission and the trade model of energy between different regions, large amounts of the generated renewable energy is wasted. In 2016, the amount of wasted wind and solar energy was $5.7\times10^{10}$ kW·h. The salt formations in these areas all provide favorable conditions for the development of large-scale caverns for energy storage. To date, a large number of salt caverns have been developed with a total volume of approximately $1.3\times10^{8}$ m$^3$. Most of them have excellent air tightness and are suitable for oil, natural gas, and compressed air storage. However, only about 40 salt caverns, approximately 0.2% of the total caverns, are utilized.

**Table 4.** Salt Caverns in East China.

| Name | Location | Volume of caverns ($10^6$ m$^3$) |
|---|---|---|
| Pingdingshan | Henan | 4.0 |
| Hainan | Jiangsu | 10.0 |
| Jintan | Jiangsu | 14.3 |
| Yingcheng | Hubei | 8.0 |
| Qianjiang | Hubei | 4.0 |
| Zhangshu | Jiangxi | 10.0 |

The peak-valley difference of the regional power grid in China shows an increasing trend, which leads to the low utilization of equipment. This situation is more severe in eastern China, where the electricity demand is high. One of the best options to store the energy and conduct peak shaving is to use compressed air energy storage in salt caverns. The distribution of salt cavern resource and available volumes of the caverns in east China are illustrated in Table 4 (Chen et al., 2017). It should be mentioned that most of the salt caverns have been built with the vertical span of the caverns greater than the horizontal one.

In China, the salt formations suitable to build salt caverns are mainly the deposits of deep-water lacustrine. Compared to the salt rock in Canada, there are many undissolved interlayers between the dissolvable salt, such as the layers of gypsum, glauberite, and mudstone, as shown in Fig. 11. In some areas, the total thickness is large, but the thickness of a single layer is relatively small. However, some of the interlayers between salt rock layers can reach 2 m. Additionally, the salt formations are closely connected to the graben tectonic basin. The differences between central and marginal areas lead to further complicated formation structures (Li et al., 2014). The differences of properties of interlayers and rock salt play an important role to determine the operating parameters and stability of salt cavern (Li et al., 2006; Liang et al., 2008).

During the dissolution process of salt cavern development, the undissolved components will have a significant effect on the general nature of salt rock and may delay the process. During process, the interlayers of gypsum, mudstone and other insoluble minerals will be soaked in the salt solution for a long time. The brine will affect the mechanical properties of the interlayers, which lead to the failure of the caverns. During the operation of gas storage in such salt caverns, the periodic changes in air pressure will induce shear stress and deformation, which may contribute to the development of slippage along the interface (Xu et al., 2009). This may seriously affect the tightness and stability of the storage caverns. Staudtmeister and Rokahr (1997) used numerical calculation methods to study the non-linear and time-dependent behavior of the rock salt and the stability of salt carven for natural gas storage for a long period. Khaledi et al. (2016) used software to study the cyclic loading operation during gas storage in salt caverns and analyzed the influence of internal pressure on the surrounding rock's stability. CAES is different from normal natural gas storages because the pressure change in the salt cavern for CAES is more frequent than the one for natural gas, and it may have an impact on the stability of salt cavern. However, little work has been published related to this issue.

In China, the salt rocks layers available for constructing caverns are usually no more than 150 m thick. During the construction of vertical air storage cavern, it is inevitable to go through a single layer or even multiple layers and cause the irregular shape of the salt cavern (Li et al., 2014). Djizanne et al. (2014) developed a model and studied the stability of a salt cavern for gas storage to find out that overhanging block trends to fall when the buoyancy is high. As mentioned before, the construction of horizontal salt caverns in salt formation can avoid crossing the insoluble interlayers and collapsing. However, the construction of horizontal salt cavern has never been conducted in China (Yang et al., 2016). In addition, the research on horizontal salt rock cavern for CAES has rarely been reported, so further study on the dissolution process, the multi-field coupling problems during the horizontal cavern development, safety assessments as well as operating parameter design need to be conducted.

## 7. Conclusion

Based on this work, the following conclusions can be addressed:

(1) Energy storage is required urgently to handle the challenges faced by the worldwide energy industry. By adopting energy storage, energy produced in off-peak period can be used to reduce the pressure on power system when the energy demand is high. In addition, energy storage is an effective way to solve the problems caused by fluctuating renewable energy to maximize the usage of renewable energy.

(2) There are various commercially available energy storage technologies or systems, and each technology or system has its advantages and disadvantages. For large- scale and long-term energy storage, CAES is one of the best options because of its high powering rating, small self-discharge, long expected lifetime, relatively low capital cost and relatively high cycle efficiency. However, further studies need to be conducted to improve the efficiency of the whole CAES system.

(3) Compared to the ground gas tank, the underground formations are the most economical options for conducting large-scale energy storage reservoirs. Salt caverns are considered one of the best options to store energy because of the characteristics of salt rock and the low development cost. The two commercial CAES plants have demonstrated the feasibility of salt caverns used for energy storage.

(4) The geological conditions in Canada and China are completely suitable for the construction and operation of CAES facilities in salt rock, and horizontal caverns would be the most suitable for the unique geological conditions. However, further research on the dissolution process of the bedded salt rock in situ, shape control of horizontal salt cavern, safety assessments, as well as operating parameter design safety assessments as well as operating parameter design for CAES in horizontal caverns, needs to be conducted.

## Acknowledgments

This research has been funded by a joint private-public partnership. The authors acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC), the Ontario Centres of Excellence, NRStor Inc., Rocky Mountain Power, Ontario Power Generation, Union Gas, Hydro One, Compass Minerals, and Alberta Innovates. This project is organized through the Waterloo Institute for Sustainable Energy (WISE). Li Li is supported by a Scholarship from China Scholarship Council. We would like to thank the anonymous reviewers for their helpful and constructive comments and suggestions.



## References

Amiryar, M., Pullen, K. A review of flywheel energy storage system technologies and their applications. Appl. Sci. 2017, 7(3): 1-21.

Barnes, F.S., Levine, J.G. Large energy storage systems handbook. CRC Press, New York, 2011.

Biasi, V. 110 MW McIntosh CAES plant over 90% availability and 95% reliability. Gas Turbine World 1998, 28: 26-28.

Bui, H., Herzog, R., Jacewicz, D., et al. Compressed-air energy storage: Pittsfield aquifer field test. Report EPRI6688, United States, 1990.

Buschbach, T.C., Bond, D.C. Underground storage of natural gas in Illinois. Illinois State Geological Survey, Champaign, 1974.

Chen, H., Cong, T.N., Yang, W., et al. Progress in electrical energy storage system: A critical review. Prog. Nat. Sci. 2009, 19(3): 291-312.

Chen, H., Liu, J., Guo, H., et al. Technical principle of compressed air energy storage system. Energ. Storage Sci. Technol. 2013, 2(2): 146-151.

Chen, L., Mei, S., Wang, J., et al. Large scale compressed air energy storage for smart grid. Adv. Technol. Electr. Eng. Energ. 2014, 33(6): 1-4.

Chen, X., Song, J., Liang, L., et al. Performance study of salt cavern air storage based non-supplementary fired compressed air energy storage system. Mater. Sci. Eng. 2017, 248(1): 012007

‘ Clayton, M.E., Kjellsson, J.B., Webber, M.E. Can renewable energy and desalination tackle two problems at once?

Retrieved from https://www.earthmagazine.org/article/can-renewable-energy-and-desalination-tackle-two-problems-once, 2014.

Connolly, D. Review of Energy Storage Technologies. University of Limerick, Ireland, 2009.

Crotogino, F., Mohmeyer, K.U., Scharf, R. Huntorf CAES: More than 20 years of successful operation. Paper AKE2003 Presented at the Proceedings SMIR SMRI Spring meeting, Orlando, Florida, USA, 15-18 April, 2001.

Daim, T.U., Li, X., Kim, J., et al. Evaluation of energy storage technologies for integration with renewable electricity: Quantifying expert opinions. Environ. Innov. Soc. Transit. 2012, 3(9): 29-49.

Dincer, I., Rosen, M. Thermal energy storage: systems and applications. John Wiley & Sons, England, 2002.

Djizanne, H., Bérest, P., Brouard, B. The mechanical stability of a salt cavern used for compressed air energy storage (CAES). Paper PA18411 Presented at the 2014 Spring SMRI Technical Conference, San Antonio, Texas, USA, 47 May, 2014.

Eckroad, S., Gyuk, I. EPRI-DOE handbook of energy storage for transmission & distribution applications. Washington, DC, Department of Energy, 2003.

Evans, D.J. An appraisal of underground gas storage technologies and incidents, for the development of risk assessment methodology. J. Fuel Cell Technol. 2007, 6 (49): 97-107.

Fernandes, D., Pitié, F., Cáceres, G., et al. Thermal energy storage: How previous findings determine current research priorities. Energy 2012, 39(1): 246-257.

Frizzell, R., Cotesta, L., Usher, S. Regional Geology-Southern Ontario. Tiverton, OPG’s Deep Geol. Repos. Low Intermed. Level Waste, 2011.

Grazzini, G., Milazzo, A. A thermodynamic analysis of multistage adiabatic CAES. Proc. IEEE 2012, 100(2): 461-472.

Greenblatt, J.B., Succar, S., Denkenberger, D.C., et al. Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation. Energ. Policy 2007, 35(3): 1474-1492.

Hadjipaschalis, I., Poullikkas, A., Efthimiou, V. Overview of current and future energy storage technologies for electric power applications. Renew. Sustain. Energ. Rev. 2009, 13(6-7): 1513-1522.

Hameer, S., Niekerk, J. L. A review of large-scale electrical energy storage. Int. J. Energ. Res. 2015, 39(9): 1179-1195.

Han, G., Bruno, M.S., Lao, K., et al. Gas storage and operations in single-bedded salt caverns: stability analyses. SPE Prod. Oper. 2007, 22(3): 368-376.

Hewitt, D.F. Salt in Ontario. Frank Fogg, Toronto, 1962.

Ibrahim, H., Ilinca, A., Perron, J. Energy storage systems-Characteristics and comparisons. Renew. Sustain. Energ. Rev. 2008, 12(5): 1221-1250.

IEA. Renewables Information. OECD Publishing, Washington, 2017.

IEA. Electric Power Monthly with Data for November 2017. U.S. Energy Information Administration, 2018.

Jakiel, C., Zunft, S., Nowi, A. Adiabatic compressed air energy storage plants for efficient peak load power supply from wind energy: The European project AA-CAES. Energ. Technol. Policy 2007, 5(3): 296-306.

Kalhammer, F.R., Schneider, T.R. Energy storage. Ann. Rev. Energ. 1976, 1(1): 311-343.

Khaledi, K., Mahmoudi, E., Datcheva, M., et al. Stability and serviceability of underground energy storage caverns in rock salt subjected to mechanical cyclic loading. Int. J. Rock Mech. Min. Sci. 2016, 86: 115-131.

Kim, H.M., Rutqvist, J., Ryu, D.W., et al. Exploring the concept of compressed air energy storage (CAES) in lined rock caverns at shallow depth: A modeling study of air tightness and energy balance. Appl. Energ. 2012, 92: 653-667.

Kondoh, J., Ishii, I., Yamaguchi, H., et al. Electrical energy storage systems for energy networks. Energ. Convers. Manag. 2000, 41(17): 1863-1874.

Konrad, J., Carriveau, R., Davison, M., et al. Geological compressed air energy storage as an enabling technology for renewable energy in Ontario, Canada. Int. J. Environ. Stud. 2012, 69(2): 350-359.

Liang, W.G., Yang, C., Zhao, Y.S. Physico-mechanical properties and limit operation pressure of gas deposit in bedded salt rock. Chin. J. Rock Mech. Eng. 2008: 27(1), 22-27.

Li, J.J., Wang, L.D., Liu, C.H. Factors affecting cavities distortion of jintan salt cavern gas storage. Oil Gas Storage Transp. 2014, 3(3): 269-273.

Liu, J., Wang, J. A comparative research of two adiabatic compressed air energy storage systems. Energ. Convers. Manag. 2016, 108: 566-578.

Li, X., Yang, K., Zhang, Y. Optimization design of compression and expansion stages in advanced adiabatic compressed air energy storage system. J. Eng. Thermophys. 2013, 34(9): 1649-1653.

Li, Y., Liu, W., Yang, C., et al. Experimental investigation of mechanical behavior of bedded rock salt containing inclined interlayer. Int. J. Rock Mech. Min. Sci. 2014, 69(3): 39-49.

Li, Y.P, Liu, J., Yang, C.H. Influence of mudstone interlayer on deformation and failure characteristics of salt rock. Chin. J. Rock Mech. Eng. 2006, 28(12): 2461-2466.

Lund, H., Salgi, G. The role of compressed air energy storage (CAES) in future sustainable energy systems. Energ. Convers. Manag. 2009, 50(5): 1172-1179.

Luo, X., Wang, J. Overview of current development on compressed air energy storage. School of Engineering, University of Warwick, Coventry, UK, 2013.

Luo, X., Wang, J., Dooner, M., et al. Overview of current development in compressed air energy storage technology. Energ. Proced. 2014, 62: 603-611.

Mahlia, T.M.I., Saktisahdan, T.J., Jannifar, A., et al. A review of available methods and development on energy storage; technology update. Renew. Sustain. Energ. Rev. 2014, 33: 532-545.

Mclarnon, F.R., Cairns, E.J. Energy storage. Ann. Rev. Energ. 1989, 14(1): 241-271.

Mei, S., Gong, M., Qin, G., et al. Advanced adiabatic compressed air energy storage system with salt cavern air storage and its application prospects. Power Syst. Technol. 2017, 41 (10): 3392-3399.

Reda, D.C., Russo, A.J. Experimental studies of salt-cavity leaching by fresh water injection. SPE Prod. Eng. 1986, 1 (1): 82-86.

Réveillère, A., Londe, L. Compressed air energy storage: a new beginning? Paper Presented at the SMRI Fall 2017 Technical Conference, Münster, Germany, 25-26 September, 2017.

Russo, A. Horizontal natural gas storage caverns and methods for producing same. United States Patent, Patent number: 5431482, 1967.

Schainker, R.B., Nakhamkin, M. Compressed-air energy storage (CAES): overview, performance and cost data for 25mw to 220mw plants. IEEE Trans. Power Appar. Syst. 1985, 104(4), 790-795.

Sciacovelli, A., Li, Y., Chen, H., et al. Dynamic simulation of adiabatic compressed air energy storage (A-CAES) plant with integrated thermal storage-Link between components performance and plant performance. Appl. Energ. 2017, 185(1): 16-28.

Statistics Canada. Table 127-0007-Electric power generation. Retrieved from http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1270007, 2017.

Staudtmeister, K., Rokahr, R.B. Rock mechanical design of storage caverns for natural gas in rock salt mass. Int. J. Rock Mech. Min. Sci. 1997, 34(3-4): 300.e1-300.e13.

Succar, S., Williams, R.H. Compressed air energy storage: theory, resources, and applications for wind power. Princeton environmental institute report, Princeton University, 2008.

Suzuki, Y., Koyanagi, A., Kobayashi, M. Novel applications of the flywheel energy storage system. Energy 2005, 30(11): 2128-2143.

Swift, G.M., Reddish, D.J. Underground excavations in rock salt. Geotechn. Geol. Eng. 2005, 23(1): 17-42.

Tessier, M.J., Floros, M.C., Bouzidi, L., et al. Exergy analysis of an adiabatic compressed air energy storage system using a cascade of phase change materials. Energy 2016, 106: 528-534.

Van der Linden, S. Bulk energy storage potential in the USA, current developments and future prospects. Energy 2006, 31(15): 3446-3457.

Walawalkar, R., Apt, J., Mancini, R. Economics of electric energy storage for energy arbitrage and regulation. Energ. Policy 2007, 5(4): 2558-2568.

Wang, J., Lu, K., Ma, L., et al. Overview of compressed air energy storage and technology development. Energies 2017, 10(7): 1-22.

Wang, T., Yan, X., Yang, H., et al. A new shape design method of salt cavern used as underground gas storage. Appl. Energ. 2013, 104(2): 50-61.

Xu, S.G., Liang, W.G., Mo, J., et al. Influence of weak mudstone intercalated layer on mechanical properties of laminated salt rock. Chin. J. Undergr. Sp. Eng. 2009, 5(5): 878-883.

Xu, Y., Chen, H., Liu, J. Performance analysis on an integrated system of compressed air energy storage and electricity production with wind-solar complementary method under energy internet background. Proc. CSEE 2012, 32(20): 88-95.

Yang, C., Wang, T., Qu, D., et al. Feasibility analysis of using horizontal caverns for underground gas storage: A case study of Yunying salt district. J. Nat. Gas Sci. Eng. 2016, 36: 252-266.

Yao, E., Wang, H., Wang, L., et al. Thermal-economic optimization of a combined cooling,heating and power system based on small-scale compressed air energy storage. Energ. Convers. Manag. 2016, 118: 377-386.

Zhuang, X., Huang, R., Liang, C., et al. A coupled thermo-hydro-mechanical model of jointed hard rock for compressed air energy storage. Math. Probl. Eng. 2014, 2014: 1-11.

Zhu, H., Chen, X., Cai, Y., et al. The fracture influence on the energy loss of compressed air energy storage in hard rock. Math. Probl. Eng. 2015, 2015: 1-11.