Comprehensive Study of Liquid-Air and Compressed Air Energy Storage

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Abstract: Continuous and clean energy generation is the goal of all energy researchers. Research is going towards this goal. This report discusses some of the thermodynamic solutions CAES and LAES for electrical energy storage based on the Carnot Battery cycle. The process flow diagram and the different components of the systems have been presented. The benefit of Carbon di Oxide as a storage medium is also discussed. Some current and future utilization of this system other than electricity generation are also mentioned. Current constraints and limitations, along with some solutions to the system are also analyzed in this report.

• Introduction

Clean energy generation and storage and transport are trending topics in the energy industry. Energy security is also a great concern regarding the future availability of non-renewable sources, increasing environmental pollution, and increasing energy per capita consumption price. Renewable energy sources such as Solar, Wind, Ocean waves, etc., are considered clean sources of energy, but their non-uniform and uncontrollable intermittent nature of energy production are big problems for rapid and large-scale utilization and adoption of these energy sources. In the area near the polar region, solar energy is not pretty significant during winter, and wind turbines also face an icing of turbine blade problem during winter. Hence, It is very crucial for continuous energy security to store the energy when it is available [1]. Scientists found some techniques to store electricity. The battery is one of them. But the batteries have limitations on the temperature of operation and their continuous reusability. Hence, Storing the energy in a thermodynamic cycle is a better alternative. The excess renewable energy can be stored in Compressed air energy storage (CAES) or Liquid air energy storage (LAES) at high pressure when available. The stored energy can be used during demand time by passing the compressed air over a turbine to generate electricity. Compressed Air Energy Storage (CAES) can convert variable power from renewable sources into a stable, large-scale, and flexible electricity grid power storage. Both the LAES or CAES cycle is based on Carnot Battery to electricity in thermal energy storage(TES). Conventional CAES systems use surplus energy to pressurize the air at high pressure and store the air for future use for gas turbines during peak demand time. A large amount of heat is wasted during compression, which is the main cause of low round-trip efficiency for this system. [2] Besides this, the other shortcomings are lower thermal efficiency, high exergy destruction in the heat exchanger, and the large storage volume of the CAES system. [1] Currently, this concept is utilized in UK and USA. Two 50 MW plant system named CRYOBattery is under operation. There are lots of research going on in this field. In the last decade alone, there have been almost 15 times a jump in CAES and LAES systems related publications. [12]

• Key Benefits of The CAES or LAES System

a) Increases flexibility of use of renewable energy:

This type of system increases the effectiveness and reliability of renewable sources. It makes renewable sources more flexible to use as grid power.

b) Reduce Energy Wastage:

Besides renewable energy sources, This CAES system can store excess waste heat in a chemical plant and conventional power plant. Using waste heat can increase the overall efficiency of a plant. This stored energy can be used during peak demand and other utility applications.

c) Decreased CO2 emission:

The effective use of waste heat and collected energy during peak demand reduce fossil fuel burning, eventually reducing CO2 emissions.

d) Less operating and installed Costs

CAES system can be installed with an existing conventional power plant. Hence it has significantly less capital installation cost. Compared with other energy production methods, it has less maintenance and operating costs. Only the compressor is used during operation, which also extends compressor life.

- # Technical Classifications based on current modification of the CAES and LAES System

The performance of Different CAES is compared based on their Round-trip efficiency (RTE) and Energy density (EVR). Round trip efficiency (RTE) is defined as the percentage of electricity put as an input into storage that is later recovered. That higher RTE signified a low percentage of energy lost in storing process. [3] Different types of CAES systems are studied for optimized energy storage. Some of the advanced and trending CAES cycles in the research area are discussed in the following paragraph-

Different types of CAES systems

a) ACAES system:

To eliminate the drawbacks, as mentioned earlier, Research is conducted to get more constructive and innovative solutions to the problem. Adiabatic compressed air energy storage (ACAES) is a potential alternative to conventional CAES. [6] Adiabatic compressed air energy storage (ACAES) is a large-scale, cost-efficient, and fossil fuel-free process where work is used to compress atmospheric air in a compressor at point 1 in Figure 1, and generated heat in the compressor is stored in a different thermal energy storage (TES) (point 2) with the help of a separate heat exchanger. The pressurized compressed air is stored in a high-pressure air storage vessel (point (3). During power generation, heat from TES is combined with high-pressure air (point (4) and transferred heated and pressurized air to the turbine for power generation (point 5) [4]. The RTE efficiency of ACAS is found in the range of 52% to 62%, with a dependency on storage temperature and heat transfer conditions such as cooling and heating. Another drawback of this type of system is its low energy density [5][6]

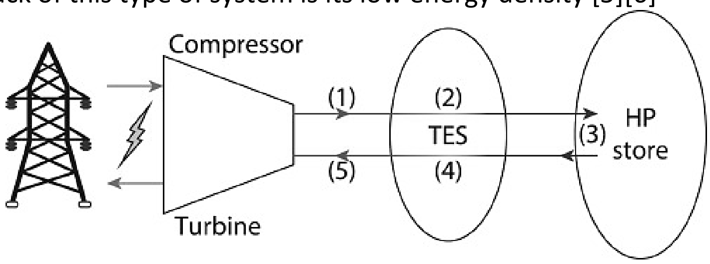

Figure 1. Diagram of ACAES System [4]

b) Combined Rankine and liquefaction cycles:

Another optimization of the CAES system is liquid air energy storage (LAES) which has high energy density compared to other forms of CAES. Liquid air energy storage is a modified version of combined Rankine and liquefaction cycles. The conventional ranking and liquefaction cycle combine the Linde process and a Rankine cycle described in Figure 2. This process begins with pressurized liquid air from a cryogenic storage tank. The liquid air is then heated (7-8) with precooled heat exchanger and heated in a boiler with an external heater (8-9). Then the heated air generated work by expanding in the turbine and released into the atmosphere (9-10). Some portion of the generated work is used to compress fresh air in the compressor (0-1) and then precooled in a recovery heat exchanger with liquid air (1-2-3), and this pressurizes air sent throttling process to make the two-phase liquid-vapor mixture. (3-4). [7]

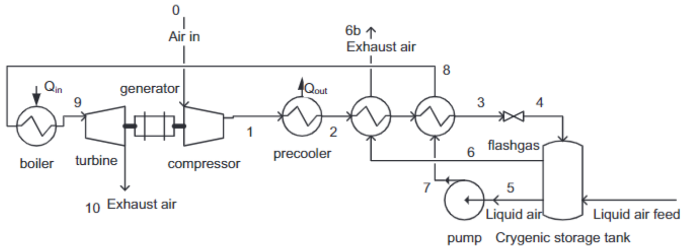

Figure 2. Diagram of combined Rankine and liquefaction cycles [7]

c) Liquid air energy storage (LAES) System:

One of the modifications of Rankine and liquefaction cycles is liquid air energy storage (LAES) (Figure 3). The schematic diagram of LAES consists of a compressor, cold energy regenerator, liquid-vapor separator, cryogenic tank, turbine, generator, and cryogenic pump. The cold storage medium is stored in a cold energy regenerator. This is two steps process, one is energy storage, and another is a power generator. Firstly, Ambient air is compressed in a high-pressure compressor and then sent to a cold energy regenerator, where compressed air is cooled to a low temperature for liquification. Then the liquid air is sent through a throttle valve to reduce pressure, and different phases of the liquid-vapor mixture are separated, and the liquid air is stored in the cryogenic tank. Again, gaseous air is sent through a cold regenerator to precool high-pressure air. During the power generation process, liquid air is compressed to high-pressure liquid by a cryogenic pump, and then it sends to a cold energy regenerator. In the regenerator, heat is added to liquid water by cold storage medium to convert it to gaseous air. In the last step, high-pressure air expands in the turbine with reheating phase to ambient pressure. The generator is coupled to the turbine for the production of power. [8]

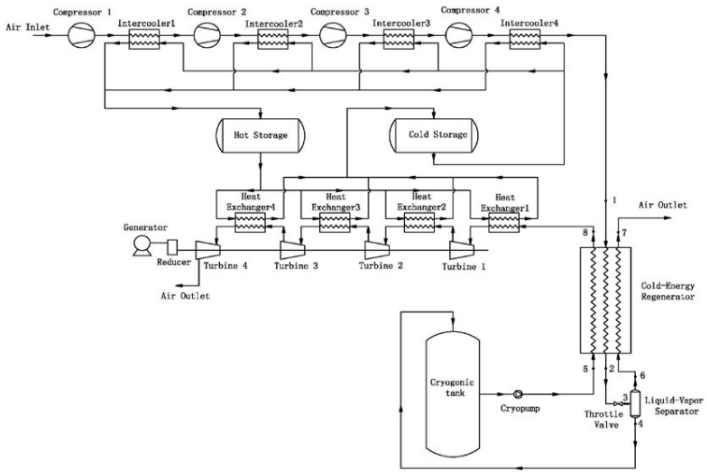

Figure3. Diagram of LAES cycles with intercooling of compressor and multistage turbine [8]

- # LAES system (Carbon-di-oxide as energy storage fluid)

In the modern LAES cycle, supercritical carbon dioxide (sCO_2) is used as an energy storage medium due to its high-density characteristics near the critical point compared with air, moderate critical temperature (30.98 ℃), and Pressure (7.38 MP). This makes the system size more compact. [9] sCO_2 recuperative Brayton cycle is used with intercooling and reheating cycles to increase power output. sCO_2 has shown a different specific heat value in the recuperator's high-pressure and low-pressure sides. This is one of the causes of low efficiency in recuperators. A split and recompression cycle is developed to eliminate the low-efficiency problem. The recompression cycle is found to be most accepted among the research community. Moreover, a high density of carbon dioxide near-critical regions helps to decrease the size of turbomachinery and to reduce the installation and operational cost, to reduce frictional loss. Printed circuit heat exchangers (PCHE) have been used as mainstream recuperator because it has higher effectiveness and higher stability against high temperature and pressure. From different studies, it is found for sCO_2 energy storage that, constant pressure storage is more suitable compared to constant volume storage. The RTE may reach up to 73.02%, and the energy density of the system may reach 57.02 kWh/m^{3,} respectively. [6] Most of the exergy destruction happens in the recuperator, almost 36.51% of the total system exergy destruction, next to the heater (32.33%) and then the turbine, low-pressure reservoir, etc. [10] [11] Figure 4, Figure 6 and Figure 7 explain different part of simple LAES cycle and Figure 8 explains T-S diagram of LAES diagram. There is some hybrid configuration of the LAES cycle on which research is going. In a Hybrid cycle, where external fluids interact with the cycle. This interaction could result from heating or cooling or heat energy provided as input after combustion, or heat and electricity can be extracted as output simultaneously. The difference between simple and Hybrid cycles can be shown in figure 6.

A. Different thermodynamic components of Liquid Air Energy Storage (LAES) system

Different thermodynamic components are showcased in figure 4 for a simple sCO_2 LAES cycle and figure 5 for the LAES cycle with a split cycle.

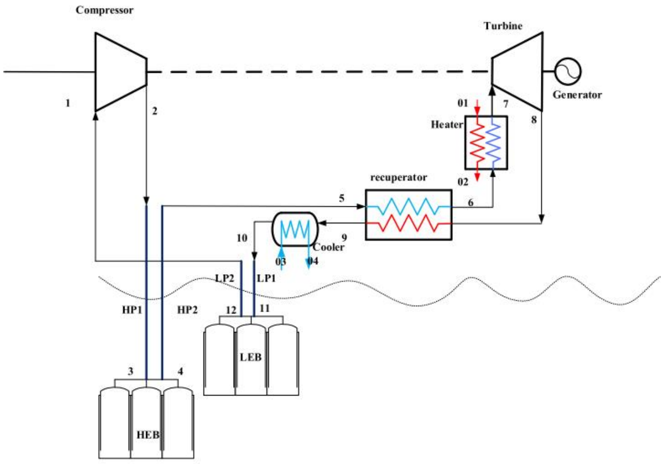

Figure 4. Diagram of simple LAES cycles [6]

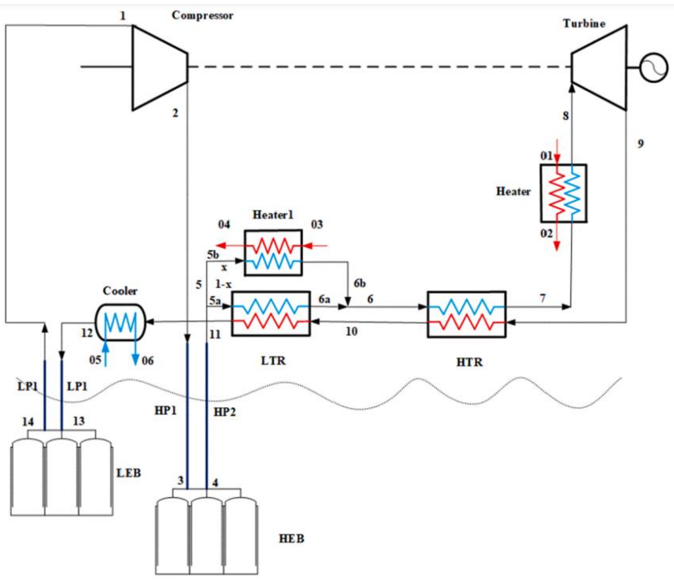

Figure 5. Diagram of split LAES cycles [6]

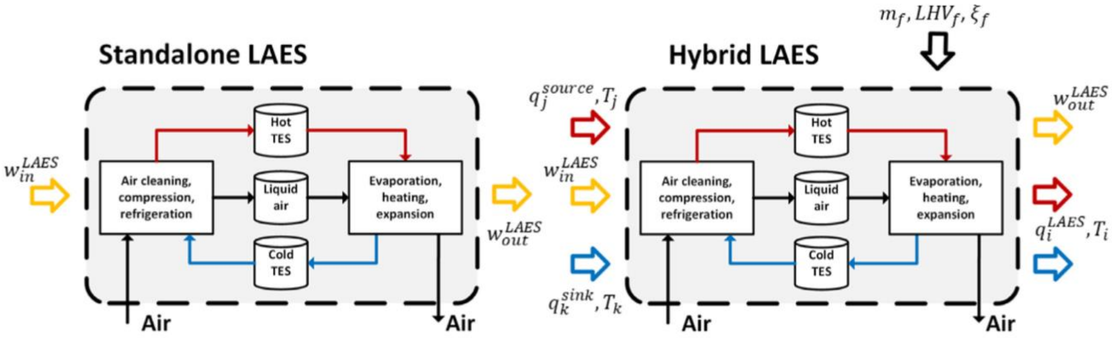

Figure 6. Details of process in Simple LAES and Hybrid cycles [6]

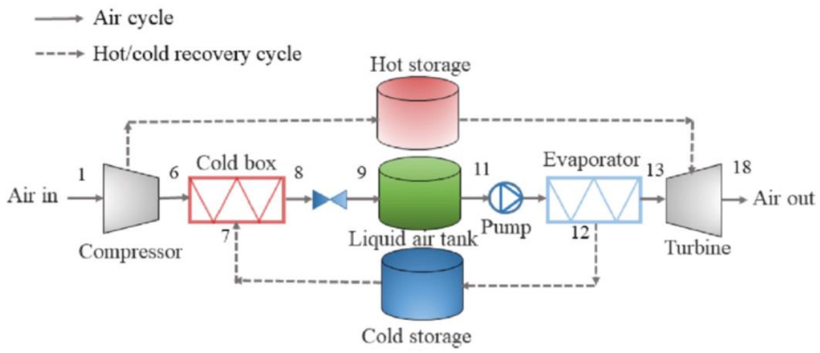

Figure 7. Process flow Diagram of simple LAES cycles [13]

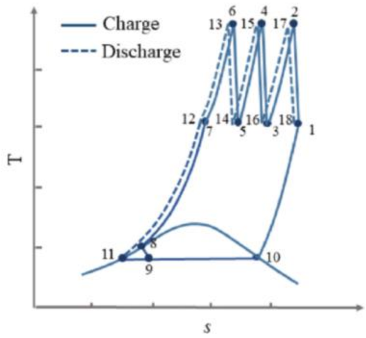

Figure 8. Diagram of simple LAES cycles [13]

i. **Compressor:** In this configuration above, the compressor is operating in a stable condition.

The isentropic efficiency of the compressor is defined as

$$\eta_{Com} = \frac{h_{s,Com\,out-}\,h_{Com\,in}}{h_{Com\,ut-}\,h_{Com\,in}} \tag{1}$$

Exergy destruction in Turbine:

$$ED_{com} = E_{ComIn} - E_{ComOut} + W_{Com} \tag{2}$$

The compressor power consumption is expressed as

$$W_{Com} = m_{air.}(h_{Comout} - h_{ComIn}) \tag{3}$$

ii. **Heat exchanger:** The heat exchanger system consists of a heater, recuperator, and a cooler.

Effectiveness of the Recuperator is defined by

$$\varepsilon_{Rec} = \frac{m_{cool}(h_{CoolOut-}\,h_{CoolIn})}{Q_{max}} = \frac{m_{hot}(h_{HotIn-}\,h_{HotOut})}{Q_{max}} \tag{4}$$

Exergy destruction in Recuperator:

$$ED_{Tur} = m_{hot}(E_{HotIn} - E_{HotOut}) + m_{cool}(E_{CoolOut} - E_{CoolIn})$$

5)

iii. **Turbine**: The isentropic efficiency of Turbine is defined as

$$\eta_T = \frac{h_{TurIn-} h_{TurOut}}{h_{TurIn-} h_{s,TurOut}}$$

6)

Exergy destruction in Turbine:

$$ED_{Tur} = E_{TurIn} - E_{TurOut} - W_{Tur}$$

7)

The turbine power production is expressed as

$$W_{Tur} = m_{Co2.}(h_{TurIn} - h_{TurOut})$$

8)

iv. **Energy Bag:** Carbon di Oxide is compressed and stored in a series of fabric-made energy bags. Due to the weight difference between air and CO2, there is a difference in buoyancy force in the energy bag. The max pressure till failure in the energy bag is 86 Mpa.[6]

v. **Pipe:** There is a different pipeline for different fluids, which contributes mainly to frictional loss. For the charging process, HP1 and HP2 pipelines are there; for the Discharge process, LP1 and LP2 pipelines are there. The pressure loss and frictional losses in the pipeline are very significant. This loss occurs due to friction, viscosity, geometry, and direction change in the pipeline.

- Scope of new solution area to counter energy losses

After analysis of a simple sCO2 energy storage system, some different areas are identified for energy and exergy losses in the system. Those losses occurred in the recuperator, the heater, the turbine, low-pressure reservoirs, and pipelines. Out of the component mentioned above, 36.51% of total system exergy destruction occurs in the recuperator and 32.33% in the heater. The main reason for this exergy loss or entropy increase is the large finite temperature difference between the hot and cold fluid. Studies are further extrapolated to optimize exergy destruction in the main two components. In this report, we discussed one of the methods to optimize the losses in the recuperator.

Comparison b/w Simple Cycle and more efficient Split Cycle

Some recent studies are going on to find out an optimized model to reduce the exergy losses in the recuperator. Researchers are trying to discrete the process in the recuperator into two or three steps such as a split cycle. Compared with the schematic diagram of Figure 4 and Figure 5, a simple one-step cycle in the recuperator is separated into a two-step cycle in the modified split cycle.

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In the split cycle (Figure 5), to improve the effectiveness of the heat exchanger, after the high-temperature recuperator (HTR), a low-temperature recuperator (LTR)is added. This arrangement decreases the energy loss in the mixing process. The main reason for exergy destruction is due to drastic changes in the specific heat value of CO2 near critical point temperature. Operating temperature and pressure also greatly impact the effectiveness of heat exchangers. [6]

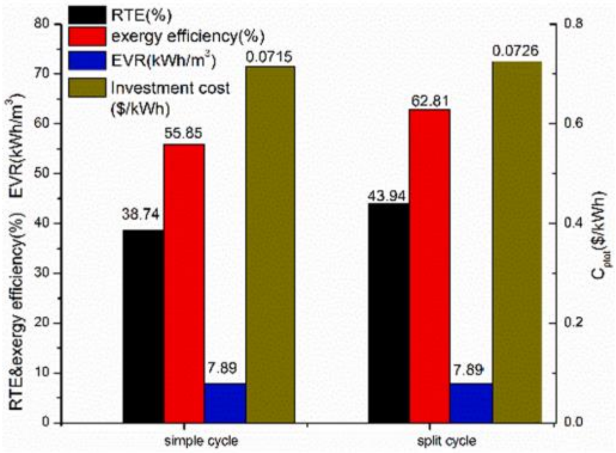

Figure 9. Comparison of simple cycle and split cycle [6]

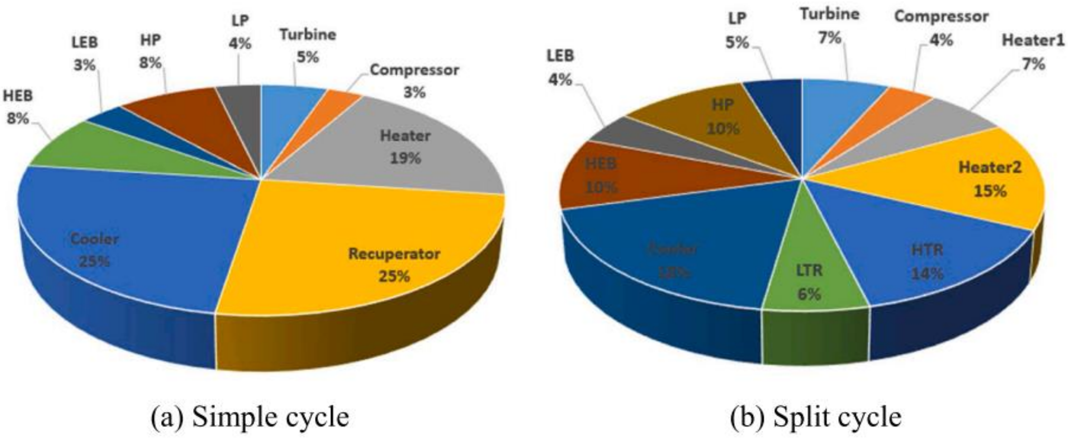

Figure 10. Exergy destruction comparison between simple cycle and split cycle [6]

Figures 9 and 10 show how the split cycle decreases the exergy destruction in the recuperator compared with the split cycle. In Figure 9, It is also shown that for the same energy density (7.89 kWh/m3) due to no change in output work and density of gas in storage, the RTE for the split cycle is higher than the simple cycle. The Round-trip efficiency of the simple and split cycles are almost 38.74% and 43.94%, respectively. When comparing the exergy efficiency, the split-cycle (62.81%) has the higher one than the simple cycle (55.85%). In the Split cycle, recovered heat is 53.19% of the total utilized heat, higher than in the simple cycle. But with the above advantage, this system has an initial capital cost for an additional low-temperature heat exchanger. [6]

- Conclusion

In the above discussion, we go through the effectiveness and utilization of the CAES system with renewable energy sources to make a flexible power grid for the future. A different aspect of the CAES cycle with liquid air energy storage and how sCO2 can be utilized to increase the energy density and reduce the storage size. Some of the points of enhancement of the system are also discussed, and one of the methods of enhancement, such as the split cycle concept, is also introduced from the paper of Mengjuan et. el. [6]

Different future methods of optimization and utilization of LAES for future work

There are other different methods of optimization on the CAES cycle. For method optimization in high-temperature compressor losses, some researcher is designing a piston cylinder compression system with some water spray arrangement to reduce the temperature during compression. Some researchers also focus on producing heat-absorbing and heat-releasing structures for the piston cylinder, which eventually reduces the temperature during compression. Research also focuses on storing solar heat in hot fluid storage and using that heat during power production.

A hybrid LAES cycle is another utilization prospect where power will be generated along with other utility applications. The Liquid energy storage LAES system can be utilized in the future hybrid vehicle where LAES stores excess energy from combustion and utilize it on a small scale for turbo power generation. Other than power generation, another utilization of this low-temperature energy storage is in utility service. sCO2 can be used as a cooling medium for large-scale data center server storage and large-scale battery storage. Based on the current trend and future possibilities, Liquid Air Energy Storage will be a good electrical energy storage solution for the future generation.

Nomenclature

com	Compressor	TES	thermal energy storage
Tur	Turbine		
h	Enthalpy		
E	Exergy		
W	Work		
m	Mass		
LAES	Liquid Air Energy Storage		
CAES	Compressed Air Energy Storage		

- # Reference

1. Jun Huang and Hui Liu 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **295** 012036**DOI** 10.1088/1755-1315/295/2/012036
2. Mandhapati Raju, Siddhartha Kumar Khaitan, Modeling and simulation of compressed air storage in caverns: A case study of the Huntorf plant, Applied Energy, Volume 89, Issue 1, 2012, Pages 474-481, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2011.08.019.
3. Alex Mey, Utility-scale batteries and pumped storage return about 80% of the electricity they store, Eia, Feb 12, 2021, https://www.eia.gov/todayinenergy/detail.php?id=46756#:~:text=Round%2Dtrip%20efficiency%20is%20the,lost%20in%20the%20storage%20process.
4. Edward R. Barbour, Daniel L. Pottie, Philip Eames, Why is adiabatic compressed air energy storage yet to become a viable energy storage option?, iScience, Volume 24, Issue 5, 2021, 102440, ISSN 2589-0042, https://doi.org/10.1016/j.isci.2021.102440.
5. Niklas Hartmann, O. Vöhringer, C. Kruck, L. Eltrop, Simulation and analysis of different adiabatic Compressed Air Energy Storage plant configurations, Applied Energy,Volume 93, 2012, Pages 541-548, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2011.12.007.
6. Mengjuan Xu, Xu Wang, Zihua Wang, Pan Zhao, Yiping Dai, Preliminary design and performance assessment of compressed supercritical carbon dioxide energy storage system, Applied Thermal Engineering, Volume 183, Part 1, 2021, 116153, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2020.116153
7. B. Ameel, C. T'Joen, K.D. Kerpel, P.D. Jaeger, H. Huisseune, M.V. Belleghem, M. D. Paepe, Thermodynamic analysis of energy storage with a liquid air Rankine cycle, Appl. Therm. Eng. 52 (2013) 130–140.
8. X.D. Xue, S.X. Wang, X.L. Zhang, C. Cui, L.B. Chen, Y. Zhou, J.J. Wang, Thermodynamic Analysis of a Novel Liquid Air Energy Storage System, Physics Procedia, Volume 67, 2015, Pages 733-738, ISSN 1875-3892, https://doi.org/10.1016/j.phpro.2015.06.124.
9. M.A.Z. T. A. Munroe, W. H. Flaspohler,R. J. Pelton, K. D. Wygant, O. B. Dubitsky, FLUENT CFD Steady State Predictions of a Single Stage CentrifugalCompressor with Supercritical CO2 Working Fluid, Proceedings of the S-CO2 Power Cycle Symposium 2009,RPI, Troy, NY, April 29-30, (2009)
10. Jun Huang, Hui Liu , Thermodynamic Analysis of a Novel Compressed Supercritical Carbon Dioxide Energy Storage System, Shenhua Guohua (Beijing) Electric Power Research Institute CO., LTD, Beijing, 100026, P.R.China

11. Mingkun Wang, Pan Zhao, Yi Wu, Yiping Dai, Performance analysis of a novel energy storage system based on liquid carbon dioxide, Applied Thermal Engineering, Volume 91, 2015, Pages 812-823, ISSN 1359-4311,https://doi.org/10.1016/j.applthermaleng.2015.08.081.
12. Andrea Vecchi, Yongliang Li, Yulong Ding, Pierluigi Mancarella, Adriano Sciacovelli, Liquid air energy storage (LAES): A review on technology state-of-the-art, integration pathways and future perspectives, Advances in Applied Energy, Volume 3,2021, 100047, ISSN 2666-7924, https://doi.org/10.1016/j.adapen.2021.100047
13. Liang, Ting & Vecchi, Andrea & Knobloch, Kai & Sciacovelli, Adriano & Engelbrecht, K. & Li, Yongliang & Ding, Yulong. (2022). Key components for Carnot Battery: Technology review, technical barriers and selection criteria. Renewable and Sustainable Energy Reviews. 163. 112478. 10.1016/j.rser.2022.112478.