Development in Energy Generation through CAES (Compressed Air Energy Storage) System

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Abstract: **This experimental study of CAES (Compressed Air Energy Storage) System dives into the usage, advantages, disadvantages and properties of energy generation using the CAES. The Compressed Air Energy Storage (CAES) System represents a promising avenue for advancing energy generation. This abstract explores recent developments in CAES technology, highlighting improvements in efficiency, scalability, and environmental impact. The integration of advanced materials and smart control systems has enhanced the overall performance of CAES, enabling better grid integration and increased renewable energy utilization. The abstract also discusses challenges and potential future directions in optimizing CAES as a reliable and sustainable energy storage system. Environmental considerations, particularly regarding air quality and noise pollution, have driven research into advanced compression and expansion techniques, as well as the exploration of alternative storage media. Additionally, life cycle assessments and techno-economic analyses have become integral to the development process, ensuring that CAES systems are not only efficient but also sustainable. This abstract also discusses the salt caverns replaced with metal air receiving tanks which meets almost all the properties of these salt caverns and decreases the initial cost of finding these salt caverns which are out of reach. Salt caverns are found far from the power stations and may induce additional economical characteristics for transmission of electricity to the CAES system.**

Keywords: **Compressed air Energy Storage, Salt Caverns, economical characteristics, alternative storage media, air receiving tanks.**

I. INTRODUCTION

Compressed Air Energy storage systems are used rarely due to the initial cost required to find the naturally formed underground salt dorms known as salt caverns. These salt caverns are formed due to the absorption of salt water into the ground at depths of about 150 – 160 meters (about 524.93 ft) with volumetric capacity up to 2000 cubic meters. Very few countries use the CAES system to store their excess energy generated in the form of compressed air to use it in the peak hours. And some domestic industries use this technology to run the factories in the time of demand. Whereas Liquid Air Energy Storage (LAES) systems require no such salt caverns or any naturally formed storage units to store the excess energy. Because the LAES system condenses the compressed air using some external agents and liquifies the air and stores the liquified air in different tanks of 1000 cubic meters each.

The study of CAES and LAES systems has concluded something common in the compression of air i.e., both the systems use *multistage reciprocating compressors* in the initial stage of compressors which results in greater pressure and temperature. But the multistage reciprocating compressors require two stages of cooling which are represented in figure 1. From the figure we can understand the working of a CAES system and make it functional. The figure given below is the conventional type of CAES system which would generate up to 110 MW power.

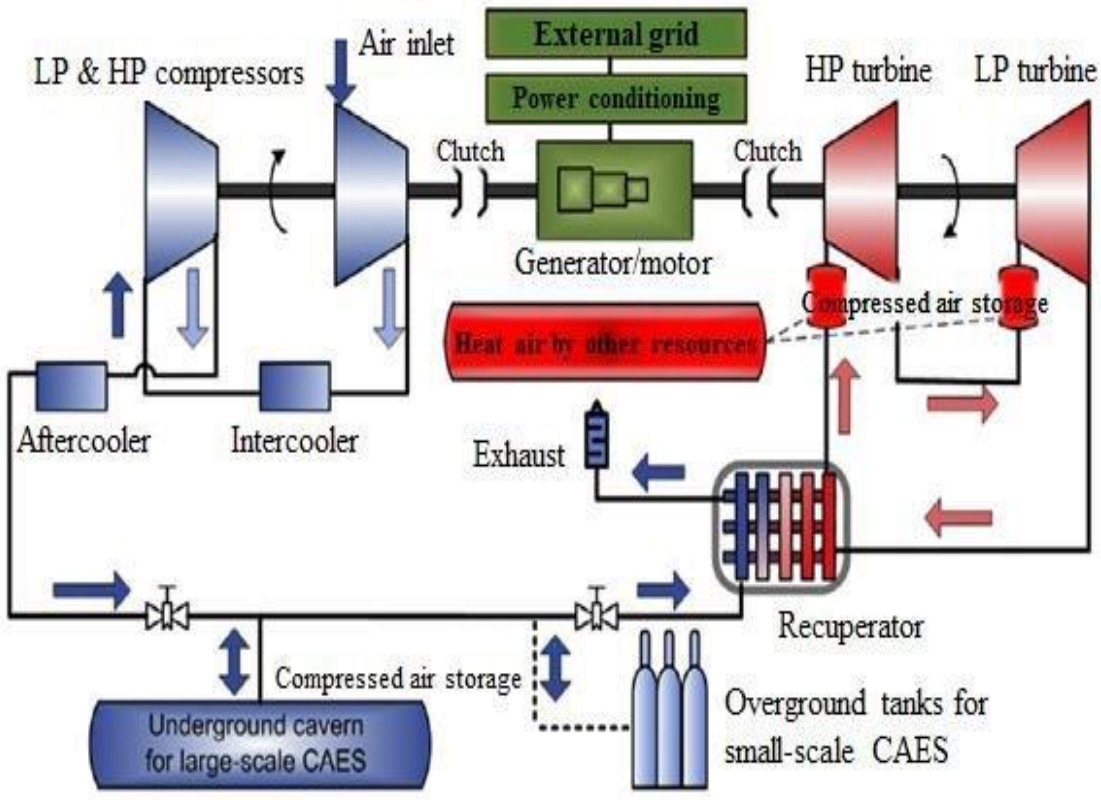
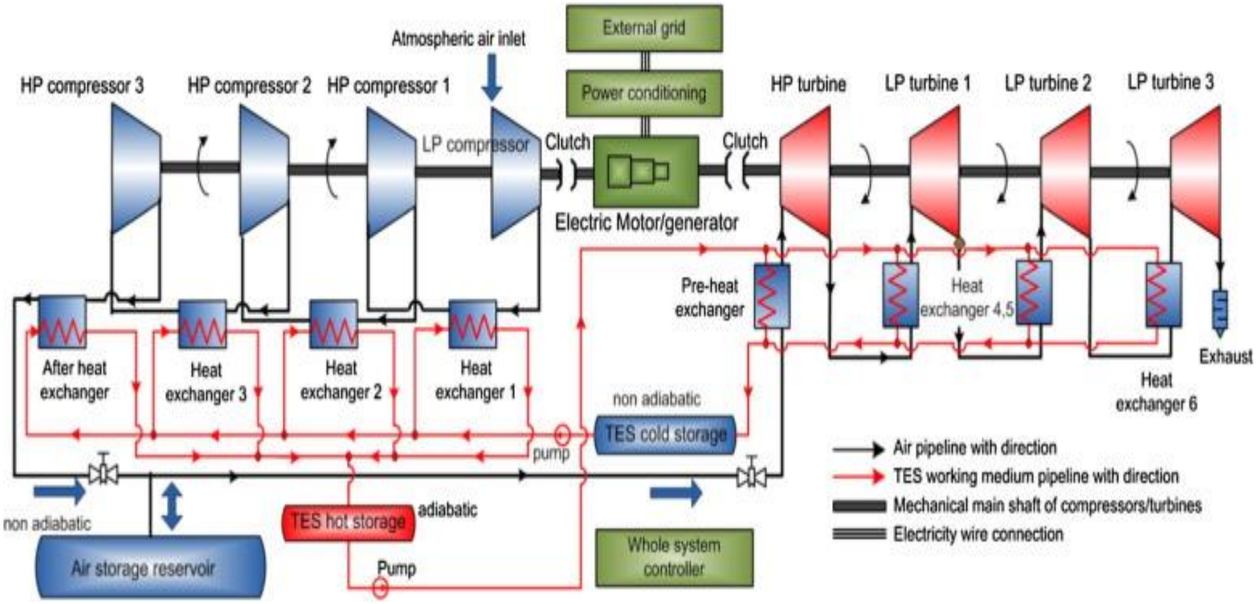


Fig.1 schematic diagram of conventional compressed air energy storage system

The working process of a traditional large-scale CAES plant is described as follows. During the compression mode the surplus electricity is used to run a chain of compressors to inject the air into a storage reservoir, normally an underground cavern for large-scale CAES. The compressed air is stored at a high pressure and at the temperature of the surrounding formation. Such a compression process can use coolers to reduce the working temperature of the injected air and thus to improve the compression efficiency. During the expansion mode, the stored high pressure compressed air is released, heated, and then expanded through a group of turbines which includes gas turbines(s) and sometimes steam turbine(s). The combustion process in the gas turbine with mixed compressed air and fuel (typically natural gas) occurs in the combustion chamber of turbine(s). The turbines are connected to an electrical generator to generate electricity. The waste heat of the overall system exhaust can be recycled before it is released into the atmosphere. The main feature of conventional large-scale CAES plants is that they involve combusting fossil fuels via gas turbines, resulting in CO_2 emissions.

With the development of technology, several improvements and advanced concepts to large-scale CAES have been proposed. Among these concepts, the most promising CAES scheme is Advanced Adiabatic CAES (AA-CAES). When the AA-CAES system is operated at the expansion mode, by integrating a Thermal Energy Storage (TES) system, the energy stored in the compressed air is converted into the electrical power output without a combustion process involved (Fig 2). Thus, the significant benefit of AA-CAES systems is zero carbon emissions, assuming that the electricity for the compression mode is also from zero carbon energy sources. The processes of cooling airflow through compressors and the heating of input airflow to each turbine are completed by using the heat exchangers. Theoretically, the overall roundtrip efficiency of AA-CAES is higher than that of the conventional CAES technology because AA-CAES system reuses the heat generated from the compression

Fig. 2 Schematic layout of AA-CAES plant



In addition, Liquid Air Energy Storage (LAES) can be considered as a variant of CAES because many components in a LAES system are also required by CAES and they have some similar sub-processes. The working process of LAES is : an electrical machine is used to drive an air liquefier and the resultant liquid air is stored in an insulated tank at atmospheric pressure; when electrical energy is required, the liquid air is released and pumped to high pressure in its liquid state, then vaporized and heated to the ambient temperature; finally, the resultant high pressure gaseous air is used to drive a combination of a turbine and an alternator to generator electricity.

Many studies have been made on the CAES system for the conservation of energy and utilization of the extra energy or power produced by the power stations at peak times like summer or the blackouts in a highly populated area. However, many companies or the countries haven't been able to succeed in the following process of conserving energy and reusing it. Some of the countries are researching CAES and facing some technical difficulties. The world's first utility-scale CAES plant was installed and commissioned by Brown Boveri at Huntorf, Germany, in 1978. It was designed to provide a load following service and meet the peak demand whilst maintaining a constant capacity factor in the nuclear power industry. After its operation, its functionality has been updated to buffering against the intermittence of wind energy production in Northern Germany. The Huntorf CAES plant employs two salt dome caverns to store compressed air, which operates at a high pressure between 4.8 MPa and 6.6 MPa. Under working conditions, the plant runs in a daily cycle with 8 hours of compressed charging and 2 hours of expansion operation at a rated power of 290 MW. It has been reported that the plant has operated in good condition and has consistently shown excellent performance with 90% availability and 99% starting reliability. The round-trip efficiency of this plant is about 42%.

The Hybrid Compressed Air Battery (CAB) system is developed by a UK based company called Energetix Group, with a small-scale power rating range between 2 KW and a few KW. Such products are currently at the early stage to be recognized by the market and consumers. The key factor for the success of the hybrid CAB is the adaptation of the newly developed scroll expander technology which has led to high expansion efficiency. As the system uses pre-prepared compressed air, it only focused on the expansion process without considering the compression process. Launched in August 2012, the Cooperative Banks Pyramid building became the first major data center in the world to use Energetix Group compressed air electricity generating system.

RWE Power, General Electric, Zublin and DLR are now working on the world's first large-scale AA-CAES demonstration project, named ADELE, in

Germany. Some challenging technical difficulties must be overcome in implementing this large-scale AA-CAES system. For instance, the AA-CAES requires the design of a high-pressure and high-temperature compressor with considerations of thermal stresses and thermal limitations for bearings and lubrication. The ADELE plant can store electrical energy completely without CO_2 emissions. The plant is planned to have a storage capacity of 360 MWh and a power output of 90 MW, with the aim of 70% cycle efficiency.

As there were quite a few projects which have been successfully operational, also there were a few projects which have been terminated based on the environmental conditions of the sites. The Iowa Stored Energy Park project was planned by the Iowa Association of Municipal Utilities. The project's intention was to build a 270 MW CAES plant coupled with 75 MW to 100 MW of wind capacity and was planned to be operational by 2015. However, the project

had to be terminated in 2011. After years of study, the investors concluded that the porous sandstone aquifers in Iowa are not suitable for CAES; the air stored in such aquifers cannot provide air flow fast enough to satisfy the requirements to form an effective CAES site.

In 2007, Luminant and Shell-Wind Energy proposed wind farm projects in Texas. The demonstration plant is planned to be used to study the potential to generate base load power using wind power combined with CAES. After a long wait, in 2013, the project began, aiming to host 317 MW of CAES underground. The US based LightSail Energy Ltd is now developing an AA-CAES facility by using a reversible electric motor/generator unit and a reversible reciprocating piston machine. The heat from compression is captured by the water spray and then stored; during expansion, the stored heat is sprayed into the compressed air. The company claimed that high thermodynamic efficiencies without sacrificing performance can be achieved based on the initial tests. When it comes down to LAES there is a UK based Highview Power Storage designed and assembled the UK's first pilot LAES facility (300 kW, 2.5 MWh) which has been operated at 80 MW biomass plant since 2010. Highview claim that this technology will be capable of supplying tens or even hundreds of MW. In February 2014, this firm was awarded £8 million in funds from the UK government for a new 5 MW/15 MW demonstration LAES project; the designed LAES system will be located alongside one landfill gas generation plant in the UK.

Technology	Energy density	Power density	Specific energy	Power rating	Rated capacity
Large CAES	2-6 Wh/L	0.5-2 W/L	30-60 Wh/kg	110 & 290 MW	580 & 2860 MWh
Small CAES	2-6 Wh/L	0.5-2 W/L	140Wh/kg at 300bar	0.003-3 MW	~0.002-0.01MWh
LAES	4 times then CAES	-	214 Wh/kg	0.3-2.5 MW	2.5 MWh
	Self-discharge	Lifetime	Cycling times	Discharge eff	Round-trip eff
Large CAES	small	20-40 years	8000-12000	~70-79%	42, 54, 70%
Small CAES	Very small	23+ years	Tested 30000	~75-90%	-
LAES	Small	20-40 years	-	-	55-80+%
	Storage duration	Discharge time	Power capital cost	Energy capital cost	O&M cost
Large CAES	Hours-months	1-24+ hours	~400-1000$/kW	2-120$/kWh	0.003$/kWh
Small CAES	Hours-months	Up to ~ 1hour	~500-1500$/kW	200-250$/kWh	Very low
LAES	-	1-12+ hours	~900-2000$/kW	260-530$/kWh	_

Table 1. Technical and Economic characteristics of CAES relevant technologies

II. MATERIALS AND METHODOLOGY

This study examines the improvement in the output of CAES system after being experimented as per the procedure stated by the previous researchers. As the experimental procedure stated the CAES system can give an output of 210 KW of power with a given number of working hours. Though the system is being developed by Advanced Adiabatic process around the world by many researchers. We wanted to develop an increased output rate by the actual CAES system. So, we have assembled a small CAES working model that can generate a minimum amount of power output. The conditions are as an input power of 2 KW to a multistage reciprocating compressor which works at a rate of 7.5 bar of pressurized air at the end of the process before being sent into storage. The storage of the compressed air has been replaced with air receiver tanks (of 15 m3 (about twice the volume of a storage unit) with a working temperature of 50-55ºC) instead of salt caverns which are highly difficult to find. After the power input given to the compressor, it draws the air through a staged filter and enters the Low-Pressure This common procedure of assembling and generating electricity using the CAES system is slightly changed, expecting some desired outcomes from the assembly made. The changes include the remove of the intercooler and the use of ADU's (Air Drying Units) before the passage of air to the turbine blades. These cylinder where the air is pressurized to 2-2.5 bar. The rise in temperature of the air is dealt with (decreased to 35-39ºC) water which is used as the coolant in the inter & after coolers in the compressor. The cooled air then passed into the High-Pressure cylinder where the air is pressurized to 7-7.5 bar with an out temperature of 150-160ºC. The outlet air is cooled by the after cooler to a temperature of 45-49ºC. The cooled air is then stored in the air receiver tanks. The stored air is re-heated by the preheater known as the Recuperator to eliminate the moisture in the air before being passed on to the turbine blades. This turbine is coupled to a generator to produce electricity.

ADU's are used to remove the moisture or water molecules in the air passing on to the turbine blades to avoid any damage to the blades. These ADU's are medium sized containers partially filled with silica gel which is also used in transformers to absorb the water molecules or moisture

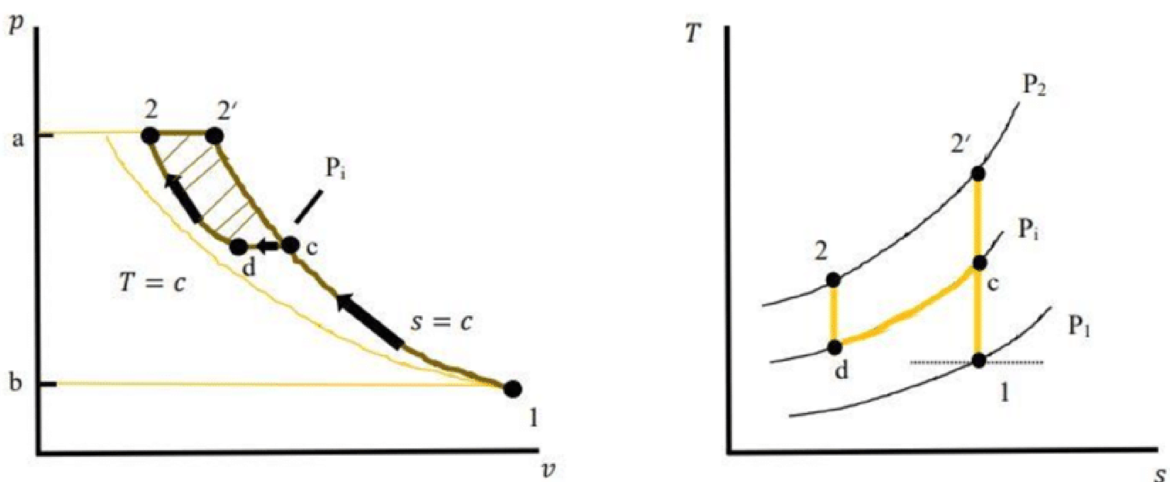


Fig 3. P-V and T-S diagrams for Two stage Compression with Intercooling.

Fig 3 represents the variations between Pressure-Volume & Temperature-Entropy in a two-stage compressor with intercooling present in the system that has been assembled. Fig 3 also represents the total pressure increase and volume decrease in the system during the process being performed. It also represents the temperature difference to the entropy during the increase in pressure and decrease in temperature during the intercooling.

The Intercooling of the compressed air plays a crucial role in the temperature and entropy difference during the transfer of air into the air receiving tanks. So, the removal of the intercoolers might result in a substantial way of getting a higher value in the temperature difference and change in entropy, which leads to better performance of air on the turbine blades and concludes a greater result than the anticipated.

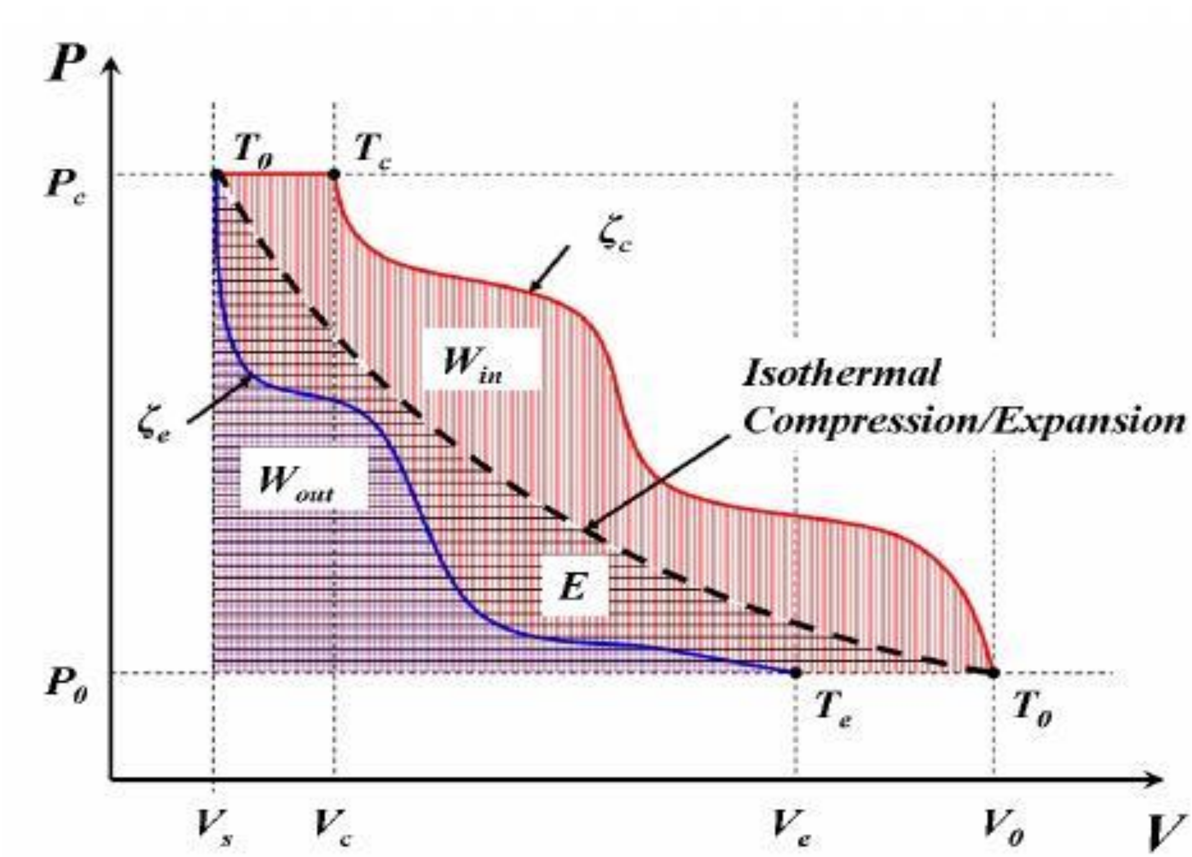


Fig 4. The work done by a multi-stage compressor with and without intercooling

Fig 4 shows the work done by the multi-stage compressor in various stages of compression with and without the intercooling in the system. The shaded region in the fig represents the work saved due to intercooling. Whereas the Adiabatic curve represents the amount of work done when there was no intercooling provided.

III. RESULTS AND DISCUSSION

Considering the fact of assembling a CAES system the results were expected as the assembly first made was the exact model of an actual CAES system. When the process was redirected to make changes in the system to obtain some better outcomes, the Adiabatic curve was introduced in the system and made a few changes in the system accordingly. During the changes, the intercooler has been removed to increase the thermal efficiency of the air passed into the receiving tank. Removing the intercooler has given a subsequent amount of temperature to the air which makes the work of the recuperator less. As there was a rise in the temperature, the tanks could not withhold the air being sent into them. So, we had to replace the tanks with the ones that have a higher working temperature. The replaced tanks have a working temperature of 120ºC and a capacity of holding 8-9 bars. It has a discharge capacity of 9 kgs/h. The discharged air from the tanks flows on to the turbine blades with a pressure of 10-12 kgs/h and a temperature of 70-75ºC.

Additionally, the Advanced Adiabatic Compression Air Storage (AA-CAES) has also been experimented with to compare the results with the on-going process. In AA-CAES, the refrigerant used in the intercoolers is again used as the re-heating agent in the process of increasing the temperature before passing the air on to the turbine blades. Fig 5 represents the flow of the cold oil used as the refrigerant in the intercoolers. Later on, the cold oil with rise in temperature due to the heat transfer between the air and the oil is used as the hot oil to increase the temperature of the air before the power generation.

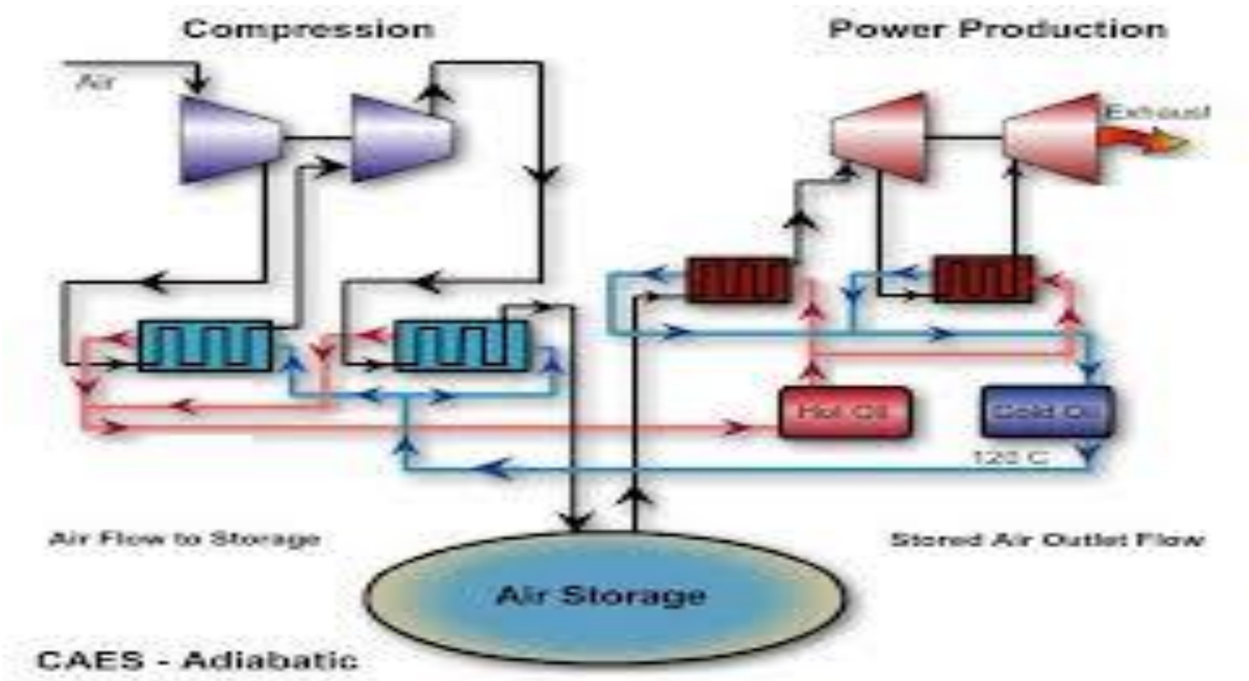


Fig 5. Schematic layout of an AA-CAES plant

The Advanced Adiabatic Compression Air Storage (AA-CAES) has shown a significant possibility in reusing the coolant oil to reheat the air, but the results and the outcome were different compared to the process of removing the intercooler. Whereas the AA-CAES is a suggested idea worldwide, it is not economical for a domestic or small-scale industry.

IV. CONCLUSION

The stated process of removing the intercooler in the process might have given the anticipated values and results but has shown a slight change in the outcome of the process compared to the AA-CAES. The outcome of the system is an addition of 0.15 KW to the input power given to the compressor. Whereas the outcome of the Advanced Adiabatic Compression Air Storage (AA-CAES) is 0.05 KW in addition to the input power. Comparatively, the process undertaken is justified and better than AA-CAES. The outcome of the process is 3.12% of the given input, which gives a better anticipation to conclude the process as a success. Although the numbers aren't great compared to the given input, these might eventually be increased with some modifications and better equipment for the development in the energy generation by the CAES technology.

REFERENCE

[1].Xiaolin Wang, Hamidreza Mozayeni, Michael Negnevitsky, Shujian Ma, Recent Development of Compressed Air Energy Storage Technologies – A Review (2014):https://doi.org/10.1016/B978-0-323-93940-9.00175-4

[2]. Guojie Zhang, Yifan Yang, Jiaheng Chen, Zunlong Jin, Mirosław Majkut, Krystian Smołka, Sławomir Dykas, Effect of relative humidity on the nozzle performance in non-equilibrium condensing flows for improving the compressed air energy storage technology (2023): https://doi.org/10.1016/j.energy.2023.128240

[3]. Ehsanolah Assareh, Ashkan Ghafouri, an innovative compressed air energy storage (CAES) using hydrogen energy integrated with geothermal and solar energy technologies: A comprehensive techno-economic analysis - different climate areas-using artificial intelligent (AI) (2023): https://doi.org/10.1016/j.ijhydene.2022.11.233

[4]. Bernardo Llamas, Marcelo F. Ortega, Gabriel Barthelemy, Ignacio de Godos, F. Gabriel Acién, Development of an efficient and sustainable energy storage system by hybridization of compressed air and biogas technologies (BIO-CAES) (2020): https://doi.org/10.1016/j.enconman.2020.112695

[5]. Edward Barbour, Daniel L. Pottie, Adiabatic compressed air energy storage technology (2021): https://doi.org/10.1016/j.joule.2021.07.009
[6]. Shengchun Liu, Sicheng Wu, Yukun Hu, Hailong Li, Comparative analysis of air and CO_2 as working fluids for compressed and liquefied gas energy storage technologies (2019): https://doi.org/10.1016/j.enconman.2018.12.031
[7]. Zuogang Guo, Guangyi Deng, Yongchun Fan, Guangming Chen, Performance optimization of adiabatic compressed air energy storage with ejector technology (2016): https://doi.org/10.1016/j.applthermaleng.2015.10.047
[8]. Iñigo Ortega-Fernández, Simone A. Zavattoni, Javier Rodríguez-Aseguinolaza, Bruno D'Aguanno, Maurizio C. Barbato, Analysis of an integrated packed bed thermal energy storage system for heat recovery in compressed air energy storage technology (2017): https://doi.org/10.1016/j.apenergy.2017.07.039
[9]. Xinjing Zhang, Ziyu Gao, Bingqian Zhou, Huan Guo, Yujie Xu, Yulong Ding, Haisheng Chen, Advanced Compressed Air Energy Storage Systems: Fundamentals and Applications (2024): https://doi.org/10.1016/j.eng.2023.12.008
[9]. Junnan Niu, Cancan Zhang, Ying Li, Yuting Wu, Hexin Sun, Design and investigation of cold storage material for large-scale application in supercritical compressed air energy storage system (2024): https://doi.org/10.1016/j.est.2023.109680
[10]. Zhan Liu, Jialu Ding, Xinyu Huang, Zhengguang Liu, Xuewen Yan, Xianglei Liu, Xiaohu Yang, Analysis of a hybrid heat and underwater compressed air energy storage system used at coastal areas (2024): https://doi.org/10.1016/j.apenergy.2023.122142
[11]. Xing Luo, Jihong Wang, Mark Dooner, Jonathan Clarke, Christopher Krupke, Overview of Current Development in Compressed Air Energy Storage Technology (2014): https://doi.org/10.1016/j.egypro.2014.12.423
[12]. Biao Yang, Deyou Li, Xiaolong Fu, Hongjie Wang, Ruzhi Gong, Energy and exergy analysis of a novel pumped hydro compressed air energy storage system (2024): https://doi.org/10.1016/j.energy.2024.130737
[13]. Fa Wan, Zhongming Jiang, Xiang Tian, Heinz Konietzky, Zhezhen Xiao, A thermo-hydro-mechanical damage model for lined rock cavern for compressed air energy storage (2024): https://doi.org/10.1016/j.est.2023.110186
[14]. Yaran Liang, Peng Li, Wen Su, Wei Li, Wei Xu, Development of green data center by configuring photovoltaic power generation and compressed air energy storage systems (2024): https://doi.org/10.1016/j.energy.2024.130516
[15]. Yao Zhang, Jiaxin Liu, Suzhen Yin, Chuanqi Su, Zhan Liu, Design and performance analysis of a novel compressed air–liquid CO2 energy storage (2024): https://doi.org/10.1016/j.enconman.2024.118068
[16]. Jingjian Huang, Yujie Xu, Huan Guo, Xuezhi Zhou, Xinjing Zhang, Yilin Zhu, Haisheng Chen, Accurate self-scheduling model of adiabatic compressed air energy storage (2024): https://doi.org/10.1016/j.est.2024.110747
[17]. Murat Emre Demir, Ibrahim Dincer, Performance assessment of compressed air energy storage systems with and without phase change materials (2023): https://doi.org/10.1016/j.ijft.2023.100489
[18]. Mahdieh Adib, Fuzhan Nasiri, Fariborz Haghighat, Karthik Panchabikesan, Gayathri Venkataramani, Saligram Tiwari, Velraj Ramalingam, Integrating compressed air energy storage with wind energy system – A review (2023): https://doi.org/10.1016/j.prime.2023.100194
[19]. Young Min Kim, Seonyeob Kim, Jiseon Choi, Adiabatic compressed air energy storage system combined with solid-oxide electrolysis cells (2024): https://doi.org/10.1016/j.egyr.2023.12.070
[20]. Yonghong Xu, Hongguang Zhang, Fubin Yang, Liang Tong, Dong Yan, Yifan Yang, Yan Wang, Yuting Wu, Performance of compressed air energy storage system under parallel operation mode of pneumatic motor (2023): https://doi.org/10.1016/j.renene.2022.09.133
[21]. Ziyu Gao, Xinjing Zhang, Xiaoyu Li, Yujie Xu, Haisheng Chen, Thermodynamic analysis of isothermal compressed air energy storage system with droplets injection (2023): https://doi.org/10.1016/j.energy.2023.129304
[22]. Hang Li, Hongling Ma, Kai Zhao, Shijie Zhu, Kun Yang, Zhen Zeng, Zhuyan Zheng, Chunhe Yang, Parameter design of the compressed air energy storage salt cavern in highly impure rock salt formations (2024): https://doi.org/10.1016/j.energy.2023.129520
[23]. Mojtaba Jabbari Ghadi, Dillip Kumar Mishra, Ali Azizivahed, Li Li, Jiangfeng Zhang, Mobile compressed air energy storage for active distribution

systems (2023): https://doi.org/10.1016/j.ijepes.2023.109434

[24]. Aibo Zhang, Zhaoyuan Yin, Zhiying Wu, Min Xie, Yiliu Liu e, Haoshui Yu, Investigation of the compressed air energy storage (CAES) system utilizing systems-theoretic process analysis (STPA) towards safe and sustainable energy supply (2023): https://doi.org/10.1016/j.renene.2023.02.098

[25]. M. Raggio, M.L. Ferrari, Compressed air energy storage with T100 microturbines: Dynamic analysis and operational constraints (2023): https://doi.org/10.1016/j.est.2023.109093

[26]. Catarina R. Matos, Patrícia P. Silva, Júlio F. Carneiro, Overview of compressed air energy storage projects and regulatory framework for energy storage (2022): https://doi.org/10.1016/j.est.2022.105862

[27]. Mahdi Zarnoush, Pezhman Pourmadadi Golaki, M. Soltani, Eliyad Yamini, Farbod Esmaeilion, Jatin Nathwani, Comparative evaluation of advanced adiabatic compressed gas energy storage systems (2023): https://doi.org/10.1016/j.est.2023.108831

[28]. Jeffrey A. Bennett, Jeffrey P. Fitts, Andres F. Clarens, Compressed air energy storage capacity of offshore saline aquifers using isothermal cycling (2022): https://doi.org/10.1016/j.apenergy.2022.119830

[29]. Hua Chen, Wen-long Cheng, Yong-le Nian, Liquid-gas heat transfer characteristics of near isothermal compressed air energy storage based on Spray Injection (2023): https://doi.org/10.1016/j.ijheatmasstransfer.2023.124530

[30]. Julian David Hunt, Behnam Zakeri, Andreas Nascimento, Jonas Rafael Gazoli, Fabio Tales Bindemann, Yoshihide Wada, Bas van Ruijven, Keywan Riahi, Compressed air seesaw energy storage: A solution for long-term electricity storage (2023): https://doi.org/10.1016/j.est.2023.106638