A REVIEW ON COMPRESSED AIR ENERGY STORAGE – A PATHWAY FOR SMART GRID AND POLYGENERATION

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<u>ABSTRACT</u>

The increase in energy demand and reduction in resources for conventional energy production along with various environmental impacts, promote the use of renewable energy for electricity generation and other energy-need applications around the world. Wind power has emerged as the biggest renewable energy source in the world, whose potential, when employed properly serves to provide the best power output. In order to achieve self-sustenance in energy supply and to match the critical needs of impoverished and developing regions, wind power has proven to be the best solution. However, wind power is intermittent and unstable in nature and hence creates lot of grid integration and power fluctuation issues, which ultimately disturbs the stability of the grid. In such cases, energy storage technologies are highly essential and researchers turned their attention to find efficient ways of storing energy to achieve maximum utilization. The use of batteries to store wind energy is very expensive and not practical for wind applications. Compressed Air Energy Storage (CAES) is found to be a viable solution to store energy generated from wind and other renewable energy systems. A detailed review on various aspects of a CAES system has been made and presented in this paper which includes the thermodynamic analysis, modeling and simulation analysis, experimental investigation, various control strategies, some case studies and economic evaluation with the role of energy storage towards smart grid and poly-generation.

Key Words: Compressed air energy storage, Wind Energy, Renewable Energy System, Smart Grid, Polygeneration.

Contents

1. INTRODUCTION

The rapid increase of the demand to electrical energy in recent years along with the impact on the environmental deterioration has led to speed up the development of renewable power generation and better value of renewable energy resources in the global scenario. The increase in demand with threatening price for power causes concerns over the security and reliability of power supply. Energy storage technologies are gaining a great deal of attention in addressing the challenging issues because of their potential roles in achieving load leveling, especially for matching intermittent source of renewable energy with customer demand and also to store the excess power during the daily cycle. Energy storage is not a new idea in itself. It has been a fundamental constituent of electricity generation, transmission and distribution systems. The storage ensures a supply of energy to offset the intermittent and thus potentially inadequate nature of the energy available, ensures that energy is available at occasional times of peak demand, and ensures a supply of energy in the event of a failure in the electrical system or poor energy quality in the local grid.

Conventionally, energy storage needs have been met by the physical storage of fuel for fossil-fuelled power plants, by keeping some capacity in reserve and through large scale pumped hydro storage plants. Various energy storage technologies are available according to different physical principles, energy range and operation time. Though energy can be stored in different forms it is advantageous to store energy in thermal or other forms of energy, based on their final application requirement. Energy storage technologies may be broadly classified as i) Mechanical Energy (Pumped Hydro, Compressed Air Energy Storage) ii) Thermal Energy Storage (Latent heat &

Sensible Energy Storage iii) Magnetic Energy Storage (SMES) iv) Electro Chemical Energy Storage (Batteries, Fuel Cells). Recently, Indian Energy Storage Alliance (IESA) published a report after analyzing the market potential of 15 GW for all types of energy storage technologies in India, by 2020. Fig.1 depicts the anticipated market size for energy storage systems in India.

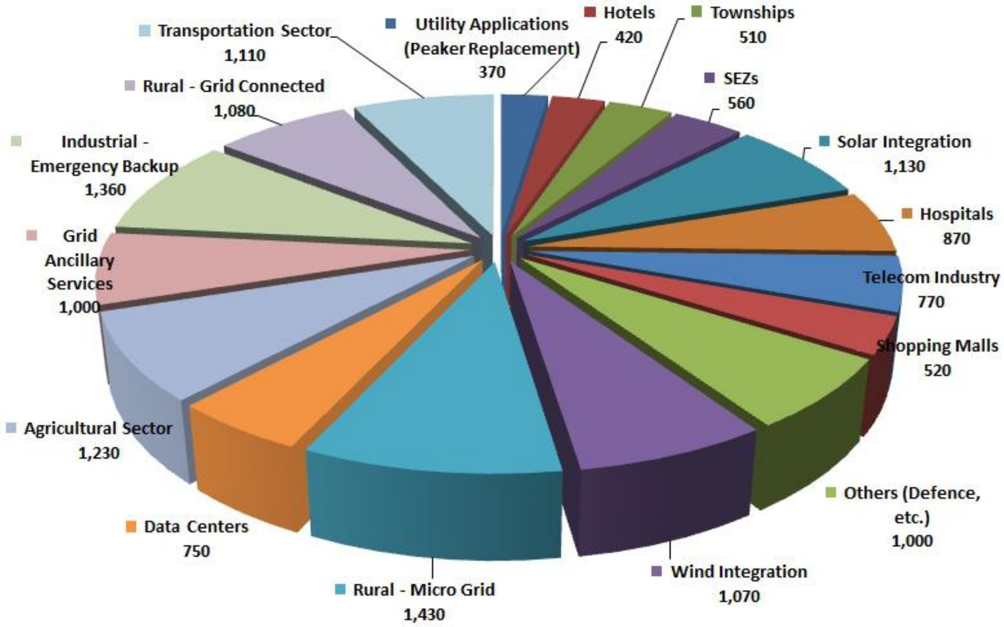

Fig.1. Anticipated Market Size in MW by 2020 for Energy storage systems in India [IESA report]

Among the various energy storage technologies, pumped hydro and compressed air energy storage alone can support large scale energy storage applications. Although pumped hydro is a well-known and widely used method of energy storage, its dependence on specific geographic features and environmental concerns make new innovations and developments quite difficult. A promising method for energy storage and an alternative to pumped hydro storage is compressed air energy storage, with high reliability, economic feasibility and its low environmental impact. Although large scale CAES plants are still in operation, this technology is not widely implemented due to large dissipation of heat of compression. However, due to the growth of wind and solar based power generation in recent years, scientists and researchers are making tremendous efforts to improve the overall turn around efficiency of the compressed air energy storage to provide a better solution for grid stability.

2. Overview of the Development of Compressed Air Energy Storage

Compressed air energy storage is one of the promising methods for the combination of Renewable Energy Source (RES) based plants with electricity supply, and has a large potential to compensate for the fluctuating nature of renewable energies. CAES plants can regenerate as much as 80% of the electricity production to support the development of RES based plants. In a CAES system the off peak power from the grid or the electricity generated from renewable sources when there is no demand is used, to compress the air and pump it into a sealed underground cavern or into a large sized storage tank at a high pressure. Whenever there is a power requirement this high pressure air from the underground reservoir or tank is retrieved and used to drive the turbine, and power is produced from the coupled generator as shown in Fig.2. Quite often the compressed air is mixed with natural gas and they are burnt together, in the same manner as that of the conventionally operated turbine plant. This method is actually efficient as the compressed air will lose less energy.

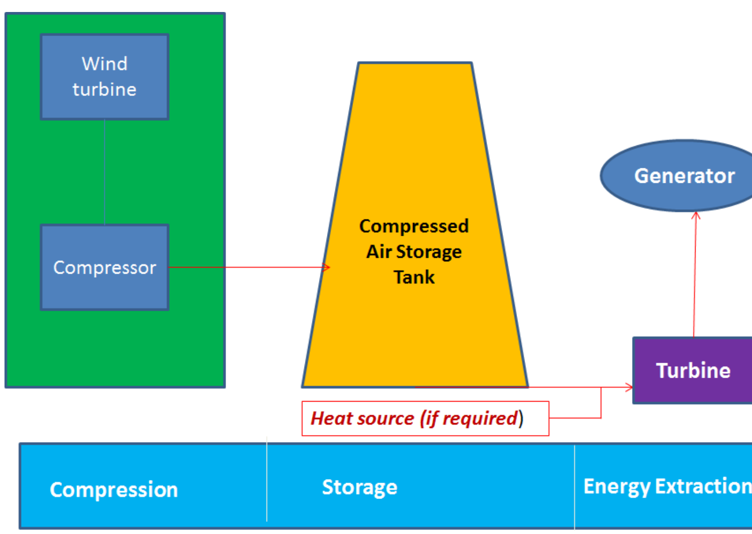

Fig.2. Process of CAES based Power Generation

The CAES system is classified into three types based on air storage and heat utilization. They are i) Adiabatic ii) Diabatic iii) Isothermal. In adiabatic process, the heat of the compressed air is not lost; it remains in the process for use in power generation. In diabatic storage the heat of compression is dissipated into atmosphere as waste. The renewable energy can be used to perform the work of compression and if the air temperature is low for the energy recovery process, the air must be considerably reheated before it is expanded in the turbine. This reheating can be accomplished with a natural gas fired burner for utility grade storage or with heated metal mass. Isothermal compression allows air to reach high pressures without the inherent challenges in temperature. Compressed air at near ambient temperature can be stored until required with minimal energy losses. When power is needed, isothermal expansion can deliver electrical energy with no requirement for natural gas combustion.

Recently, **Luo** et al. [1] presented an overview of current developments in CAES technology in which they discussed the commercialization of Compressed Air Batteries (CAB) by an U.K based company. They are of the opinion that it will soon be available in the market and are likely to be a successful commercialization because of the newly developed scroll expander. They have also predicted the CAB to be a clean energy technology after observing its performance in the U.K national grid. **Luo** et al. [2] made an overall analysis of various energy storage technologies and identified that pumped hydro storage had relatively low energy densities and hence was used in stationary large-scale energy storage systems. The factors to be considered in storage technology like energy density, reliability, toxic content with its overall economic evaluation were also carried out. **Hasan** et al. [3] made a review of large scale CAES wind energy systems and concluded that storage gave better performance in providing invariable dynamic wind power to grid even at low wind speed compared to Superconducting Magnetic Energy Storage (SMES) system, Flywheel Energy Storage (FES) system etc. **Gonzaleza** et al. [4] analyzed and reviewed various energy storage systems for wind power integration and concluded that the integration of CAES system with wind power farm resulted in the benefit of reduction in operation cost**.**

Sonal Patel [5] reported the importance of a CAES system for its geographical flexibility and its largest battery among the presently available battery models suitable for wind power generation; she also discussed the car that runs on compressed air, developed by the Luxembourg-based MDI Group. **Gardner et al.** [6] **and James** [7] presented an initial overview of the CAES system along with their major case studies, advantages and disadvantages of the system. **Allen** et al. [8] gave the guidelines for storage of compressed air in solution mined salt cavities and considered the major geo factors to be caprock instability, creep deformation, surface subsidence, cavern characteristics like lateral stresses, height to diameter ratio etc.

Katz & Lady [9] published a research book on "Compressed Air Storage for Electric Power Generation" in which they discussed the integration of Renewable Energy System (RES) with CAES as a viable solution for reliable large scale power generation. **Drost** et al. [10] coupled a steam power plant with a CAES system. The objective of coupling a steam plant with a CAES system was to operate the steam power plant continuously while the combined plant operated as an intermediate load or peaking load facility. **Mehta** [11] studied the geographical siting of CAES system and explained the possibility of CAES to facilitate the RES after considering the specific conditions of Ontario. **Finkenreth** et al. [12] discussed the status and major technical challenges of an advanced CAES system with stress on the research developed in turbo-machinery and thermal Energy Storage for a CAES system.

3. Performance Evaluation of CAES Systems

3.1 Thermodynamic Analysis:

Kushnir et al. [13] studied the thermodynamic characteristics of an underground CAES system by performing numerical modeling with the support of two major governing equations and validated it with analytical results for charging and discharging cycle of the system. Through their experimental results they observed that the cavern wall heat transfer played a vital role in enhancing the storage capacity, as the cavern heat transfer was mainly governed by rock effusivity and concluded that a thermally effusive site had to be chosen for the CAES system. **Audrius** et al. [14] conducted exergy and exergoeconomic analysis of a CAES system with and without Thermal Energy Storage (TES) and found an increase in energy efficiency to 86% and exergy efficiency to 55.8% for the CAES-TES system in comparison with CAES system alone, which reported energy efficiency of 48 % and exergy efficiency of 50.1%.

Niklas et al. [15] thermodynamically calculated the efficiencies for various CAES configurations for one full charging and discharging cycle. Their numerical investigations showed that the polytropic system had an efficiency of 60% and the adiabatic system had an efficiency of 70%. Their investigation on a realistic CAES plant demonstrated the efficiency of a two stage adiabatic CAES system, between 52% and 62%, depending upon the heating and cooling demands. They found that the efficiency was greatly dependent on high temperature thermal storage and heat resistant compressor material. **Fernando** et al. [16] developed a thermodynamic model for an advanced adiabatic CAES (AA- CAES) system comprising of compression/expansion trains, a TES system, and an underground cavern for compressed air storage, where they formulated a multi period optimization issue and solved it using model predictive control strategy. **Nejad** et al. [17] undertook thermodynamic analysis of a wind integrated CAES system and they highlighted the fact that the energy conversion process could be adiabatic or isothermal. The major parameters in their analysis were storage pressure, temperature and tank volume.

Vongmanee [18] discussed the various renewable energy applications integrated with a CAES system focusing mainly on the thermodynamic and simulation analyses; they proposed a new system as a kind of back-up power and to ensure reliability of power in a compressed air UPS system. **Giuseppe** et al. [19] made an exergy analysis of Adiabatic-CAES with some major designs for operating pressure changes of the storage tank. They depicted the compression process with various configurations and finally estimated the global exergy efficiency to be 67.5%. **Sylvain** [20] presented the idea of power-electronic interfacing along with the maximum efficiency point algorithm. They also discussed the characteristics of high-competence storage systems in which the pneumatic system was substituted with an oil-hydraulic and pneumatic converter, and it could be used under isothermal conditions. **Arsie** et al. [21] developed a thermodynamic model using MATLAB Simulink for multi stage compression system, inter cooler, after cooler, wind turbine and also for heat recovery unit and expander system. **Pickard** et al. [22] presented energy and exergy analysis of an AA-CAES and estimated the cycle efficiency; they concluded that such a system was technically feasible and had a cycle efficiency of 50% or better.

Wenyi et al. [23, 24] undertook second law thermodynamic analysis (exergy analysis) and combined cycle thermal performance analysis to present the effect of combustion chamber outlet temperature variation on system efficiency; they also stressed the importance of increase in flexibility because of the intercooler. **Najjar & Jubeh** [25] coined a new terminology called CASH, Compressed Air Storage with Humidification, in order to increase the generated power and primary energy efficiency. They concluded that the generated power was about 14% more in CASH than that of CAES without humidification.

3.2 **Performance Analysis via Modeling and Simulation Study**

Proczka et al. [26] provided new guidelines for optimum pressure for operating the Small Scale-CAES (SS-CAES) system, geometric considerations (i.e. shape, size) along with its number of vessels through their investigations. They also observed that the key parameter for economic analysis in compressed air storage vessel was length to diameter ratio and obtained an optimized L/D value of around 3. Rutqvist et al. [27] numerically modeled underground CAES cavern coupling thermodynamic, multiphase fluid flow and heat transport. They considered a tangible lining with permeability less than 10^{-18} m^2 and observed an air leakage less than 1%. They also observed that the heat conduction of rock had an impact on the air tightness of the caverns. **Basbous** et al. [28] studied the effect of intake pressure, temperature and the exhaust pressure on combined diesel generator CAES system assisted by wind turbine. In their study they demonstrated that pneumatic hybridization minimized fuel consumption by directly connecting the CAES tank with the intake valve. **Jubeh & Najjar** [29] investigated the performance of CAES-Air Injection (AI) and CAES-Inlet Chilling (IC) systems and compared their operating parameters and their effects on efficiencies. Using their results they demonstrated that CAES-IC had better power generation and efficiencies but lower energy ratio than CAES-AI.

Kim et al. [30] numerically modeled a shallow underground cavern for no isothermal condition to study thermodynamic and geo mechanical behavior. They used TOUGH-FLAC software for multiphase flow of the system, TOUGH 2 for heat transport and FLAC3D for geo mechanical behavior. The simulations were conducted for two different linings which showed a 96.7% energy recovery and tensile stress of 8MPa. They showed how the inclusion of internal synthetic seal reduced the tensile stress from 8MPa to 5MPa. **Wang** et al. [31] designed a new refrigeration system, a combination of gas refrigeration and vapor refrigeration cycle and carried out thermodynamic and economic analysis for that system. They concluded that the system was primarily useful for power load shifting applications, could reach very low refrigeration temperature and had wide industrial applications. **Wang** et al. [32] proposed a novel pumped hydro and CAES energy storage system where they observed that the work density increased when pre-set pressure and water to air volume ratio increased. In addition, any two of the pre-set pressure, vessel volume, and water to air volume ratios had a reverse correlation in the condition of certain total work input and output.

Kahrobaee et al. [33] modeled a wind integrated CAES system using two optimization methodologies for short term and long term planning of the system integrated with the grid. They inferred that the cost effectiveness of wind generation system integrated with CAES system depended on its efficiency, cost, electricity rate and wind speed. **Budt** et al. [34] made a simulation analysis using Modleica software for adiabatic CAES system. The major focus of their study was with regard to pressure losses, heat exchange, turbo machinery stages design etc. They analyzed the heat flow rates for the heat exchangers during the compression process. **Daniel** [35] made a dynamic modeling of an adiabatic CAES system for a low temperature TES system, in order to avoid the design of a huge packed bed thermal energy storage unit, to withstand high temperatures and high pressure up to 70 bars. **Yang** et al. [36] proposed a new hybrid Thermal-CAES system and compared it with an advanced adiabatic CAES system. The hybrid system showed better result in-terms of power generation and they found that power ratio decreased and power efficiency increased with operating pressure.

Zimmels et al. [37] coined an advanced design of CAES systems in the rocks of Israel, and evaluated the design performance via predictions available from numerical models. Underground space gave opportunities for safe accumulation of energy. This concern improved the protection and lower response to outside thermal and mechanical influences. **Li and Dai** [38] undertook mathematical modeling and simulation analysis of the vertical axis wind turbine (VAWT) integrated with CAES system and concluded that the inclusion of the VAWT control strategy resulted in an increase in the round-trip efficiency by 5.21% and the number of hours in the protection mode to decrease by 22 h in four weeks. **Saadat & Li** [39] carried out a set of simulation analyses including the control strategy for the storage vessel, compressor and expander. They presented some case studies graphically for various wind speeds and stored energy and also pictorially indicated the average power flow for high and low wind speed conditions.

Wang et al. [40] made the dynamic analysis on scroll expander; they also made the chamber volume calculations and identified that the chamber wall thickness was an important parameter to enhance energy efficiency. **Wang** et al. [41] presented the geometrical description of the scroll air motor and derived the scroll driving torque. Further, the mathematical model for the scroll dynamic process was defined, elaborated and confirmed by comparing the simulated and experimental results.

3.3 **Experimental Investigations**

Wang et al. [42] carried out a lot of research on compressed air storage and expansion using a small air motor; he published a chapter titled "Study on a wind turbine in hybrid connection with an energy storage system" in the text book "Electrical Engineering and Applied Computing". **Yongliang Li** et al. [43] developed a CCHP (Combined Cooling, Heating & Power) system using compressed air and thermal energy storage and evaluated it in a small office building located in Chicago. They concluded that the efficiency of the system was more in winter, around 50% and less in summer, around 30% due to large power consumption in summer and its inefficient expansion of compressed air. But it was much better compared to a conventional absorption chilling system. **Kim** et al. [44] investigated the performance characteristics of a CAES system with pumped hydro storage by energy and exergy analysis for different compression and expansion process and found that during charging process hydraulic part accounted for 37% of total power while discharging accounted for 23% of total power delivered. Through their investigation it was understood that the cavern height and heat transfer affected the system performance proportionately.

Nease et al. [45] simulated solid oxide fuel cell (SOFC)/CAES system for sixteen SOFC plants of different configuration by engaging and disengaging carbon-di oxide capture (CCS) and water gas shift (WGS) in MATLAB/ASPEN Plus combination. The key findings were validated by experimental results, by adding CAES based load-following metrics that improved the overall efficiency of the system and decreased the cost of electricity. **Kushnir** et al. [46] designed and experimentally investigated the steady periodic gas flow around a well in porous reservoirs for a CAES plant and concluded that it was the best way to expand the compression and power generation time spans, to the extent possible, to ease the pressure fluctuations and its associated losses, for a given air mass.

4. **Control Strategies of CAES systems**

Sun et al. [47] made a feasibility study on hybrid wind system integrated with CAES system. They indicated a new mechanism developed to smoothly integrate the torque developed by the expander and wind turbine system. For the above mentioned system a prototype was developed and tested. **Luo** et al. [48] developed a novel efficient pneumatic electrical control system focusing mainly on energy efficiency improvement by utilizing the exhaust air energy from pneumatic actuator outlets to produce electricity. Mathematical modeling, simulation analysis and even lab experimental results were also presented for the novel compressed air energy recovery system. **Sun** et al. [49] developed a multi-mode process control strategy to achieve steady power, which was combined with fuzzy logical pitch control and proportional integral (PI) air pressure control unit. Through the simulation analysis they confirmed the feasibility of the developed novel hybrid wind turbine system. **Luo** et al. [50] discussed the latest development in the pneumatic actuator system energy efficiency by linking a scroll expander for recuperating exhaust compressed air energy. From the simulation and experimental analysis it was concluded that the suggested strategy was suitable for improving pneumatic actuator system energy efficiency.

Luo et al. [51] made a feasibility study for recovering exhaust energy from a vehicle engine system by a scroll expander and concluded that the present existing scroll expander was not suitable for recycling work. Then the team planned to develop a new control strategy for coordinate operation accompanied by the upstream vehicle engine and the down-stream energy recycling system. **Luo** et al. [52] further developed a pneumatic- system for exhaust compressed air energy recycling from conventional pneumatic actuator systems. A novel control strategy was developed and the adverse effects from the down-stream connection were also evaluated and presented. **Martinez** et al. [53] made the dynamic performance analysis of CAES for power system applications and concluded that the optimized power strategy could prominently improve thermodynamics conversion. However, their scheme required an auxiliary device in order to produce a better output power, consuming excess energy and delivering it at the time of requirement. **Li** et al. [54] focused on the varying outlet pressure of the compressor and designed an efficient fuzzy controller. By this control they found that the reliability of the system and efficiency improved. It was found that the control efficiency was much better than standard PID controller. **Li** et al. [55] analyzed the defects prevailing in the intrinsic control system of air compressors and used the distributed control system (DCS) technology for the efficient monitoring of the air compressor system. The monitoring system was effective to fail close by safety interlock of compressors to minimize equipment harm when time of outlet pressure was higher than the assigned value in the discharge.

Saadat et al. [56] designed a non linear controller and observed that the methodology used in their work matched the architecture of the storage system and the physical constraints of different subsystems in the proposed CAES system. **Li** et al. [57] analyzed the non linearity of the air compressor system. They also stated that under constant pressure control care had to be taken to avoid compressor surges. They also included the accident interlocking security control for operating the compressor. **Nejad** et al. [58] developed a novel control strategy based on the energy harvest index which specified the quantity of energy that could be trapped from renewable energy systems and needed storage. . They calculated the Harvest Energy Index (HEI) at various working pressures. **Nejad** et al. [59] made a steady state modeling of a small scale CAES system, particularly for remote and rural applications. They carried out the analysis using MATLAB simulink for the control and optimization of air motors. The expander portion was coupled with synchronous generator and the steady state performance evaluation was also carried out. **Latha** et al. [60] observed the variable operating condition of the electrical system and discussed the utilization of the CAES system at the time of peak demand. They also made an air flow controller for the CAES system to adapt to various load demands to maintain a stable microgrid frequency. **Kokaew** et al. [61] developed a novel controller with maximum power tracking system for a small scale CAES system. They controlled the output power of the DC generator by buck converter and experimentally implemented a dSPACE system. They calculated the air motor speed from the motor characteristics, and measured the speed and pressure for maximum efficiency.

5. **Case Studies and CAES Potential**

Ma et al. [62] discussed the extraction of heat after the process compression and cool energy after the expansion process. The proposed concept was a novel idea in the field of CAES systems. They also made a detailed case study of the Huntorf Plant commissioned in 1978 at Germany; Fig. 4 shows the block diagram of the plant.

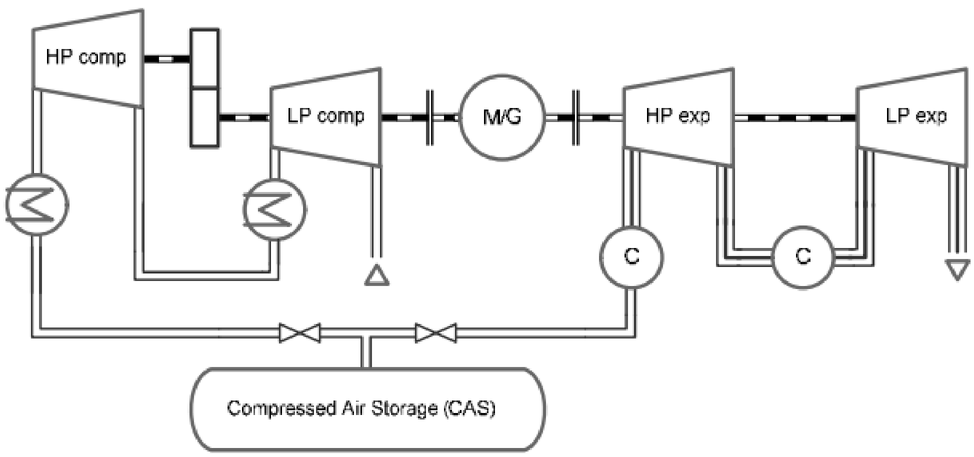

Fig. 3 Block diagram of first CAES system at Huntorf plant in Germany [59]

Zunft et al. [63] discussed the **AA CAES** project, their major finding states that large scale, central storage systems are highly configured in a combined one stage system and such plants can reach storage efficiencies of 70% or even beyond. **Davis** et al. [64] described the history and overview of the first highest, large scale CAES plant at Alabama of about 110 MW which was able to generate the full output for 26 hours. **Marean** [65] discussed the CAES turbo machinery concept suitable for New York conditions and they highlighted the major design difference between the German Huntorf plant and Alabama plant. The Alabama plant had a recuperator, which reduced fuel use by 25%, to heat the air that came out of the reservoir.

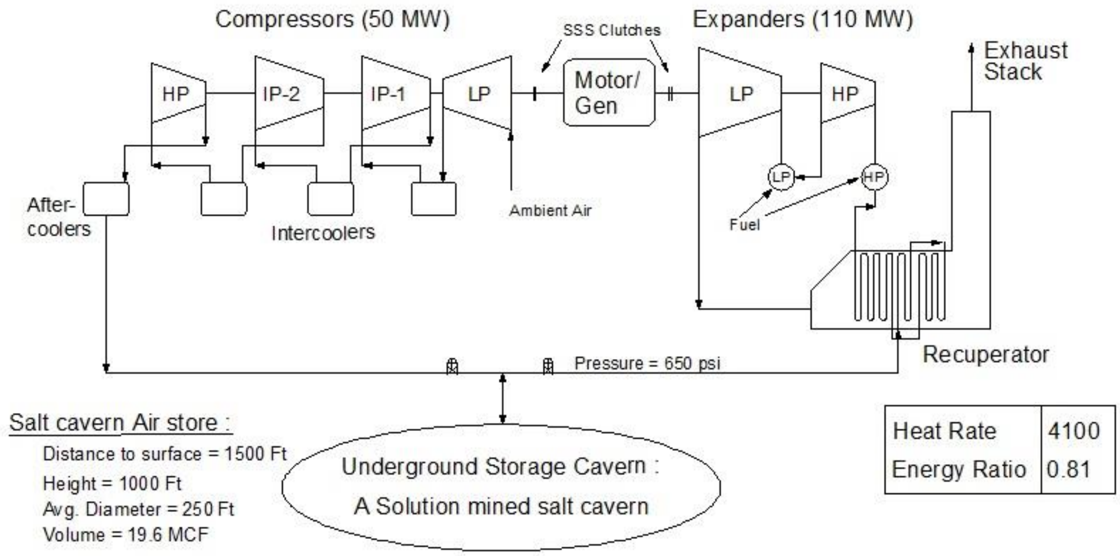

Fig.4 Alabama – CAES plant 110 MW with 26 hours of operation [62]

Zhou [66] stated the scenario in China and concluded that CAES systems were highly suitable for large scale energy storage. Although pumped hydro was a close competitor, it had some geographical constraints which left the CAES system as the alternate choice. **SustainX** [67] is a leading company which recently applied for a patent on isothermal CAES system at the process of compression. Occasional temperature rise was controlled with spray mechanism facility to maintain isothermal condition. However, the temperature usually rose and a spray mechanism discharged the spray at a low temperature such that an isothermal condition was maintained. The major highlight of **Light Sail Energy** Company [68, 69] technology which founded compressed air energy storage CAES system was quite different in utilizing the piston movement that could divide the cylinders into two parts; the piston movement was effected either by high-pressure expansion in one part or by the gas compression in the second part. A novel concept to recover high temperature hot water after the process of compression was also discussed. **John** [70] from Green media stated that Texas had announced the construction of the first big CAES project in the United States in decades, the project termed as the Bethel Energy Center was of 317-megawatt capacity.

Linden [71] made a detailed review of the current developments in the CAES system and various case studies, particularly on the Huntorf plant in Germany. His reviews of various companies involved in CAES systems, like Mesa Power of 4000 MW of intended Wind Energy in Texas, showed the positive benefits of CAES to provide grid stability during peak demand. **Nakhamkin** et al. [72] and **Pollak** [73] made a case study report on the 110-MW Compressed Air Energy Storage (CAES) plant built by the Alabama Electric Cooperative. The report detailed the issues, major problems and their solutions, current information regarding the project, a brief description of the plant and operation, major startup problems, field testing, and initial operating performance. **Crotogino** et al. [74] gave a detailed report about the successful operation of the Huntorf plant. With an aerial view they tabulated the major specifications of the plant which are as follows,

Table: 1 Specifications of Huntorf Plant in Germany [70]

Output Turbine operation - 290 MW Compressor operation- 60 MW	No: of air cavern- 2 Total Cavern volume- 310 000 m³
Air Flow rates Turbine operation - 417 kg/s Compressor operation – 108 kg/s Air mass flow ratio in/out- ¼ Maximum pressure reduction rate: 15 bar/hour	Maximum diameter- 60 m Well spacing-220m Minimum permissible: 1 bar Maximum permissible: 70 bar Minimum operational: 43 bar

Shidahara et al. [75] carried out a **case study** for the CAES that included drilling a borehole of 600 m in depth, performed on the paleogene sedimentary rock that consisted mainly of conglomerate in northeast Kyushu, Japan. They also devised a novel procedure for geotechnical evaluation of sedimentary rocks that surround the CAES reservoir. **Raju & Khaitan** [76] made a modeling and simulation analysis of the Huntorf plant in Germany with proper mass and energy balance, comparing for both isothermal and adiabatic models. **Baqari &Vahidi** [77] demonstrated a small scale CAES showing better performance with clean storage. The key finding of the research showed dependency of efficiency and mechanical torque on compression pressure and wind speed. **Safaei & Keith** [78] performed an economic analysis of the CAES and DCAES systems in Alberta City and concluded that there was an additional profit observed in DCAES when compared with CAES system. Also, there was a drastic reduction in the CO_2 emission that added to the economic enhancement. All the results were graphically plotted and analyzed.

Lund & Salgi [79] carried out both system economic analysis and business economic evaluation of CAES in Danish electricity supply with simulation results obtained through Energy- PLAN computer model. They concluded that the CAES system was feasible and could n operate on spot regulating power market. **Fertig & JayApt** [80] presented the economic evaluation of a CAES system integrated with a wind farm in central Texas to offer firm, transmittable base-load power and the consequent shoot up in electricity prices. They considered the load patterns in Dallas, and Houston, with a CAES plant at ERCOT and found that pairing CAES with the wind farm was not economically viable in ERCOT at the farm level. **Salgi & Lund** [81] analyzed the CAES system behavior at Denmark and observed that during low wind penetration, the major obstruction was the lack of sufficient excess electricity; whereas at high penetration, the major issue became the lack of discharging hours in a system with a high CHP capacity. **Saidur** et al. [82] carried out energy audits to estimate the compressed air energy usage and their results predicted that by using variable displacement compressor ample amount of energy and cost could be saved together with reduced of environmental emissions. **Loisel** et al. [83] studied and evaluated the economics of a wind farm with a long-standing market viewpoint, considering high shares of wind energy, constraints set on the energy variability, and the removal of support schemes such as feed-in tariffs. The main barriers, according to their investigation, were the complementary needs that the French market could face in the future, other power quality issues, and the social cost of the supply security. **Satkin** et al. [84] developed a factor map for wind-CAES power plant using ArcGIS software for selection of power plant sites. They simulated for Iran environment and found 30 sites at 5 major zones had enough potential for power plant installations.

6. Economic Analysis:

Safaei et al. [85] evaluated the economics of DCAES for various pipe lengths between compression and storage optimized for different gas prices and capital investment on pipes. His final investigations concluded that DCAES was more economical compared to CAES for shorter distance. **Madlener & Latz** et al. [86] developed an economic model and compared three variants of CAES, namely wind-park without CAES, wind-park with centralized CAES and wind-park with integrated CAES considering data of 2007. Through their algorithm for profit maximization they calculated net present value (NPV), return on investment (RoI), generation cost and payback period for all variants. Their results showed that the wind park with centralized CAES was the economical first choice followed by wind-park integrated with CAES system. The study showed diabatic system had more attractive results than adiabatic system. **Marano** et al. [87] developed a mathematical model for thermo-economic analysis of CAES coupled with wind and photovoltaic plants. They optimized the hybrid plant management by dynamic programming algorithm and found that the integration of CAES made the system economically viable, and reduced the cost by 80% and CO_2 emission by 74%.

Foley & **Díazlobera** [88] developed SEM_2020 model in PLEXOS for a techno economic investigation of the impact of CAES on the wholesale electricity market. The overall study demonstrated an increase in pool revenues and decrease in CO_2 emission by 3%, in renewable energy portfolio of 2020. **Abbaspour** et al. [89] developed a mixed integer non-linear programming with the objective function of profit maximization and cost minimization for a wind firm integrated with CAES. Simulated mathematical model showed an increase in profit of around 43% and decrease in total cost of 6.7%. **Yucekaya** [90] developed a mixed integer programming for operational scheduling for optimum market profit which was estimated using Markov -based probabilistic model. He simulated two separate modules for annual operation and profit for 100 iterations and found that the CAES system was economically viable. **Karellas &Tzouganatos** [91] conducted a steady state analysis of compressed air storage and compressed hydrogen storage in terms of energy and exergy, using IPSE pro simulation software and HOMER energy software. The analysis was conducted on four micro system models of single and two stage systems with and without preheating. Through their analysis they proved that the air preheated system was more efficient in terms of energy and exergy. They have also given the details of the initial capital cost investment estimate of the CAES system.

Table: 2 Capital cost of the CAES system

System Component	Compressor	Turbine	Generator	Storage tank	Wind farm	System
Capital Cost (Euro)	18,20,000	11,70,000	11,70,000	13,30,000	25,50,000	80,40,000

Manchester & Swan [92] modeled a CAES system both numerically and thermodynamically, simulated for 10 mins in WEC time step-data for economic viability. Through their investigation they observed that the income generated was increased by 30% and round-trip efficiency was 66%. **Denholma & Sioshansi** [93] examined the major benefits of colocation of wind energy and energy storage facilities to enhance the transmission and utilization, and to bring down the transmission cost. They concluded that if the CAES system optimally dispatched the response closer to the wind patterns converging, the performance of wind and load would reduce the penalty and transmission cost extensively. **Drury** et al. [94] quantified the dispatching value of CAES plant and they found that by providing the operating reserve, the plant appreciably increased the net annual revenue by $23±10/kW-yr for conventional devices and for adiabatic devices it was 28±13/kW-yr. **Succar** et al. [95] performed optimization on wind turbine system jointly with CAES system and they observed that the ability to transmit more wind energy using low rated wind turbine gave a 3-8% drop in overall Cost of Energy (CoE). **Succar** et al. [96] discussed the wind driven CAES base load market strategies and they highlighted the performance indices like heat rate, charging electricity ratio and round trip efficiency. They provided graphs, under various conditions like constant cavern pressure, variable cavern pressure, variable turbine inlet pressure and constant turbine inlet pressure. **Denholm** [97] developed a marketable model for the effects of significant wind power generation on system operation and on economic value of investments in compressed air energy storage (CAES) system. The objective function used in their model was cost minimization and they finally predicted that CAES for Germany was suitable for large scale power generation and was economically feasible. **Denholm** et al. [98] made a detailed economic analysis of the CAES system focusing on net revenue, device efficiency, and other parameters like sensitivities, sizing of compressor and expander units.

7. CAES – A Pathway to Smart Grid and Polygeneration:

Energy Storage technologies, will play a major role in the field of smart grid and poly-generation in the near future. CAES assures reliability, increase the utilization of renewable resources and also acts as a buffer to mitigate the fluctuations in the grid power output.

Smart Grids: In the last few years a lot of research has been conducted in the field of control and monitoring, development of novel power converters, cloud computing, use of electricity for various applications like plug in vehicles during the off peak power etc., emerging rapidly towards the development of smart grids. However, the development of efficient energy storage technologies will be the ultimate solution to make this smart grid stable.

Polygeneration: Among the various storage technologies, CAES system is more suitable for large capacity storage. However, the overall turnaround efficiency is lesser due to the dissipation of heat during compression and cool energy during expansion. Incorporating Polygeneration by utilizing the heat of compression for some process industrial heating applications and cool energy generated during the expansion for some air-conditioning and chiller applications will improve the turnaround efficiency to a greater extent. Hence the research focus in the future will be the introduction of CAES system in the grid along with poly-generation cascaded concept to improve the turnaround efficiency of the CAES system.

8. Conclusion:

A detailed review of various published CAES system has been condensed in this study on various aspects such as thermodynamic analysis, modeling and simulation, experimental investigation, case studies, potential analysis and economic evaluation. It is concluded from the present review that the integration of CAES with renewable power generation such as solar and wind will improve the utilization of resources through demand side management, and make it an attractive proposition in increasing renewable power recovery around the globe. Small scale CAES systems are also gaining the attention of scientists as these systems can be extended towards smart micro grids to avoid several blackouts that happen very often in developing countries. Further, CAES addition for poly-generations with cascaded heating, cooling and power generation will be the future technology to improve overall efficiency for sustainable generation from renewable sources along with a solution for smart grids.