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Modelling and Thermodynamic Analysis of Small Scale Compressed Air Energy Storage Systems with Thermal Recovery

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Abstract — The global fossil fuel source is limited and is getting depleted rapidly. The growth in energy demand worldwide is ever increasing, thus increasing fossil fuel consumption. Use of fossil fuels in electrical energy generation have environmental impacts like global warming , CO_2 emissions etc., This necessitated use of alternate renewable energies like solar, wind to meet energy requirements. But the limitation of renewable energy sources are that they are intermittent in supply, uncertainty of availability etc., lead to difficulties in ensuring stability in electrical grid networks. These constraints led to the development of various energy storage technologies so that available surplus energy from renewable sources can be stored and released as and when needed to maintain grid supply stability both in terms of power and frequency. Thus Electrical Energy Storage (EES) is of great importance to ensure striking a balance between demand and supply .Many storage technologies have been developed and used at present like pumped hydro, solar thermal, batteries, compressed air, flywheel etc., Compressed air storage technology has the advantage of reduced emission and possibility of large capacity plants. About 440 MW installations of CAES are available at present around the world. Compared with other energy storage technologies, CAES is proven to be a clean and sustainable type of energy storage with the unique features of high capacity and long-duration of the storage.

The intention of this paper is to model and analyse a small scale compressed air storage system useful for standalone and micro-grid applications. The economics of CAES is also discussed. Thermodynamic analysis of the charging and discharging cycles in the storage tank is modelled and analysed for a small capacity CAES. A thermodynamic study on the proposed system covering all components like compressor, expander is also done and related models analysed. The heat energy released during compression stage is recovered, utilized during expansion so that the round trip efficiency improves. This paper also covers this aspect , comparing the efficiencies of systems with and without heat recovery.

Keywords- Compressed air Energy storage System (CAES), Heat Recovery, Thermodynamic analysis.

1. INTRODUCTION: Compressed air energy storage (CAES) is a method to store enormous amounts of renewable power by compressing air at very high pressure and storing it in large cavern. The compressed air can be discharged and surged through turbines to generate power when Photovoltaic (PV) array lessen its output and power is required. In solar power system, the electrical energy produced by the photovoltaic panels cannot be used directly all the times. If the demand from the load is not always equals to the solar panel capacity, in this case battery banks are generally used to store energy. Here the energy is stored in Compressed air energy storage in the form of air pressure.

Recently South Ausralia has approved a renewable energy project to build a $30 million advanced compressed air energy storage (A-CAES) facility at the Angas Zinc Mine near Strathalbyn. An air-storage cavern 240 metres below ground using their innovative design to achieve emissions free energy storage is planned [off grid energy independence.com reports 23.7.2019]

The present article aims to provide an overview on present and past approaches by classifying and comparing CAES processes. This classification and comparison is authenticated by a wide historical background on how compressed air energy storage (CAES) has developed over time. The concept of energy is applied to CAES to enhance the basic understanding of CAES System.

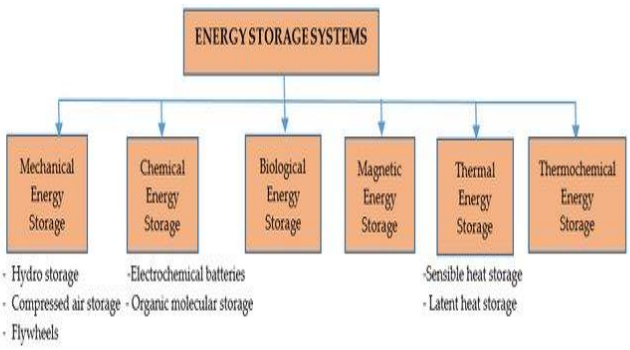
2. Energy Storage:

The use of electricity from grid has two constraints, imbalance between demand and supply , geographical separation between electricity generating plant and location of consumption points. The consumer always wants uninterrupted demand based power supplies. To meet this customer demand the generation plant should have sufficient power generation at a controlled frequency[7]. Renewable energies like solar and wind do not satisfy these two functions of sufficiency and frequency , a suitable storage technology will be able to fill the gap and achieve these important qualities.
The energy storage power capacity world wide (2018 in GW)[8]

Storage Technology	Capacity
Pumped storage	128.1
Thermal	2.3
Electro-Chemical	1.6
Electro-Mechanical	1.1

In energy storage system, energy conversion from one form (mostly electrical) to an intermediate storable form and then reconverted back to electrical energy when needed [9,10,11]. Various storage technologies like pumped hydro, batteries, thermal, CAES and flywheel

Fig 1: Classification of Energy Storage System



have been discussed in the report by Edison Electrical Institute. In US almost 93% of energy storage is by pumped storage , followed by thermal storage [12,13].A review of selected energy storage technologies in terms of energy density, efficiency, cost has been presented in the Environmental and energy study institute fact sheet, USA. Various energy storage technologies like pumped hydro, compressed air , thermal, Li-ion battery, lead acid battery, flow battery and flywheel has been studied and reported[14]

The various energy storage technologies can be classified as under:[15]

2.1 Compressed Air Energy Storage System (CAES):

The basic principle involved in CAES is that the ambient air is compressed into one or more storage reservoirs using available surplus energy during off peak periods thus storing energy and during peak period needs the compressed air is expanded in turbines/expanders to generate electricity [16,17].The main components of a CAES system are compressors, driving motors,generators, air reservoirs/ underground caverns, turbines/expanders and other components. [16,17]

A typical CAES system is shown in figure [18]

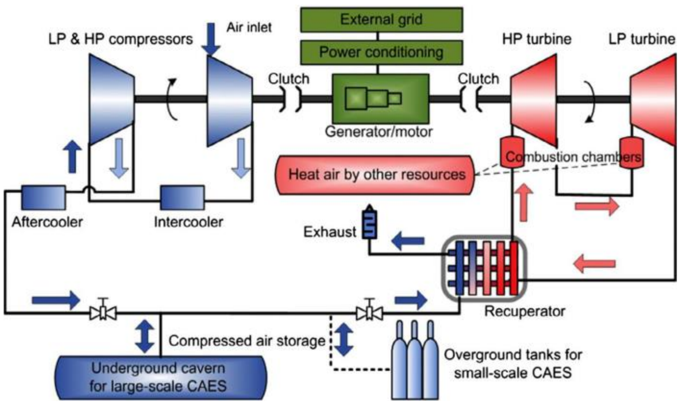
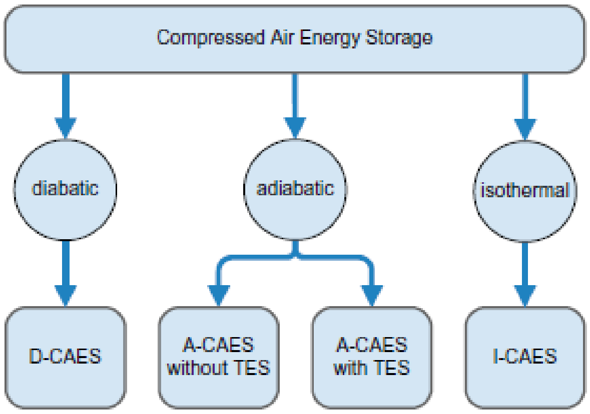


Fig 2: Structure diagram of CAES system (Luo et al., 2015)

2.2 Historic Development of CAES:

The development of CAES started with 1949 when patent was filed to store air power inside an underground air storage cavern[19,20].The world's first CAES power station, HUNTORF plant of 290 MW capacity was commissioned in 1978 in Germany. The storage capacity is 11 million cubic feet at 1000psi in underground salt cavern situated at 2100-2600 feet below surface[21].A 110MW Alabama, US plant called MC Intosh project started working from 1991 with a 19 million cubic feet storage at 1080 psi in a slat cavern 2500 feet deep[22]. A 270 MW $ 400 million CAES plant in IOWA was terminated as the storage reservoir was not suitable[23]. A 324 MW CAES plant is under construction at Anderson County, Texas and will go commercial by fall 2022 [24]

2.3. Classification of CAES systems:



CAES systems classified as per change of state[25]

2.3.1.Adiabatic CAES (A-CAES):[26]

The heat energy produced while compressing ambient air is stored and used for preheating ; cold energy produced while expanding air is used for inter stage pre cooling of compressor. Thus the use of fossil fuel is eliminated resulting in green house gas emission.

2.3.2.Diabatic Compressed Air Storage system(D-CAES): [27]

There will be no heat exchange links, heat generated during compressor is released to atmosphere.

2.3.3.Isothermal CAES (I-CAES) : [28]

The temperature variations during compression and expansion is minimized and near constant temperature is maintained throughoutMarco Antonelli etal., [29] discussed about Liquid air energy storage system (LAES) an interesting solution with a relatively large volumetric energy density and ease of storage. Power recovery from liquid air, either with or without combustion has also been studied besides power recovery from liquid and related efficiency parameters. Bernd Ameel et al.,[30] has also studied LAES , comparing LAES with CAES . The problems associated with CAES like underground storage tanks and related huge investments can be overcome by LAES where in liquid air is pressurized , evaporated, warmed and then expanded to generate electricity. A comparative study of liquid ,solid and hybrid adiabatic compressed energy storage system was carried out from thermodynamic and economic points of view by Haobai Xue and others, investigating tradeoffs as well [31].

2.4 .Modelling CAES systems:

Models for the compressor, turbine module, cavern, TES (Thermal Energy Storage), induction motor, and generator of A-CAES are created using software Matlab/Simulink®. The models are made flexible, modular, and extensible; and will aid a CAES plant designer to obtain an accurate first order thermodynamic evaluation of a proposed CAES plant[32]. Ivan Calero and others proposed a detailed mathematical model of the diabatic Compressed Air Energy Storage (CAES) system and a simplified version ,considering independent generators/motors as interfaces with the grid. The models can be used for power system steady-state and dynamic analyses.[33] .A comparison between the static and dynamic modeling of the A-CAES system performed by a computer simulation using "Modelica" was studied by Youssef Mazloum and others .Unlike the static model, the dynamic model takes into account the mechanical inertia of the turbomachinery (compressors and turbines) as well as the thermal inertia of the heat exchangers[34]. Studies on development of a plant model was done by Sciacovelli, A and others that blends together algebraic and differential sub-models detailing the transient features of the thermal storage, the cavern, and the compression/expansion stages. The model allows us to link the performance of the components, in particular those of the thermal storage system, with the performance of the whole A-CAES plant. It was found that an A-CAES efficiency in the range 60-70% is achievable when the TES system operates with a storage efficiency above 90%.[35].

An accurate dynamic simulation model for compressed air energy storage (CAES) inside caverns has been developed. Huntorf gas turbine plant is taken as the case study to validate the model. Accurate dynamic modeling of CAES involves formulating both the mass and energy balance inside the storage.[36]. Mohamad Cheaybab et al., modeled the all the three phases , charging, storing and discharging of a tri-generative CAES based on thermodynamic parameters and the results of experiments conducted found to be in good agreement [1,37,38]. Niklas Hartmann and others analyzed the energy balance and efficiency of one full charging and discharging cycle of several adiabatic Compressed Air Energy Storage (CAES) configurations . Highest efficiency was found in highest the two-stage adiabatic CAES configuration[39].Studies and numerical analysis of a 2kW small CAES system using was conducted by Gayathri Venkataramani and others .The system performance was evaluated using TRNSYS V17 platform for CAES and optimum design parameter values were determined [40] A detailed mathematical model of a diabatic CAES system and a simplified version are proposed based on the existing Huntorf CAES system in Germany and a commercially available CAES system , studying the dynamic response of frequency variations was proposed by Ivan Calero and others., [33,41]. The simulations agree with the model values.

2.5.CAES for standalone applications:

A novel CAES system for the energy storage in a small scale stand-alone renewable energy power plant to satisfy the energy demand of a radio base station for mobile telecommunications was suggested by Jannelli, E and others . This system used integrated thermal energy storage (TES) unit with inter-cooling compression and inter-heating expansion. [42]. A prototype system 1.273

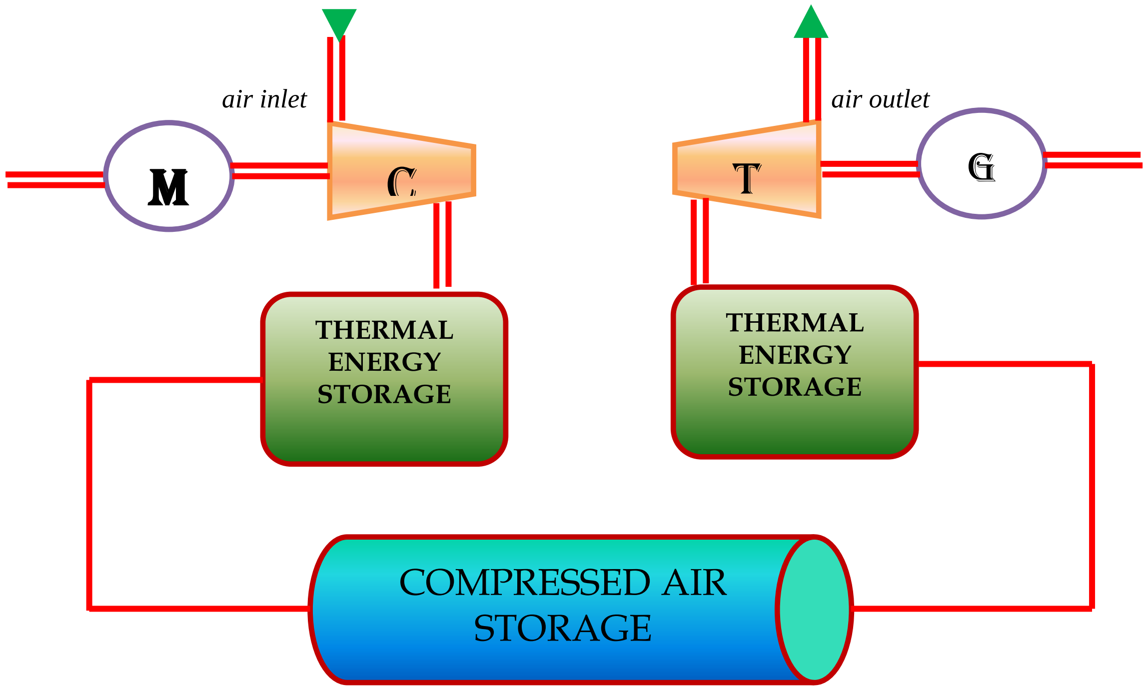


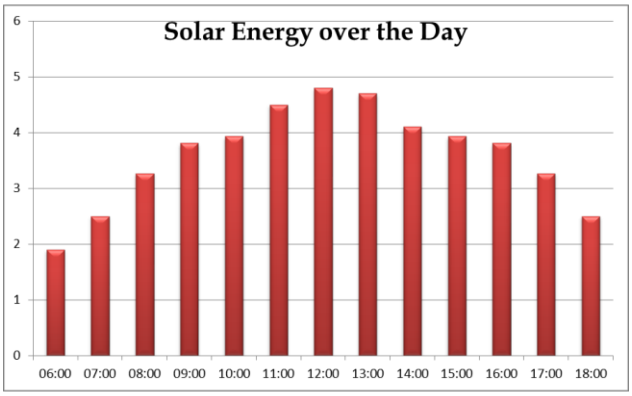
Fig 3: Block diagram of CAES with TES

kWh capacity consisting of using the renewable energy from a photovoltaic (PV) array to compress air for a later expansion to produce electricity when needed was developed by Maia, T.A.C and others [43]. Another study focused on energy analysis, dwelling applications and architectural constraints was done by Minutillo, M et al.,[44].An extensive model of the main component of a CAES system, storage container , was developed by Erwan Adi Saputro. The charging and discharging processes were modeled using differential equations, experiments conducted in a tank of 2L capacity with a maximum pressure of 200bar [45].

The load graph of standalone PV solar system is illustrated below:

2.6.CAES for microgrid applications:

Micro grids are essential parts of electricity networks and many researchers studied the development of storage systems for micro grids.H.Ibrahima and others investigated the use of CAES in micro grids operating in remote areas[46] Latha et al. used Compressed Air Energy Storage (CAES) system for microgrids under variable load conditions, to meet the demand using an air flow controller designed so that the microgrid follows the various load demands to maintain the stable frequency. The performance of the proposed system was validated through simulation study for various load conditions is carried out using MATLAB/Simulink.[47].



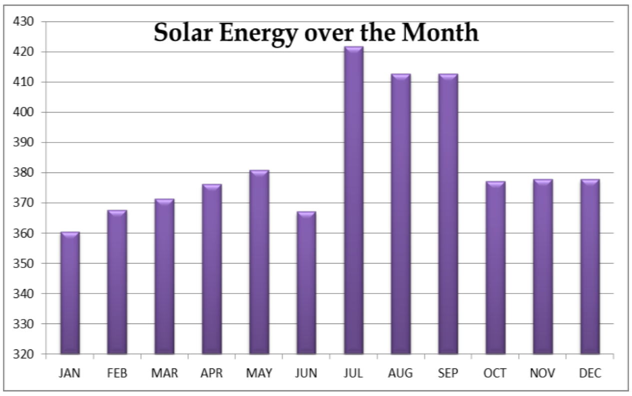


Fig 4: Load Profile of PV on daily and monthly basis

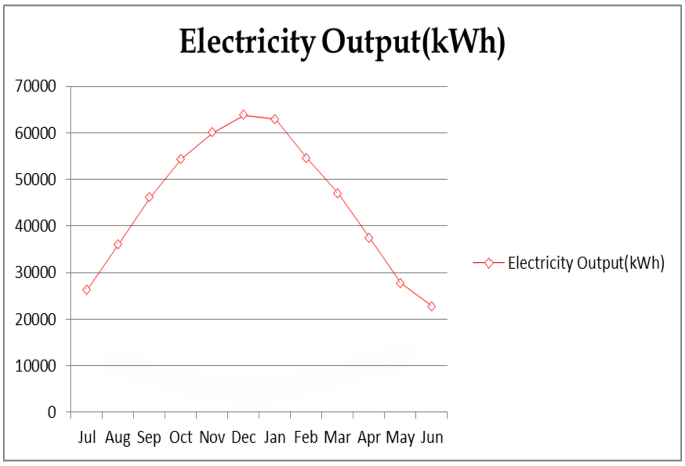


Fig 5: Electricity output of PV

Saili Li and Yiping Dai modelled , simulated and experimented a 30 kW CAES system with vertical axis wind turbine and developed control strategy to improve round trip efficiency.[48]

2.7.CAES for Large grid applications:

Stefan Zunft and others studied technical feasibility of the A-CAES and its economical viability in detail.[26,49].O.Ramadan et al., developed a parametric analysis of sizing a large-scale energy storage system that may help to stabilize energy supply based on large-scale grid integration in Suez area in Egypt. Mat lab models were developed to size and simulate CAES system.[50]

2.8. Results & Discussions:

Simulation data is applied to the research work at instance. The calculation of Power generated by the selected PV system and the total estimation of PV energy production and consumption is monitored. The Small scale CAES is assumed to store the excess PV energy by compression and expansion on regular basis to produce the power when there is no demand.

According to the thermodynamic modeling, the compressed air at maximum pressure of 220 bar is stored in Air storage tank with volume of 1 m^3. By considering the cylinder pressure, ambient pressure, volume of the cylinder, temperature and heat capacity the air is compressed at 293 K. The minimum output ranges from 0.1 to 0.24kwh during isothermal expansion and 0.1 to 0.5 kWh during adiabatic expansion can be obtained by the simulation as daily basis. The total stored energy can be generated and utilized when there is demand for electricity.

2.9.Conclusions:

CAES has vast potential as a energy storage technique . This paper outlined the various works undergone in this front besides covering the basics, modeling and applications. One area of importance is to improve the efficiency of compression, expansion and storage systems which form the basic components of a CAES systems. The energy losses should be minimized by detailed

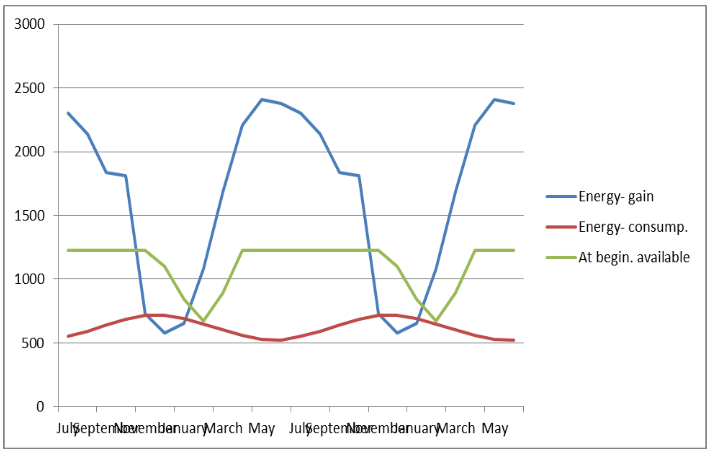


Fig 6: Energy production & Consumption

modeling and simulating of the entire system both the components and overall systems. The Economics of the storage system needs to modeled for standalone, micro grid and large scale grids including the site selection, partial loading ,emission control , materials for storage systems etc.,

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