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Solar-Based Compressed Air for Energy Generation

N. S. Patil [1*], M Sharmila[2], Ashish Vilas Lohar [3], Tanmay Bajirao Jeughale[4], Pawan Santosh Jadhav [5], Soham Anil Rane[6]

[1,2]Assistant Professor, Electrical Engineering, Sandip Institute of Technology & Research Centre, Nashik, Maharashtra, India

[3,4,5,6] Students, Electrical Engineering, Sandip Institute of Technology & Research Centre, Nashik, Maharashtra, India

Abstract: The growing use of renewable energy has made energy supply less steady, creating a strong need for reliable and eco-friendly energy storage to keep the power grid stable. One such method is Compressed Air Energy Storage (CAES), which has good potential but is not widely used. Although it has been around since the 1970s, CAES has faced challenges like high costs and the need for large storage space. However, with the increasing need to stabilize power systems and reduce carbon emissions, interest in CAES is rising again. This technology offers a viable alternative to chemical batteries, particularly for bulk energy storage applications, by utilizing compressed air to store and deliver energy without relying on environmentally harmful chemicals. Modern CAES systems are designed to meet specific customer requirements, operating efficiently at 8 bar air pressure to provide consistent 12- volt, 10-watt power output, showcasing the potential of renewable technologies to revolutionize energy storage and support a sustainable energy grid

INTRODUCTION

Electrical Energy Storage (EES) refers to a process of converting electrical energy from a power network into a form that can be stored for converting back to electrical energy when needed. Such a process enables electricity to be produced at times of either low demand, low generation cost, or from intermittent energy sources and to be used at times of high demand, high generation cost, or when no other generation is available. The history of EES dates back to the turn of the 20th century, when power stations often shut down for overnight, with lead-acid accumulators supplying the residual loads on the then direct current (DC) networks. Utility companies eventually recognized the importance of the flexibility that energy storage provides in networks, and the first central station energy storage, a Pumped Hydroelectric Storage (PHS), was in use in 1929. Up to 2011, a total of more than 128 GW of EES has been installed all over the world. EES systems is currently enjoying somewhat of an arenaissance, for a variety of reasons including changes in the worldwide utility regulatory environment, an ever- increasing reliance on electricity in industry, commerce and the home, power quality/quality-of-supply issues, the growth of renewable energy as a major new source of electricity supply, and all combined with ever more stringent environmental requirements. These factors, combined with the rapidly accelerating rate of technological development in many of the emerging electrical energy storage systems, with anticipated unit cost reductions, now make their practical applications look very attractive in the future timescales of only years. The anticipated storage level will boost to 10~15% ofdelivered inventory for the USA and European countries, and even higher for Japan in the near future. There are numerous EES technologies, including Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage system (CAES), Battery, Flow Battery, Fuel Cell, Solar Fuel, Superconducting Magnetic Energy Storage system (SMES), Flywheel and Capacitor and Supercapacitor. However, only two kinds of EES technologies are credible for energy storage in large scale (above 100MW in a single unit) i.e. PHS and CAES. PHS is the most widely implemented large-scale form of EES.Its principle is to store hydraulic potential energy by pumping water from a lower reservoir to an elevated reservoir. PHS is a mature technology with large volume, long storage period, high efficiency and relatively low capital cost per unit energy.

However, it has a major drawback of the scarcity of available sites for two large reservoirs and one or two dams. A long lead time (typically ~10 years) and a large amount of cost (typically hundreds to thousands of millions of US dollars) for construction and environmental issues (e.g., removing trees and vegetation from the large amounts of land prior to the reservoir being flooded) are the other three major constraints in the deployment of PHS. These drawbacks or constraints of PHS make CAES an attractive alternative for large-scale energy storage.CAES is the only other commercially available technology (besides the PHS) able to provide the very-large system energy storage deliverability (above 100MW in a single unit) to use for commodity storage or other large-scale storage. The chapter aims to review research and application state-of-the-art of CAES, including principles, functions, and deployments. The chapter is structured in the following manner. Section 2 will give the principle of CAES. Technical characteristics of the CAES will be described in Section 3 in terms of power rating and discharge time, storage duration, energy efficiency, energy density, cycle life and life time, capital cost etc.

LITERATURE REVIEW

Deployment Although CAES is a mature, commercially available energy storage technology, there are only two CAES operated all over the world. One is in Huntorf in Germany, another is in McIntosh, Alabama in the USA. The CAES plant in Huntorf, Germany, is the oldest operating CAES system. It has been in operation for about 30 years since 1978. The Huntorf CAES system is a 290 MW, 50Hz unit, owned and operated by the Nordwestdeutsche Kraftwerke AG. The size of the cavern, which is located in a solution-mined salt dome about 600m underground, is approximately 310,000 m3. It runs on a daily cycle with eight hours of charging required to fill the cavern. Operating flexibility, however, is greatly limited by the small cavern size. Compression is achieved through the use of electrically driven 60 MW compressors up to a maximum pressure of 10 MPa. At full load the plant can generate 290MW for two hours. Since its installation, the plant has shown high operation ability e.g., 90% availability and 99% starting reliability. The second commercial CAES plant, owned by the Alabama Energy Cooperative (AEC) in McIntosh, Alabama, has been in operation for more than 15 years since 1991. The CAES system stores compressed air with a pressure of up to 7.5 MPa in an underground cavern located in a solution-mined salt dome 450m below the surface. The storage capacity is over 500,000 m3 with a generating capacity of 110 MW. Natural gas heats the air released from the cavern, which is then expanded through a turbine to generate electricity. It can provide 26 hours of generation. The McIntosh CAES system utilizes a recuperator to reuse heat energy from the gas turbine, which reduces fuel consumption by 25% compared with the Huntorf CAES plant.

SYSTEM TOPOLOGY AND CONFIGURATION

The architecture of the Solar-Based Compressed Air Energy Storage system represents a paradigm shift from traditional passive battery setups. The Parallel Active Setup is the most important part of this system. In a normal setup, solar panels are directly connected to a battery through a charge controller, which can slow down performance during strong sunlight. In this new micro-CAES system, solar power and air storage are connected but work independently. The DC bus (which supplies power to the load) acts like a main road, while the solar panels and air tank act as two separate energy sources. Because of this setup, the solar panels can work at their best efficiency (MPPT) to compress air quickly, while the air tank can release energy through a turbine at its own steady and controlled rate. Both processes happen smoothly without affecting each other.

3.1 POWER ELECTRONICS: THE DC-DC CONVERSION AND MPPT BRIDGE

The electrical control system adjusts the power going into the storage system according to the needs of the compressor motor. When sunlight is strong, the MPPT converter helps the 150W (12V) solar panel work at its highest efficiency. It takes the maximum power from the sun and sends it directly to the 12V DC compressor. When energy is being used, another voltage controller manages the power coming from the turbine generator. It increases (boosts) or decreases (bucks) the voltage as needed to keep a steady 12V output for the user, even if the turbine speed changes slightly.

3.2 MODELLING THE PNEUMATIC AND THERMAL STRESS

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Instead of thinking of a chemical battery as a simple storage tank, we see the CAES (Compressed Air Energy Storage) tank as an active and changing thermodynamic system. Our system has three main types of stresses:

Heat from Compression (Immediate Thermal Resistance):

When air is quickly compressed by the piston, it heats up due to the laws of gases. If this heat is not controlled, the air becomes less dense, which means more mechanical effort is needed to reach the desired pressure.

Mechanical Delay and Volume Limits:

As air is pumped into the tank, the compressor takes time to push against the increasing pressure inside. When the tank pressure gets close to its limit (around 8 bar), the compressor becomes less efficient and cannot fill the tank as easily.

Maximum Pressure and Safety Limits:

At very high pressure, the mild steel tank can no longer safely handle more air and may fail or burst. To prevent this, pressure relief valves are used to release excess pressure and avoid dangerous situations.

In simple terms, the system is not just storing air—it is constantly dealing with heat, pressure, and safety limits while operating.

3.3 ENERGY MANAGEMENT LOGIC FLOW

The system is designed with a main control unit that works like an air traffic controller, managing everything automatically.

It follows a simple priority rule:

Safety comes first:

The system always checks the pressure inside the air tank. If the pressure gets close to the maximum limit (8 bar), it stops sending electricity to the compressor. Instead, it may send the extra electricity somewhere else or reduce the solar power output. This helps prevent the tank from getting too much pressure and bursting.. Peak Solar Shaving: It keeps a track of peaks in solar power generation during mid-day high irradiance. These peaks are "shaved" off the immediate grid and absorbed entirely by the compressor, sinking the energy into dense pneumatic storage. State-of-Energy Balancing: It ensures the air tank never over pressurizes (so it remains safe) and manages the discharge rate so it never drains to absolute zero prematurely (ensuring it can always provide baseline electrical energy through the turbine)

COMPONENTS

1 Solar Panel:150 Watt

The Solar Panel is used for the conversion of Solar energy to Electrical output. The Electrical output obtained is DC

Air fitting tubes:6mm tube

We are storing air in the Storage Tanks, so these air fitting tubes are used to allow for the seamless air flow and connections, and to avoid any leakages of air from the tank.

6mm Press Fittings

Non-return valve: Up to 10 Kg/Cm

MS Air Tank: 25 liter

E-Vehicle Motor: Rated Speed: 3300RPM

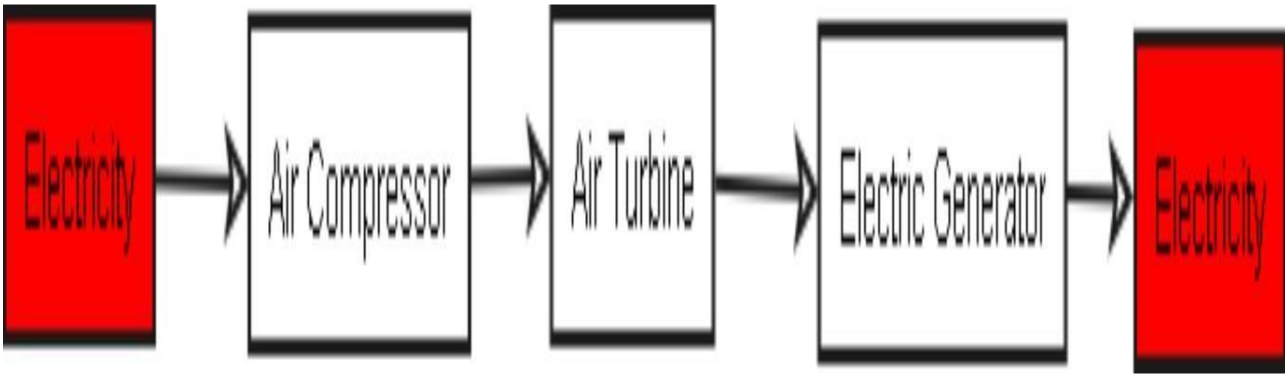
E bike MY1016Z2 250W 360rpm Geared DC motor is a popular reduction DC motor & it's simply the most commonly used motor for scooters, bikes, and quads available in the market! Also, due to its robustness, it is used in many DIY projects like Segway, e-cars, etc., and in many robots like ATV robots, combat robots, etc.

3.4 INTEGRATION WITH THE MICROGRID CONTROL UNIT (MCU)

The system architecture is explicitly modeled so that it can seamlessly communicate with the rest of a decentralized microgrid. It does not operate in isolation; it gathers information about the immediate load demands and forecasts data regarding upcoming solar irradiance. This predictive information is used to aggressively "recharge" or strategically "pre-empty" the air tank. For instance, the MCU will aggressively dispatch the stored compressed air to power loads during the early morning if it predicts an incoming period of high, cloudless solar irradiance, ensuring there is maximum pneumatic "space" available to

3.5 Compressed air energy storage – Working

Energy from solar or wind and even electricity from a thermal power plant during off- peak period may be utilized to compress air by a compressor, and the same air may be utilized to produce electricity during peak-hour.



Compressor Working

METHODOLOGY

To optimally operate the physical system described above, we propose a three-stage methodological framework: Solar Output Forecasting, Thermodynamic State Modeling, and Mixed-Integer Unit Commitment Optimization. The first stage utilizes a deep learning predictive pipeline to forecast the available solar power for the upcoming 24 to 72 hours. We take ideas from weather forecasting to predict how much solar power will be available. The system uses past weather data, current Air Quality Index (AQI), and local weather conditions in a smart deep-learning model (Conv2D LSTM). This model gives an hourly prediction of how much electricity will be available to run the air compressors.

Because of this prediction, the system can see when solar power might suddenly drop (like during clouds) and plan when to release stored air energy.

Next, the system carefully models how the air storage tank works in real life. Instead of using simple estimates, it calculates the temperature and pressure inside the tank using basic physics laws (like energy and gas laws). It also considers how heat moves between the air and the tank walls while filling or emptying the tank.

To keep things simple and efficient, complex calculations are reduced into a manageable form, while still making sure:

- The pressure never becomes too high (to avoid damage), and
- The pressure never becomes too low (so the system keeps working properly).

In the final step, all this information (solar power prediction + tank conditions) is used in an optimization program (MILP). This program decides:

- When to store energy (compress air), and

- When to use it (release air).

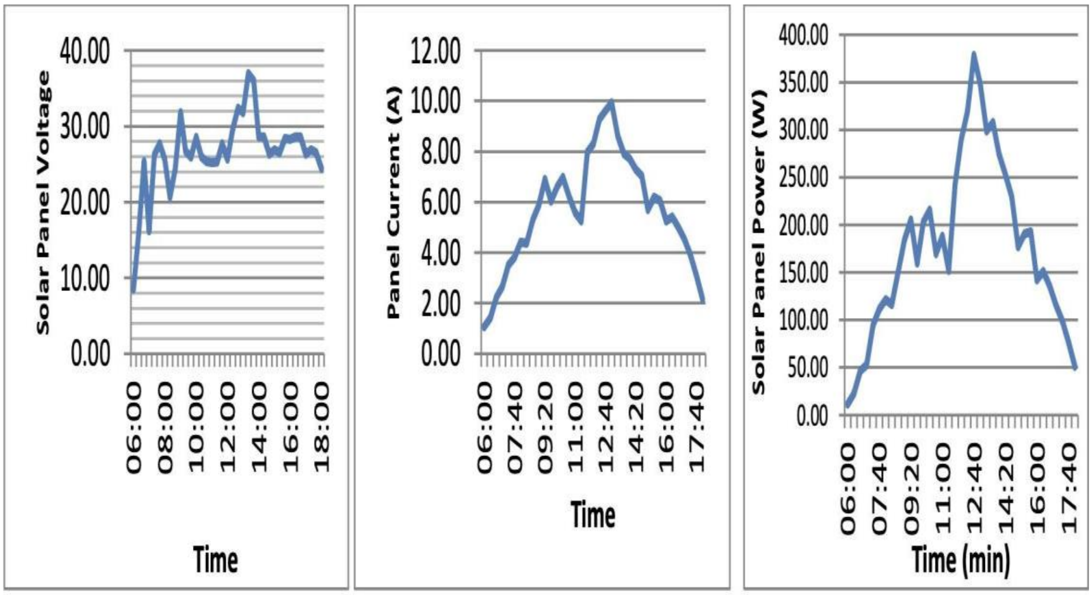
The goal is to:

- Use as much solar energy as possible,
- Reduce dependence on external electricity, and
- Follow safe operating rules, like not switching too quickly between charging and discharging.

An evaluation plan for this methodology involves running hypothetical annual simulations using historical weather datasets. The benchmark for success in these evaluations will be the system's ability to maintain a continuous baseline power output to the grid with zero loss-of-load events, while keeping the computational solution time of the daily UC problem under a 15-minute operational threshold

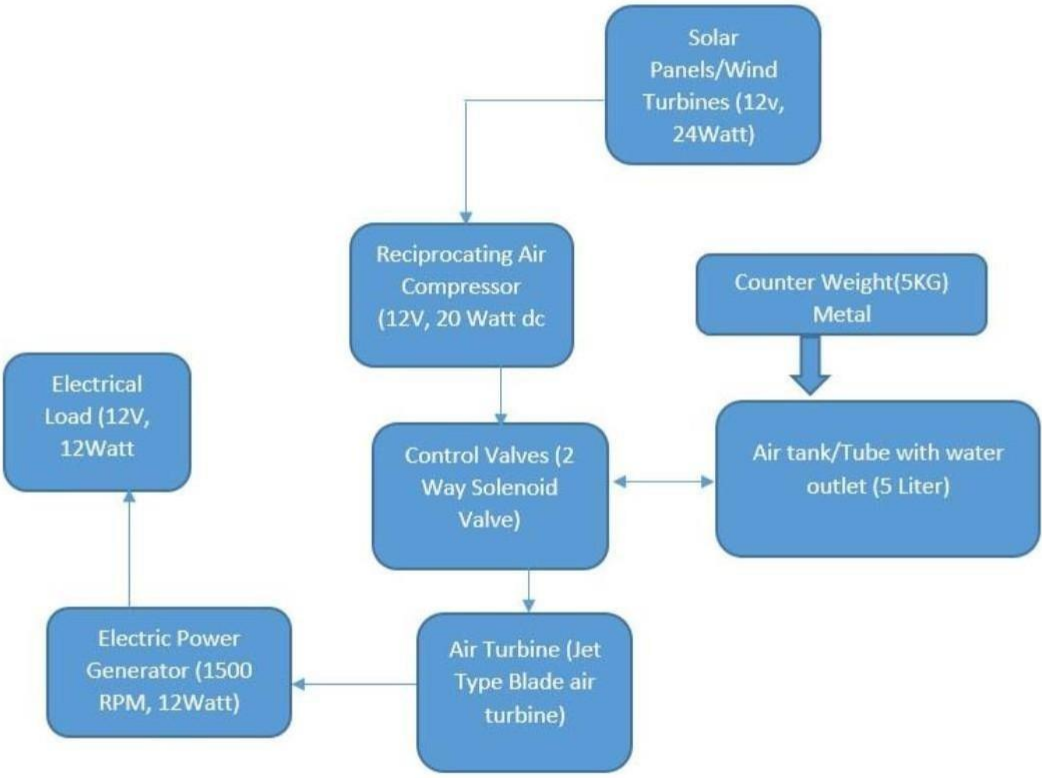
COMPONENTS AND SYSTEM SETUP

The set-up is as shown in Figure 3, consisting of components such as a solar PV array, DC motor, compressor, storage tank, air motor as a turbine and electric generator. a. Solar PV unit: this unit is an array of six 250W each amorphous PV panels, a PWM charge controller and a 24V/100Ah activation battery. While the PV array generates the required electrical power to continuously run the system, charge controller helps regulate the panel’s PV output to the motor. The battery is used to activate the DC motor by ensuring adequate activation current is available to drive the motor at start up. b. DC Motor: The DC motor serves as the prime mover for the compression stage. It helps to convert the DC electrical energy from the PV array to a mechanical power for driving the compressor. The motor used is a 24V/30Ah system, capable of delivering a torque of 60Nm at a speed of 2500rpm. c. Compressor: the compressor used is an 8bar, 1000rpm compression with a compression ratio of 5:1. d. Storage tank: the storage tank consists of three cylinders of 50kg each, providing a total air volume of approximately 120m3.These cylinders are connected in parallel between the inlet and outlet air piping. The cylinders are not however, lagged but are shaded and used in ambient temperature. e. Air turbine: the air turbine is a rotary vane air motor from Hongxin with an operational speed of 3000rpm, output torque of 4.1 N · m, and input air consumption of 78CFM. f. Electric generator: the generator used is a single-phase 2kVA, two (2) pole synchronous generator.



(a) (b) (c)

Fig. 4: (a) Average daily generated panel voltage (b) Average daily panel current (c) Average daily generated electrical power



Block Diagram

PERFORMANCE ANALYSIS

To check if this system works well in real life, we need to study two things:

- how efficiently it stores and uses energy, and
- how fast and smart the software makes decisions.

Energy Efficiency (Thermodynamic Performance):

The efficiency of this CAES system depends on how well it stores and uses heat. In older systems, a lot of heat is lost during air compression, and extra fuel is needed later, which reduces efficiency.

In this system, we carefully control how air flows and how heat is managed inside the storage tank. This helps reduce heat loss and improves overall performance.

Studies (simulations) show that:

- If air is compressed during peak solar hours, and
- The tank pressure is kept in the best range,

Then the system becomes much more efficient.

Also, 3D solar panels produce more steady solar energy throughout the day compared to normal flat panels. This means:

- More hours of good power generation
- Smoother operation of compressors
- Less damage and longer life of machines

Software Efficiency (Computational Performance):

The system also needs to make quick and correct decisions. Very complex models are slow and not practical for real-time use.

So, we simplify the system into an easier mathematical form. This allows the computer to quickly plan a full 24-hour schedule for:

- When to store energy (compress air), and
- When to use it (release air).

To make it even faster, the system uses the previous day's data as a starting point.

Because of this, operators can:

- Quickly test different situations
- Make fast decisions
- Adjust the system when the weather changes suddenly or solar power drops

In short:

The system is designed to be both energy-efficient and fast in decision-making, making it practical and reliable for real-world use.

RESULT AND DISCUSSION

Using advanced solar panels together with Adiabatic CAES can have a big impact on the future of energy.

Benefits:

Long-term energy storage is very important to reduce pollution and move away from fossil fuels. Instead of depending only on lithium-ion batteries, using underground air storage (CAES) allows energy to be stored for many days or even weeks.

As these systems grow bigger (from 10 MW to 100 MW), their cost keeps reducing, which makes them more attractive for large investments—especially in places with suitable underground structures.

When combined with high-efficiency 3D solar panels, companies can create power systems that:

- Run on clean energy
- Do not depend on fossil fuels
- Can supply stable electricity for long periods

Limitations and Risks:

1. Location Limitations:

CAES cannot be built everywhere. It needs special underground spaces like salt caves or old gas fields, so it is not as flexible as batteries.

2. Technical Risks:

If the heat storage system does not work properly or heat is lost, the system efficiency will drop. In some cases, parts like turbines may even freeze and get damaged.

3. Weather Dependency:

If there is bad weather (like many cloudy or snowy days for weeks), solar power generation will drop. This means the stored energy can run out, leading to the need for expensive backup power or even power cuts.

4. Environmental Risks:

Building large underground storage spaces can affect nature. It may:

Damage groundwater systems

- Cause saltwater contamination

- Lead to small earthquakes if not managed properly

5. Social and Land Use Issues:

Large projects may also create problems related to land use, local communities, and fair distribution of resources.

Large solar power plants need a lot of land, even if they use advanced 3D designs. Because of this, building these projects can force farmers or rural communities to leave their land. It can also disturb indigenous (native) communities. In many cases, these people may not get fair payment or proper benefits, and they might not even receive enough electricity from the project built on their own land.. Future work in this domain should address both the financial and physical barriers of the proposed framework. One critical area of future research is the integration of real-time, blockchain-enabled parametric solar energy insurance [6]. Since solar generation remains fundamentally weather-dependent, deploying zero-knowledge proofs and smart contracts via satellite remote sensing could allow CAES operators to automatically hedge financial risks and stabilize income during periods of poor weather [6]. Another avenue for future exploration is the development of artificial, deep-water offshore CAES systems.

Prototype Model of Solar-Based Compressed Air for Energy Generation

ENERGY LOSS

To identify potential points of energy loss through the system, thermal behaviour at various stages was considered. Energy loss reduces system efficiency as output power tends to be less relative to design effort. These losses may occur in different forms, more notably in heat and mechanical frictional forces. Frictional losses can be reduced by design and are usually minimal compared to heat energy losses. However, both heat and frictional losses can lead to each other in rotational parts, creating a resultant combination with grave losses and subsequent damage. Figures 5a and 5b indicate the energy losses in expansion and compression, respectively. These losses were, however, obtained as a measure of change in temperature in the component parts. Figure 6 compares compression and expansion losses and clearly shows that more energy loss takes place at compression.

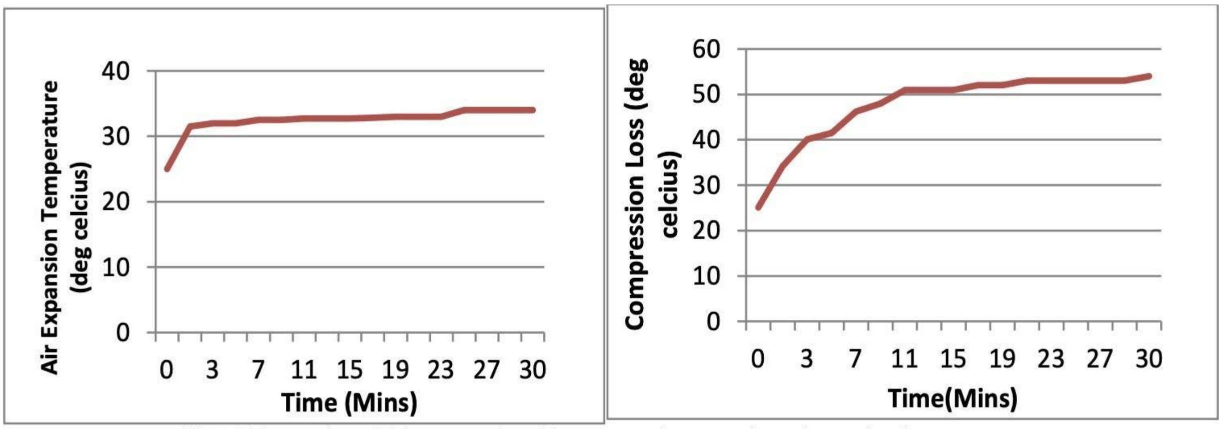
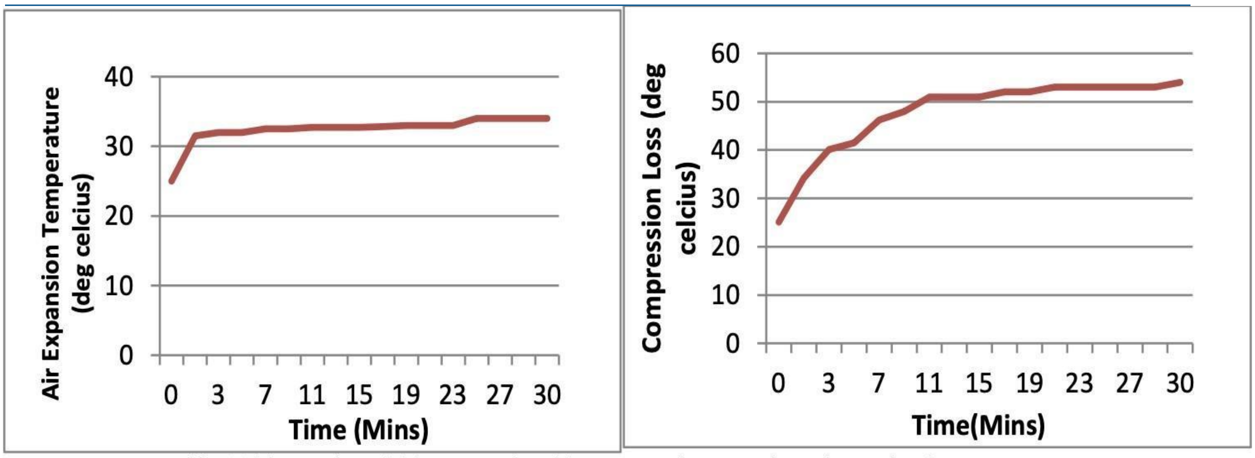


Fig. 5: Energy loss (a) in expansion (b) compression over time due to rise in temperature



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CONCLUSION

The transition toward a carbon-neutral global economy inherently relies on our ability to harness and continuously dispatch renewable energy, the complex unit commitment problem. Large solar power plants need a lot of land, even if they use advanced 3D designs. Because of this, building these projects can force farmers or rural communities to leave their land. It can also disturb indigenous (native) communities. In many cases, these people may not get fair payment or proper benefits, and they might not even receive enough electricity from the project built on their own land. This system carefully controls how heat and pressure behave inside underground air storage, making sure everything stays within safe limits. Overall, combining smart prediction (machine learning), efficient 3D solar panels, and well-managed compressed air storage is a very good solution for storing energy for a long time. There are still some challenges, like needing special underground locations and high initial costs, but the system can become cheaper over time and can store large amounts of energy for many days.

With more research, the system can become even more efficient. New financial tools, like insurance for solar power losses due to bad weather, can also reduce financial risks and make these projects more attractive for investors. In addition, small-scale air storage systems can help provide electricity in remote rural areas, especially in developing countries. Although some energy is lost as heat, this method shows that electricity can still be produced using stored compressed air. With improvements like better heat recovery (adiabatic processes), this technology can become a low-cost and practical solution for providing energy in remote locations.

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