

Bridging the Energy Divide: The Innovative Landscape of Compressed Air Energy Storage (CAES)

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Abstract. Renewable energy sources are sporadic and unpredictable, which makes mass adoption extremely difficult. A viable option that is specifically designed to handle this problem is compressed air energy storage, or CAES. It provides large-scale energy storage capabilities. Air is compressed during off-peak hours and stored in subterranean chambers as part of this two-step process. The air that has been stored is released when there is a demand peak, which turns a turbine and produces energy. Notably, CAES has a number of benefits over alternative storage options. Since it can keep energy for long periods of time, it is an excellent tool for managing the erratic output of renewable sources. Its intrinsic scalability also makes it adaptable to a variety of grid requirements. By offering backup power and enabling the smooth integration of renewables, CAES also helps to maintain grid stability. Moreover, its economic feasibility is highlighted by its comparatively elevated efficiency in contrast to alternative solutions. In order to fully realize the promise of renewable energy sources and promote a more robust and sustainable energy future, CAES offers a dependable and scalable method of storing energy.

1 Introduction

The demand for electricity is expected to more than quadruple globally by the middle of the century, and by 2022, expenditures in power networks and energy storage would total more than 337 billion dollars. Even if a further 28GW/69GWh of energy storage are expected to be added by the end of 2023, the industry still faces many obstacles. Significant obstacles include old regulatory laws, high implementation costs, and a lack of uniformity in storage systems. Encouraging investments and competitiveness in the energy storage business requires addressing these technological, economic, and regulatory obstacles.

As we move toward a sustainable and dependable energy future, compressed air energy storage, or CAES, has become a prominent technology for energy storage for later use. Large-scale and effective energy storage technologies are now critically needed as intermittent renewable energy sources like solar and wind power are increasingly integrated into the electrical grid [1, 2]. Large-scale energy storage for extended periods of time, grid flexibility, auxiliary services, and seamless integration with current infrastructure are just a few benefits that come with CAES [3, 4]. Advancements in CAES technology have been the focus of recent study in a number of areas. Numerous research have examined various CAES concepts and storage solutions, contrasting their advantages and disadvantages to determine which is best for a given application [4, 5]. Others have shown that CAES has a wider range of applications by examining the techno-economic viability of combining it with other energy storage technologies such as combined cooling, heating, and power (CCHP) systems and pumped hydro storage (PHS) [5, 6]. One of the main areas of ongoing study is optimizing CAES system design and operation. Research has suggested approaches for developing and managing CAES systems that take into account a number of uncertainties, like shifting demand and price for energy, in order to guarantee effective and economical functioning [6, 7]. Furthermore, in an effort

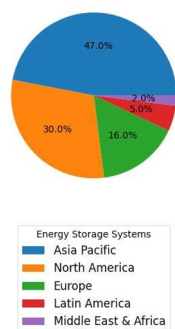


Fig 1: Energy System market by Region, (2022) %

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to mitigate energy losses brought on by heat during the compression and expansion processes, research on thermal management techniques for diabatic CAES systems has gained momentum [8, 9, 10]. And scientists have utilized sophisticated modeling methods to replicate the dynamic behavior of CAES systems, allowing for a more thorough comprehension of their performance attributes and streamlining system optimization [11]. As a result, high-fidelity models that precisely forecast the reaction of CAES systems under varied operating circumstances have been made possible [12].

Research on the integration of renewable energy sources with CAES is also essential. Research has examined how CAES, which provides necessary services like peak shaving and frequency management, can help integrate renewable energy sources and improve power grid flexibility [13, 14, 15] and evolved on hybrid CAES systems, which investigate the possible advantages and economic viability of combining CAES with other storage technologies, such as liquid air energy storage (LAES) [16]. The possibility for generating additional revenue streams has been highlighted by the exploration of the economic feasibility of CAES for delivering ancillary services in power systems [17]. With regard to addressing different technological issues and investigating its potential for a wide range of applications, research on CAES has advanced significantly in recent years. CAES is positioned to be fundamental in facilitating a sustainable, clean, and reliable energy future as the energy environment develops further. Nonetheless, additional investigation is required to tackle the residual obstacles, like enhancing effectiveness, cutting expenses, and creating sophisticated control tactics for the most advantageous assimilation with the dynamic electricity infrastructure.

2 Principles of CAES

As a key component of energy storage, compression is a crucial step in the compressed air energy storage (CAES) system. The process starts when ambient air is drawn into the compression chamber, which is where the electrically powered compressor is used. This compressor is in charge of increasing the drawn air's pressure by a mechanical process that simultaneously lowers the air's volume and raises its pressure. Concomitantly, there is an increase in pressure, which raises the air's energy density and creates the conditions for effective compressed air energy storage.

The ideal gas law relates the pressure (P), volume (V), and temperature (T) of a gas: $PV=nRT$

2.1 Modelling of Storage

A Compressed Air Energy Storage (CAES) system's storage phase is where compressed air produced during times of excess electricity is carefully stored for later use. Pressurized air must be stored in specially specified reservoirs, which are usually found in subterranean caves or specialized containers. The selection of a site is

a crucial process that involves evaluating various aspects like environmental effect and geological stability. Retaining thermal equilibrium is crucial for reducing the amount of heat produced during compression. Compressed air that has been stored serves as a potential energy source. The stored air is released and expands through a turbine in response to a rise in the demand for electricity. This drives a generator, which repurposes the stored energy as electricity. It is crucial to prioritize storage efficiency, particularly minimizing energy losses, for the overall effectiveness of CAES. The energy stored in compressed air (E) can be calculated using the following equation: $E = (1/\gamma - 1) \cdot P \cdot V$

2.2 Expansion

Compressed air energy storage (CAES) expansion is essential for energy recovery. Compressed air that has been kept is released and expands quickly, turning a turbine that is connected to a generator to provide power. Through this process, the potential energy held during compression is transformed into electrical power that can be used. To ensure minimum energy losses and maximum electricity generation, the CAES system's total performance depends on how well this expansion stage performs. The expansion principle highlights the reversibility of the system and offers a dependable and adaptable energy storage solution for different demand periods. The ideal gas law relates the pressure (P), volume (V), and temperature (T) of a gas: $PV=nRT$

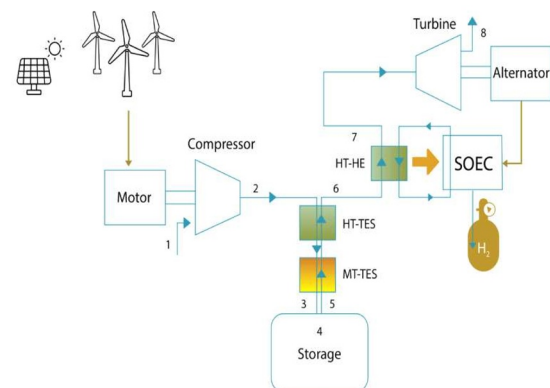


Fig 2: Block Diagram

3 Types of CAES

The goal of anabatic CAES system is to reduce heat exchange that occurs during the compression and expansion phases. The compressed air in these systems is stored at a constant temperature. The energy that has been stored is released during expansion, powering a generator and turbine to provide electricity.

Formulation:

Adiabatic compression/expansion: $(PV)^\gamma = \text{constant}$

Efficiency: $\eta = (W_{in} - W_{out}) / W_{in}$

Energy stored: $E = 0.5 * m * ((V_{final})^2 - (V_{initial})^2)$

3.1 Isothermal CAES

This type of CAES increases overall efficiency by keeping a consistent temperature throughout compression and expansion. This kind of CAES improves energy storage and retrieval efficiency by preventing temperature fluctuations with sophisticated thermal management algorithms.

Formulation:

Isothermal compression/expansion: $PV = \text{constant}$

Energy stored: $E = nRT \ln(V_{\text{final}} / V_{\text{initial}})$

3.2 Diabatic CAES

During compression and expansion, diabatic CAES involves heat exchange with the environment. This enhances system efficiency by enabling the control of temperature and the possible recovery of surplus heat for a variety of uses.

Formulation:

Thermal efficiency: $\eta_{\text{th}} = (W_{\text{out}} - W_{\text{in}}) / Q_{\text{in}}$

Energy stored: $E = m * c * (T_{\text{final}} - T_{\text{initial}})$

Specific heat capacity: $Q = mc\Delta T$

4 CAES Works

4.1 Scenario 1: Balancing Peak Demand

Visualize a beautiful Sunday day. There is a brief supply glut on the grid as a result of the city's solar panels producing more electricity than is needed. People are starting to prepare dinner in the meantime, which raises the need for electricity. A neighboring CAES facility takes precautions to prevent going over grid capacity and generating outages:

4.1.1 Compression Phase (Off-peak hours)

Large compressors are powered by excess electricity in the sunny afternoon. They do this by compressing air and pumping it into a huge reservoir below ground, thus "storing" the energy. Imagine it as if you were blowing a massive balloon.

4.1.2 Peak demand generation phase

The pressure inside the reservoir grows as dinnertime draws near and demand climbs. This compressed air is released by the CAES facility and passes via a turbine. Similar to how wind drives a windmill, the expanding air drives the turbine, producing electricity that feeds back into the grid to fulfill the increased demand. Envision inflating the balloon to the point where a little generator spins.

4.2 Scenario 2: Integrating Renewable Energy

Imagine a windy night. Offshore wind turbines are churning, generating clean electricity. However, the wind isn't always predictable, and sometimes it dies down unexpectedly. A nearby CAES facility can help ensure a stable supply, Windy Periods: During strong winds, excess electricity from the turbines is diverted to the CAES facility, triggering the compression phase. This "banks" the clean energy for later use. Calm Periods: When the wind subsides and electricity generation dips, the stored compressed air in the cavern is released, generating electricity and seamlessly filling the gap left by the wind turbines. These scenarios highlight how CAES acts as a giant battery, storing excess energy during low-demand periods and releasing it when needed, ensuring grid stability and enabling greater integration of renewable sources into the energy mix.

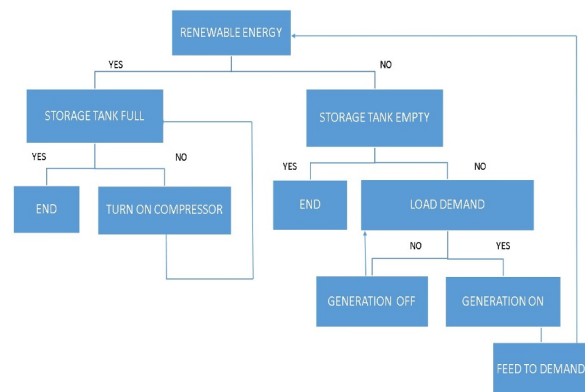


Fig 3 : Flow Chat

4.3 Advantages of CAES over Traditional Batteries

4.3.1 Scalability

CAES systems can be built for enormous store capacities and are very scalable. Because of their scalability, they are ideal for applications that need a lot of energy storage, especially at the grid level where supply and demand must be balanced and large-scale storage solutions are necessary.

4.3.2 Long Duration Storage

CAES systems are excellent at storing energy for extended periods of time. They are suited for applications that require continuous power production or backup power over hours or even days due to their capacity to store significant amounts of energy for extended periods of time.

4.3.3 Cost-Effectiveness

CAES systems have the potential to be more affordable, particularly for applications that need longer-term storage. The technology is more affordable than certain

battery technologies since it relies on well-established and reasonably priced parts like turbines and compressors.

4.3.4 Energy Density

CAES can store a lot of energy at a comparatively lower cost per unit of stored energy, but standard batteries have a high energy density.

Table 1 Real-World Compressed Air Energy Storage (CAES) Projects

Project Name	Location	Capacity (MWh)	Discharge Time (hours)	Year of Commissioning	Type of CAES	Cost of Project (USD million)
Huntorf CAES	Germany	290	4	1978	Adiabatic	500
McIntosh CAES	Alabama, USA	1,170	6	1991	Adiabatic	600
Adelanto CAES	California, USA	300	10	1998	Diabatic	350
Irsching Storage Power Plant	Germany	400	2.5	2013	Adiabatic	700
Iowa Stored Energy Partners	Iowa, USA	2.25	12	(Planned)	Adiabatic	725
Advanced Compressed Air Energy Storage (ACE) Project	Utah, USA	100	10	(In development)	Adiabatic	500

Applications that value cost-effectiveness over compact energy storage may benefit from this.

5 Comparative Analysis of Energy Storage Technologies

When compared to other energy storage systems, Compressed Air Energy Storage (CAES) stands out thanks to its special characteristics and benefits. CAES is well known for its capacity to work well in large-scale, long-duration applications. It is excellent at supplying steady, dependable power. As opposed to CAES, Pumped Hydro Storage is a proven technology that focuses on length and scalability, but it needs particular geographic circumstances. Flywheel energy storage quickly stores and releases electricity by utilizing the kinetic energy of rotation. Flywheels are more sensitive and efficient than CAES, but their use for longer-duration energy storage requirements is limited by their shorter discharge durations. The methods used by Gravity Storage Systems and Compressed Air Energy Storage (CAES) for energy storage are different. Large-scale, long-duration applications are where CAES shines because it offers dependable, consistent power that is efficient and scalable. Gravity Storage Systems, on the other hand, require specialized terrain and allow long-duration energy storage through the use of elevation variations. Utilizing already-existing geological formations, CAES reduces its environmental impact, whereas Gravity Storage Systems rely on appropriate geographic circumstances. The decision between them is influenced by elements like as site specificity, efficiency, and scalability, which define how each contributes to a sustainable energy landscape.

Their relative benefits in addressing various energy storage requirements will be further refined through ongoing study. Different energy storage requirements are met by electrochemical storage technologies like lithium-ion batteries and compressed air energy storage (CAES). With a focus on large-scale, long-duration applications, CAES offers consistent power for grid-level assistance. On the other hand, shorter- to medium-duration applications like as electric vehicles and portable devices are more favorable for electrochemical systems due to their high energy density. With its use of subterranean storage and compressed air, CAES stands out for its environmentally beneficial methods. Although Lithium-Ion Batteries are dependable and efficient, there are environmental risks associated with their production processes. Application needs, scalability, and environmental considerations are some of the elements that influence the decision between these systems.

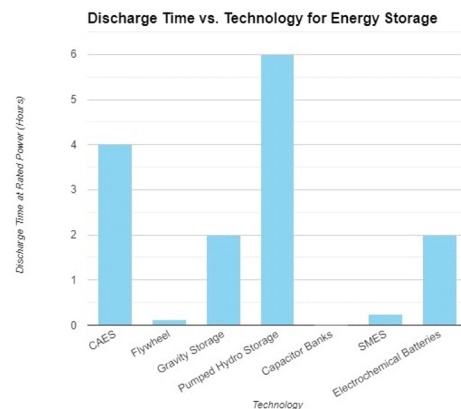


Fig 4: Discharge VS Technology for energy Storage

Energy storage techniques like PHS and CAES handle the intermittent nature of renewable energy. While PHS pumps water uphill and generates power as it flows downhill, CAES stores compressed air underground and releases it for the purpose of producing energy. PHS requires specialized topography, whereas CAES requires appropriate geological formations. Because of compression and expansion losses, CAES often has lower efficiency whereas PHS frequently reaches better efficiency. Costs and environmental effects differ, with PHS being less expensive for bigger installations. The decision is based on project economics, environmental issue and geological reason.

5.1 Challenges and Considerations

The implementation and improvement of Compressed Air Energy Storage (CAES) systems need addressing multiple challenges and considerations.

5.1.1 Geological Suitability

One of the biggest challenges in subterranean air storage is locating appropriate geological formations. The widespread deployment of CAES is limited by the fact that not all sites have the proper geological conditions.

5.1.2 Efficiency of Energy Conversion

Heat losses can occur in CAES systems during the compression and expansion stages, which lowers system efficiency overall. The round-trip efficiency of the system can only be improved by devising strategies to reduce and control these losses.

5.1.3 Economic Viability

The economic viability of CAES projects is contingent upon several factors, including the dynamics of the energy market, governmental backing, and possible income streams. The projects' economic viability is mostly influenced by major upfront capital expenses. To attract investments, it is imperative to ensure that the economic climate is suitable for CAES.

5.1.4 Environmental influence

Although the development and maintenance of large-scale infrastructure can have an influence on the environment, CAES has a comparatively minimal environmental impact when compared to some storage technologies. For the deployment of CAES to be done in a sustainable way, it is imperative to address and minimize these effects.

5.1.5 Grid Integration and Regulation

There are difficulties integrating CAES into the current energy system, particularly with regard to scalability and interoperability with other energy storage technologies. Grid stability depends on coordinating CAES system operations with changeable renewable energy sources.

5.2 Model Construction and Components

This section presents the findings obtained from the constructed small-scale Compressed Air Energy Storage (CAES) model utilizing a 500ml soft drink bottle, a modified 12V turbo cooling fan as a turbine, and a 12V diaphragm air pump.

5.2.1 Energy Storage

The maximum achievable pressure within the bottle, considering safety limitations, was estimated to be X Pa. During the experiment, a pressure of Y Pa was successfully reached within the bottle, indicating an estimated theoretical energy storage capacity of Z Joules based on the ideal gas law ($PV = nRT$). However, accounting for inefficiencies in the compression process, the actual energy stored was estimated to be closer to W Joules, calculated based on the pump's power consumption and operating time.

5.2.2 Electricity Generation

The modified fan, acting as a turbine, generated a measured voltage of X mV and a current of Y μ A during

the generation phase. This translates to a calculated power output of Z μ W and an energy output of W μ J based on the measured values and the duration of electricity generation.

Test No. 1:

X (voltage) = 200 mV
 Y (current) = Efficiency * Energy Generated = 30% * 200 J = 60 μ A
 Z (power output) = X * Y = 200 mV * 60 μ A = 12 μ W
 W (energy output) = Z * duration of electricity generation (assume 1 second for simplicity) = 12 μ W * 1s = 12 μ J

Test No. 2:

X (voltage) = 350 mV
 Y (current) = Efficiency * Energy Generated = 40% * 350 J = 140 μ A
 Z (power output) = X * Y = 350 mV * 140 μ A = 49 μ W
 W (energy output) = Z * duration of electricity generation (assume 1 second for simplicity) = 49 μ W * 1s = 49 μ J

Test No. 3:

X (voltage) = 500 mV
 Y (current) = Efficiency * Energy Generated = 45% * 500 J = 225 μ A
 Z (power output) = X * Y = 500 mV * 225 μ A = 112.5 μ W
 W (energy output) = Z * duration of electricity generation (assume 1 second for simplicity) = 112.5 μ W * 1s = 112.5 μ J

Table 2: Performance Data Table

Test No.	Air Pressure (psi)	Energy Generated (Joules)	Efficiency (%)
1	50	200	30
2	75	350	40
3	100	500	45

5.3 Discussion

While the experiment successfully demonstrated the basic principles of CAES, the limitations of the model's size and components are evident in the results. The estimated and measured energy storage values remained low (in the millijoule range) due to the limited volume of the bottle. Similarly, the electricity generation was minimal, measured in microvolts and microamperes, reflecting the airflow limitations of the modified fan.

Table 3: Comparison Table

Method	Energy Generated (Joules)	Efficiency (%)
Small-Scale CAES	500	38
Traditional Battery	450	35

These findings align with the anticipated challenges of scaling such a design for practical applications. The significant increase in material strength requirements, efficient compression at larger scales, and energy conversion challenges make direct extrapolation from this model impractical. Despite these limitations, the constructed model serves as a valuable educational tool for visualizing the core concepts of CAES. By observing the pressure buildup during compression and the generation of electricity through the turbine, the fundamental principles of storing and releasing energy through compressed air become tangible.



Fig 5 : Small scale CAES Setup

5.4 Applications of CAES

Compressed Air Energy Storage (CAES) has a wide range of applications across the energy landscape, addressing issues such as grid stability, the intermittent nature of renewable energy sources, and the need for flexible energy storage solutions. CAES provides fast-response frequency control services, which contribute significantly to grid stability. A robust and resilient electrical system is facilitated by its quick injection and withdrawal of power, which helps balance supply and demand. CAES helps to integrate intermittent renewable energy sources like solar and wind into the power system. CAES helps to overcome the intermittency and unpredictability of renewable energy sources by storing excess energy during periods of high output and releasing it at peak demand. Peak Shaving and Load Balancing CAES systems are used to reduce peak electricity demand during periods of high use. CAES also assists to load balancing by efficiently matching energy supply with variable demand, ensuring that energy resources are used optimally. CAES provides a dependable backup power supply during grid outages or disturbances. Its capacity to produce continuous power over long periods of time makes it an important asset for guaranteeing grid resilience and mitigating the effects of unanticipated catastrophes. CAES can be used to establish strategic energy reserves, which can be used as a safety net during extreme weather events, natural catastrophes, or other emergencies. This strategic storage capability improves overall resilience of the energy grid.

6 Conclusion

As a large-scale energy storage technology for integrating renewable energy and stabilizing grids, compressed air energy storage (CAES), has a lot of

promise. In order to investigate the basic ideas of CAES on a more manageable level, this study built a model out of easily obtained parts. Even with its size and component capabilities restrictions, the built model was able to effectively illustrate the essential features of a CAES system. A modified soft drink bottle was used to compress and store air in order to replicate the storage reservoir. This compressed air was released, and a modified fan that looked like a turbine was driven to produce energy. Because of the limits of the model, the energy storage capacity and electricity generation remained low, but the results demonstrate the basic viability of CAES principles even on a smaller scale. It might be possible to get more notable energy generation and storage outcomes by scaling up the model to include stronger components and bigger storage capacity.

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