PDHonline Course E365 (4 PDH)

Compressed Air Energy Storage

Instructor: Lee Layton, PE

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
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Compressed Air Energy Storage

Lee Layton, P.E

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Credits

The line drawing on the cover page is courtesy of the Dresser-Rand Corporation. Some of the material in this course is based on a DOE report, Handbook of Energy Storage for Transmission & Distribution Applications, 2003.

Introduction

Large quantities of electrical energy cannot be stored. Since the advent of the electric power industry, engineers have looked for ways to store energy for consumption at a later time. At the present, we really have only practical two choices to store energy; Pumped Storage Hydro-electric power or Compressed Air Energy Storage (CAES). The Electric Power Research Institute (EPRI) says that lithium-ion batteries are okay for electric vehicles and flywheels can store energy in short bursts. New technologies like flow batteries are emerging but they're still years away from utility-scale cost requirements. Pumped hydro is very site-specific and very little new pumped hydro sources have come on line in the last decade. Compressed Air Energy Storage, or CAES, is one of the few practical methods to store energy.

Compressed Air Energy Storage (CAES) is the term given to the technique of storing energy as the potential energy of a compressed gas. Usually it refers to air pumped into large storage tanks or naturally occurring underground formations.

While the technique has historically been used to provide the grid with a variety of ancillary services, it is also gaining attention as a means of addressing the intermittency problems associated with wind turbine electrical generators. When energy is available, it is used to run air compressors which pump air into the storage cavern. When electricity is needed, it is expanded through conventional gas turbine expanders. Note that some additional energy (typically natural gas) is used during the expansion process to ensure that maximum energy is obtained from the compressed air (albeit as much as 67% less gas than would be used for an equivalent amount of electricity using gas turbine generators without CAES).

With Compressed-Air Energy Storage (CAES), energy generated during periods of low energy demand can be released to meet higher demand periods. Off-peak electrical power compresses air into an underground air-storage “vessel”, and later the air feeds a gas-fired turbine generator complex to generate electricity during on-peak times.

Figure 1, shown on the following page, is a conceptual representation of a compressed-air energy storage system.

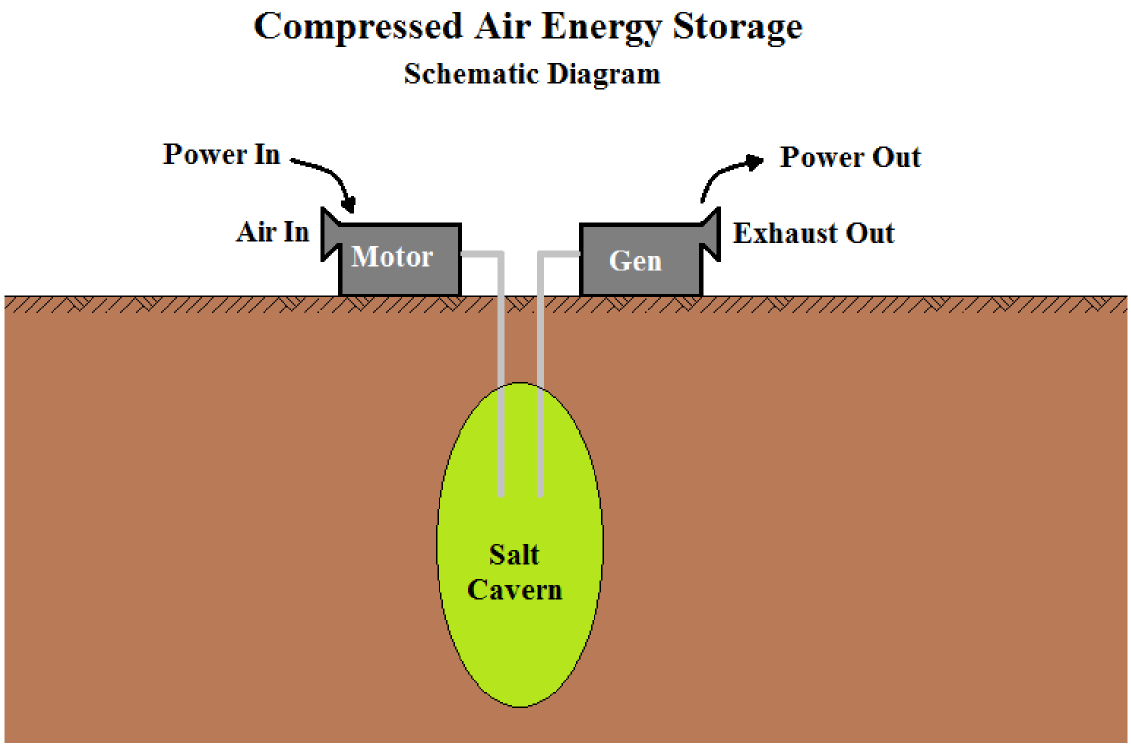


Figure 1

CAES technology uses low cost, off-peak energy to run a compressor train to create compressed air, which it stores, usually in an underground cavern, the air is then released during peak load hours and heated with the exhaust heat of a standard combustion turbine in an air bottoming cycle. This heated air is converted to energy through expansion turbines to produce electricity. Various power augmentation procedures can be added at this point (including air injection and inlet chilling), taking advantage of the cooled air, creating “free” megawatts.

History

City-wide compressed air energy systems began operation in the 1870’s to power machinery in cities such as Paris, France, Birmingham, England, and Dresden, Germany. These systems quickly evolved to deliver power to homes and industry. By 1896, the Paris system had 2.2 MW of generation distributed at 80 psi in 30 miles of air pipes for motors in light and heavy industry. Usage was measured by meters. The systems were the main source of house-delivered energy and also powered the machines of dentists, seamstresses, printing facilities and bakeries.

The technological concept of compressed air energy storage for electric power generation is more than 40 years old. CAES was seriously investigated in the 1970’s as a means to provide load following and to meet peak demand while maintaining constant capacity factor in the nuclear power industry.

In 1978, the first utility-scale compressed air energy storage project, the 290 megawatt Huntorf plant, began operation in Germany. The 290 MW Huntorf plant, located in Bremen, Germany, is used to provide peak shaving, spinning reserves and VAR support. A total volume of 11 million cubic feet is stored at pressures up to 1,000 psi in two underground salt caverns, situated 2,100-2,600 feet below the surface. The Huntorf plant requires 12 hours of off-peak power to fully recharge, and then is capable of delivering full output for up to four hours and some additional power for another 10-hours.

The second plant was the 110 megawatt McIntosh plant in Alabama, which was built in 1991. The McIntosh plant is used to store off-peak power, generate peak power and provide spinning reserves. Approximately 19 million cubic feet is stored at pressures up to 1,080 psi in a salt cavern up to 2,500 feet deep and can provide full power output for 26 hours. This system recovers waste heat which reduces fuel consumption by approximately 25% compared to the Huntorf Plant.

Key Features

In CAES systems, electricity is used to compress air during off-peak hours when low-cost generating capacity is available. Electricity is cheapest in the middle of the night and by running air compressors, air can be pumped into a cavern or vessel. In the daytime, when the price of electricity is expensive, the compressed air is preheated with the heat generated and stored during compression and then used to help power a turbine.

For power plants with energy storage in excess of approximately 100 MWh or five hours of storage, the compressed air is most economically stored underground in salt caverns, hard rock caverns, or porous rock formations. A CAES plant with underground storage must be built near a favorable geological formation. Above ground compressed air storage in gas pipes or pressure vessels is practical and cost effective for storage plants with less than about 5 hours of capacity, however some above ground systems with up to about 10 hours of storage may be economically attractive depending on plant design and site conditions.

The project lead times for CAES plants are typically not more than three years, including development, design, construction, and startup. For example, the contract for the 110 MW McIntosh plant was signed on June 1, 1988, and the plant was commissioned on June 1, 1991. For smaller plants, the construction time is about one year. Table 1 shows some of the common parameter ranges for CAES plants.

Table 1

Key Features

Compressed Air Energy Storage

(100 MW Plant)

Feature	Parameter Range
Space Requirements	1 Acre
Efficiency	85%
Life	30 years
Maintenance	Comparable to CCGT
Environmental Impact	Minimal (below 5ppm for NOx
Auxiliary Equipment	Water for wet cooling
Power Conditioning Needs	None

Compressed-Air Energy Storage (CAES) is relatively low efficiency and costs about $1,000 per kilowatt of storage. The 290 MW Huntorf plant functions primarily for cyclic duty, ramping duty, and as a hot spinning reserve for the industrial customers in northwest Germany. Recently, this plant has been successfully leveling the variable power from numerous wind turbine generators in Germany.

The PowerSouth McIntosh CAES facility performs a wide range of operating functions; namely,

- Load management
- Ramping duty
- Generation of peak power
- Synchronous condenser duty
- Spinning reserve duty

CAES is less complex and cheaper to construct and operate than a combined cycle. Energy arbitrage is a large value driver of a CAES plant, as it uses cheaper off-peak power combined with minimal fuel, to provide on-peak power, usually at a significant spark margin to the market clearing on-peak price. CAES provides exceptional ancillary service value, as its speed and flexibility allow for area regulation, synchronized spinning, non-synchronized reserve and other ancillary services.

CAES can optimize use of transmission system through storing power for better line loading. CAES can defer upgrade of transmission and manage peaks. CAES is very reliable generation resource. Two thirds of the generation is from the release of compressed air.

Environmental considerations, as always, are location specific but in general there are less environmental concerns for permitting a CAES plant than for a new combined cycle. The combustion turbine emissions are diluted with the output of the air cycle, reducing emissions by roughly one-third and since there is no steam cycle, limited water is needed. Cavern permitting is well developed for the mining and gas storage industries and the humid air injection process lowers NOx emissions.

CAES plants start reliably more than 90 percent of the time and have 95 percent operating reliability. CAES plants can be brought to full load in less than 10 minutes.

In this course, we will look at some of the technical aspects of compressed-air storage systems, including storage options and the state of the art in CAES designs. In Chapter One we look at the Huntorf and McIntosh plants in more detail as well as a few of the planned projects for the future. Chapter Two discusses the storage options for CAES systems, and Chapter Three delves into CAES designs. Finally, Chapter Four reviews the advantages and disadvantages of Compressed-Air Energy Storage systems.

Chapter 1
Current and Planned Designs

As of 2012, there were only two operational CAES plants in the world; however, there are several plants in the planning stages.

Huntorf Plant

The Huntorf plant, Figure 2, was the first compressed air storage power station in the world. It began commercial operation December 1978. Today, E.ON Kraftwerke of Bremen, Germany owns the 290 MW CAES plant in Huntorf, Germany. ABB was the main contractor for the plant. The compressed air is stored in two salt caverns between 2,100 and 2,600 feet below the surface with a total volume of 11 million cubic feet. The caverns have a maximum diameter of about 200 feet and a height of 500 feet. The cavern air pressure ranges from 620 to 1,010 psi. At the compressor airflow rate of 187,000 scfm, the plant requires 12 hours for full recharge. At full power, the turbine draws 720,000 scfm of airflow from the caverns for up to 4 hours. After that, the cavern pressure is too low to allow generation at 290 MW and the airflow supplied by the caverns decreases although the plant will produce power at an exponentially declining power level for over 10 more hours.

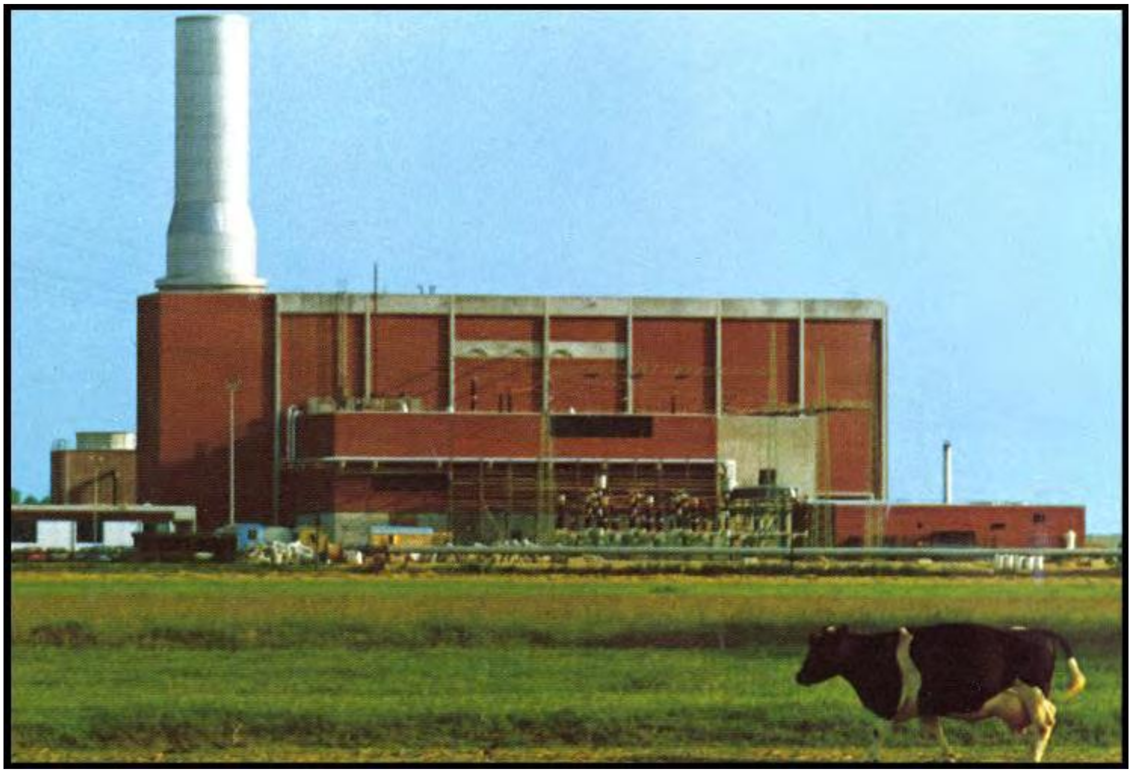


Figure 2

McIntosh Plant

The 110 MW McIntosh plant, shown in Figure 3, which is owned by the PowerSouth Electric Cooperative, is the second CAES power plant in the world, and the first in the United States. Dresser-Rand designed and constructed the entire turbo-machinery train. The overall plant (turbo-machinery, building, and underground cavern) was constructed in less than three years for a cost $51 million and was completed on June 1, 1991. The air is compressed in three stages, each followed by an intercooler. The compressed air is stored in a salt cavern between 1,500 and 2,500 feet below the surface with a total volume of 19 million cubic feet, yielding a power generating duration of 26 hours at full power and at 267,000 scfm. The cavern air pressure ranges from 650 to 1,080 psi during normal operation. The reheat turbo-expander train has high and low pressure expanders with high and low pressure combustors and drives the electric motor/generator to produce peak electric power. Dual-fuel combustors are capable of burning natural gas or fuel oil. An advanced recuperator is used to extract thermal energy from the low-pressure expander exhaust to preheat inlet air from the storage cavern before it goes to the inlet of the high-pressure combustor. The recuperator reduces fuel consumption by approximately 25%.

Figure 3

Norton Plant

First Energy is planning a 2,700 MW CAES plant. This plant, formerly known as the Norton CAES power plant, Figure 4, will be the world's largest when it is fully completed. It is anticipated that the first 268 MW unit will come on line later in this decade. The site, which is in Norton, Ohio, is located on a limestone mine. The compressed air is stored in an abandoned limestone mine at a depth of 2,200 feet below the surface with a total volume of 338 million cubic feet. The cavern air pressure will range between 800 to 1,600 psi during operation.

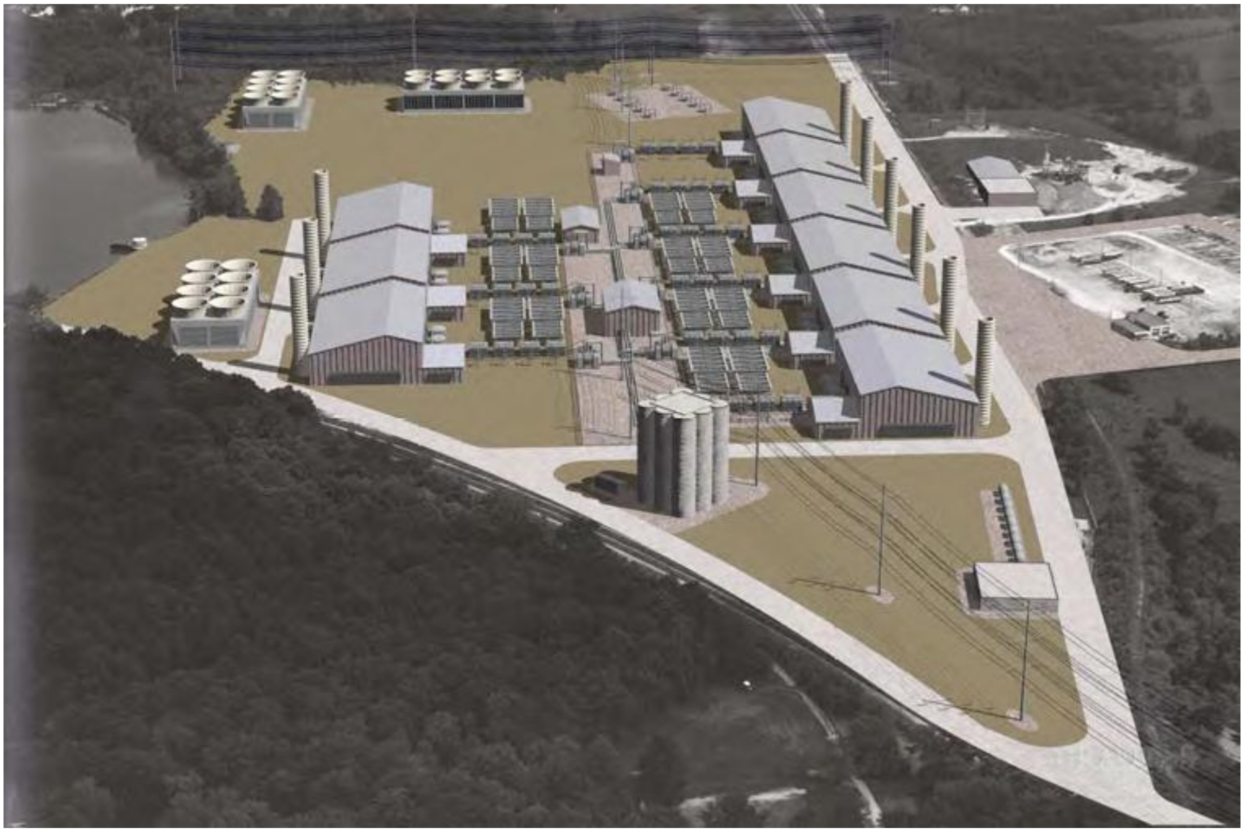


Figure 4

Matagorda Plant

Houston-based Ridge Energy Storage had planned a 540 MW CAES plant in Matagorda, Texas, but as of the present time the plant is on hold. The plant was based on an upgraded version of the Dresser-Rand design utilized at the McIntosh plant. The design called for four independent 135 MW power train modules; each of which could reach full power in 14 minutes.

The compressed air was to be stored in a previously developed brine cavern and delivered to the expander at a pressure of 700 psi and a flow rate of 400-407 lb/sec. The heat rate of the Matagorda plant at full load was expected to be 3,800 Btu/kWh, and at 20% of full load, the plant heat rate was anticipated to be 4,100 Btu/kWh. The total cost of the plant was estimated to be $243 million or $450 per kilowatt.

The future status of this plant is uncertain at this time.

Chapter 2
Storage Facilities

Compressed Air Energy Storage systems need a suitable storage vessel for the compressed air. Generally this storage is in underground geologic foundations. The storage medium is dictated by where the CAES facility needs to be located, how much storage is required, and how much space is required for the type of plant design.

The storage site must be in a stable geologic formation that is well sealed and can withstand the repeated pressure cycles required for a CAES system.

The Electric Power Research Institute (EPRI) has determined that up to 80 percent of the United States has geology suitable for CAES. EPRI says that a single 300MW CAES plant would require about 22 million cubic feet of storage space; this storage space would yield eight hours of electricity.

In general, a geological formation suitable for underground air storage must meet the following requirements:

- The formation must have sufficient depth to allow safe operation at the required air pressure.

- For porous rock formations, the storage zone must be sufficiently porous to provide the required storage volume at the desired pressure and sufficiently permeable to permit the desired airflow rates. In addition, the over-burden and adjacent geological formations must have sufficient structural integrity to contain the air vertically and laterally; that is, the storage zone must be overlain by an impermeable rock layer to prevent the air from leaving the storage zone and escaping to the surface. All of these types of characteristics are the same as those used for over 80 years in the porous rock aquifer-based natural-gas storage industry.

- Porous rock formations need to possess a mineralogy that does not result in rapid chemical consumption of the oxygen in the stored air through oxidation reactions. This concern can be evaluated via laboratory tests of core samples from a site under consideration.

Geologic opportunities for CAES plants in the U.S. are shown in Figure 5, which indicates that over 80% of the United States has some type of geological formation suitable for the underground air storage.

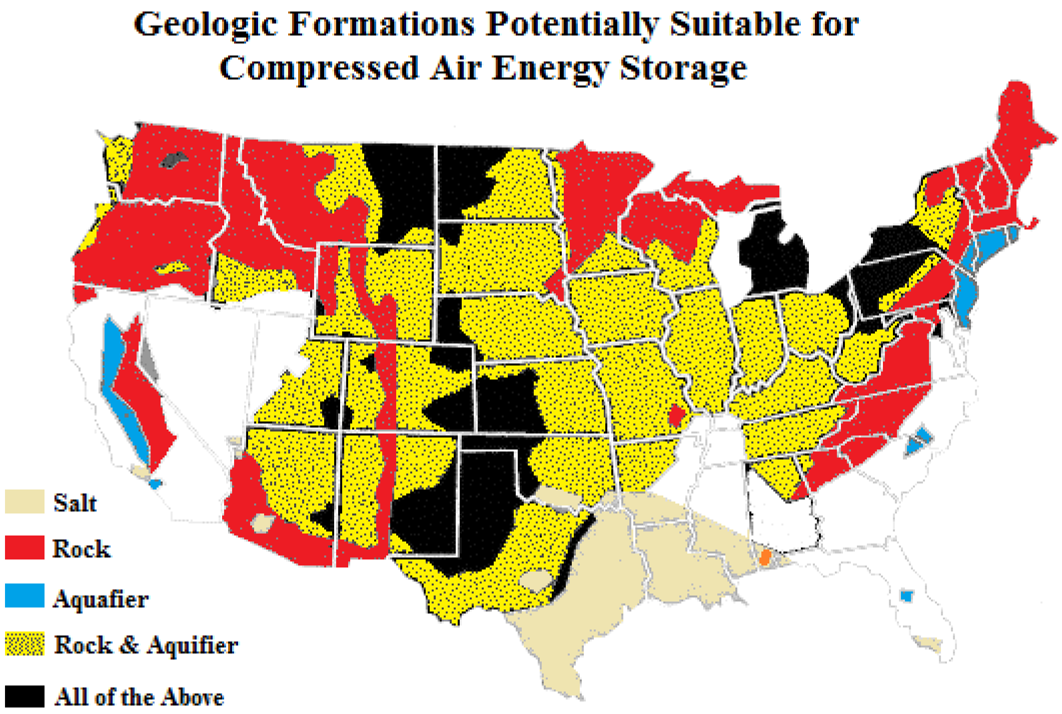


Figure 5

Compressed-Air Energy Storage technology is based on the natural gas industry which has many years of experience in storing natural gas underground. Underground natural gas storage fields grew in popularity shortly after World War II. At the time, the natural gas industry noted that seasonal demand increases could not feasibly be met by pipeline delivery alone. In order to meet seasonal demand increases, the deliverability of pipelines (and thus their size), would have to increase dramatically. However, the technology required to construct such large pipelines to consuming regions was, at the time, unattainable and unfeasible. In order to be able to meet seasonal demand increases, underground storage fields were the only option.

There are three main types of underground natural gas storage facilities; depleted reservoirs, aquifers, and salt caverns. Essentially, any underground storage facility is reconditioned before injection, to create a sort of storage vessel underground. The chart in Figure 6 shows the use of underground storage for the natural gas industry.

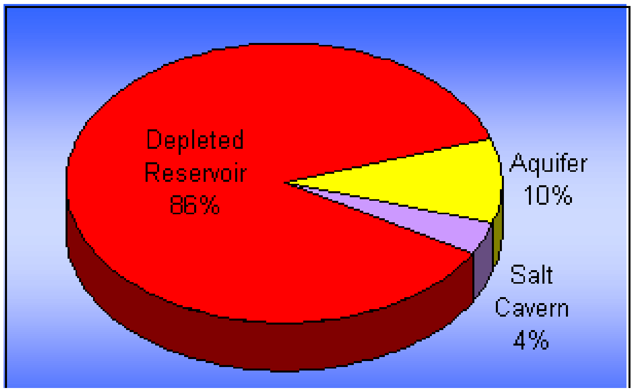


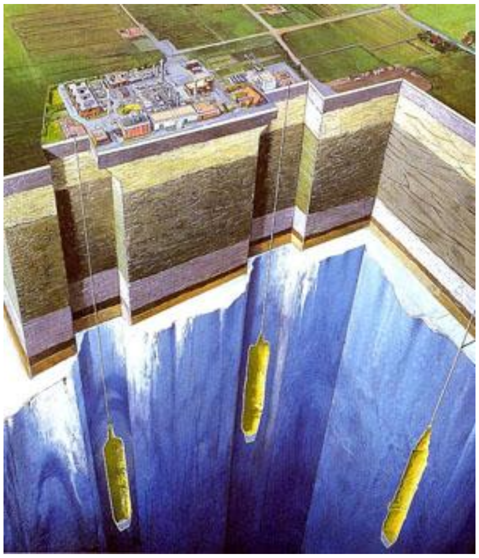
Figure 6

Like the natural gas industry, compressed air for the CAES plant may be stored underground, near the surface, or aboveground. Underground storage media may be in any of the following man-made and naturally occurring geological formations:

- Salt caverns
- Underground hard rock caverns
- Porous rock formations
- Abandoned limestone or coalmines
- Underground aquifers
- Lakes and Oceans

Let's look at each of these in a little more detail.

Salt Caverns



Salt caverns are created by solution mining or dry mining. Once the caverns are mined out to their desired size and shape, they are ready to be converted to underground storage wells.

One of the most beneficial characteristics of these underground caverns is their ability to store large quantities of compressed air. Salt caverns are essentially impermeable, meaning no fluid or gas can escape through the surrounding rock salt. This makes them ideal for storing high pressure air.

The size of the caverns average around 300 to 600 feet in diameter and can be up to 2,000 – 3,000 feet tall. The walls of a salt cavern also have the structural strength of steel, which makes it very resilient against reservoir degradation over the life of the storage facility.

If enough heat and pressure is applied to salt it will slowly flow, much like a glacier that slowly but continually moves downhill. Unlike glaciers, salt which is buried thousands of feet below the surface of the Earth can move upward until it breaks through to the Earth's surface, where it is then dissolved by ground- and rain-water. To get all the way to the Earth's surface, salt has to push aside and break through many layers of rock in its path. This will ultimately create a *trap*.

Essentially, salt caverns are formed out of existing salt deposits. These underground salt deposits may exist in two possible forms: salt domes, and salt beds. *Salt domes* are thick formations created from natural salt deposits that, over time, leach up through overlying sedimentary layers to form large dome-type structures. In Figure 7 we see salt that has moved up through the Earth, punching through and bending rock along the way. Oil can come to rest right up against the salt, which makes salt an effective trap rock. However, many times, the salt chemically changes the rocks next to it in such a way that oil will no longer seep into them. In a sense, it destroys the porosity of a reservoir rock.

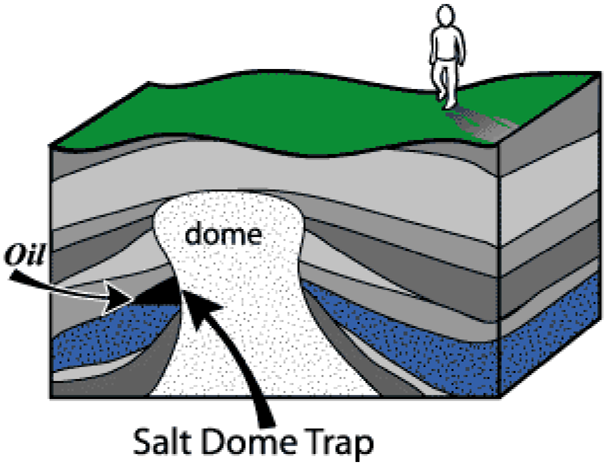


Figure 7

Salt domes can be as large as a mile in diameter, and 30,000 feet in height. Typically, salt domes used for storage are between 6,000 and 1,500 feet beneath the surface, although in certain circumstances they can come much closer to the surface.

Salt beds are shallower, thinner formations. These formations are usually no more than 1,000 feet in height. Because salt beds are wide, thin formations, once a salt cavern is introduced, they are more prone to deterioration, and may also be more expensive to develop than salt domes.

Once a suitable salt dome or salt bed deposit is discovered, and deemed suitable for storage, it is necessary to develop a *salt cavern* within the formation. Essentially, this consists of using water to dissolve and extract a certain amount of salt from the deposit, leaving a large empty space in the formation. This is done by drilling a well down into the formation, and cycling large amounts of water through the completed well. This water will dissolve some of the salt in the deposit, and be cycled back up the well, leaving a large empty space that the salt used to occupy. This process is known as *salt cavern leaching*.

Salt cavern leaching is used to create caverns in both types of salt deposits, and can be quite expensive. However, once created, a salt cavern offers an underground storage vessel with very high deliverability. Figure 8 shows a typical salt cavern.

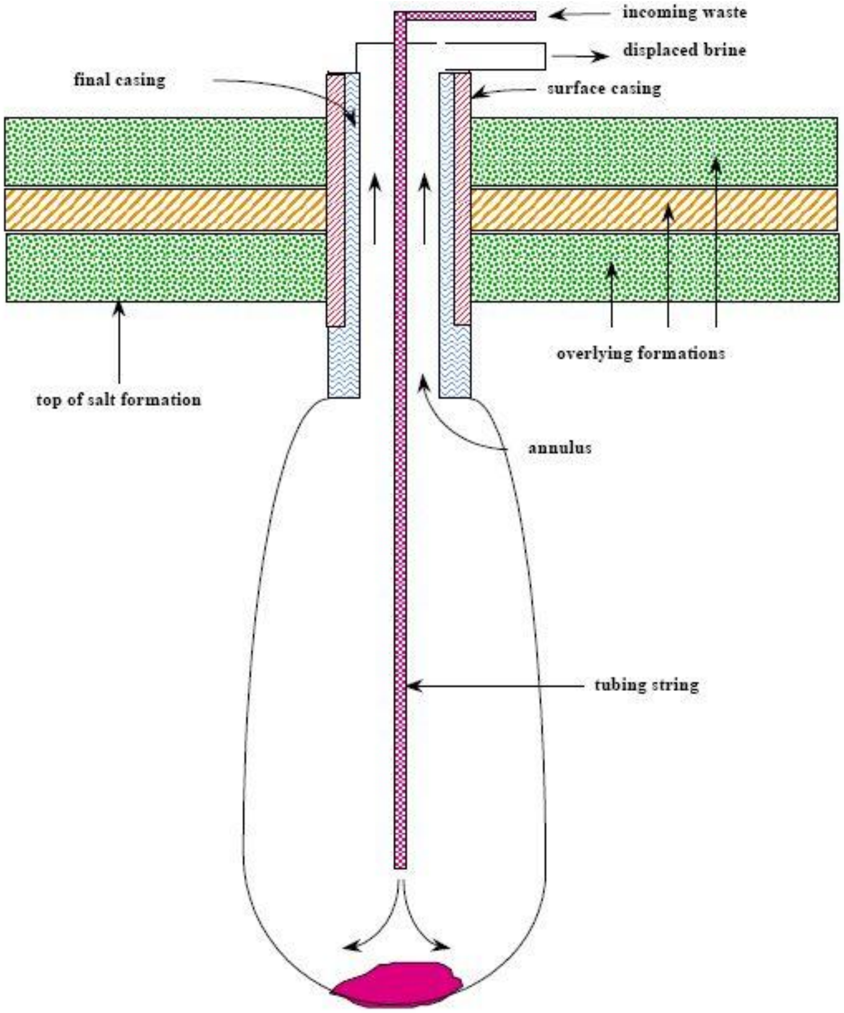
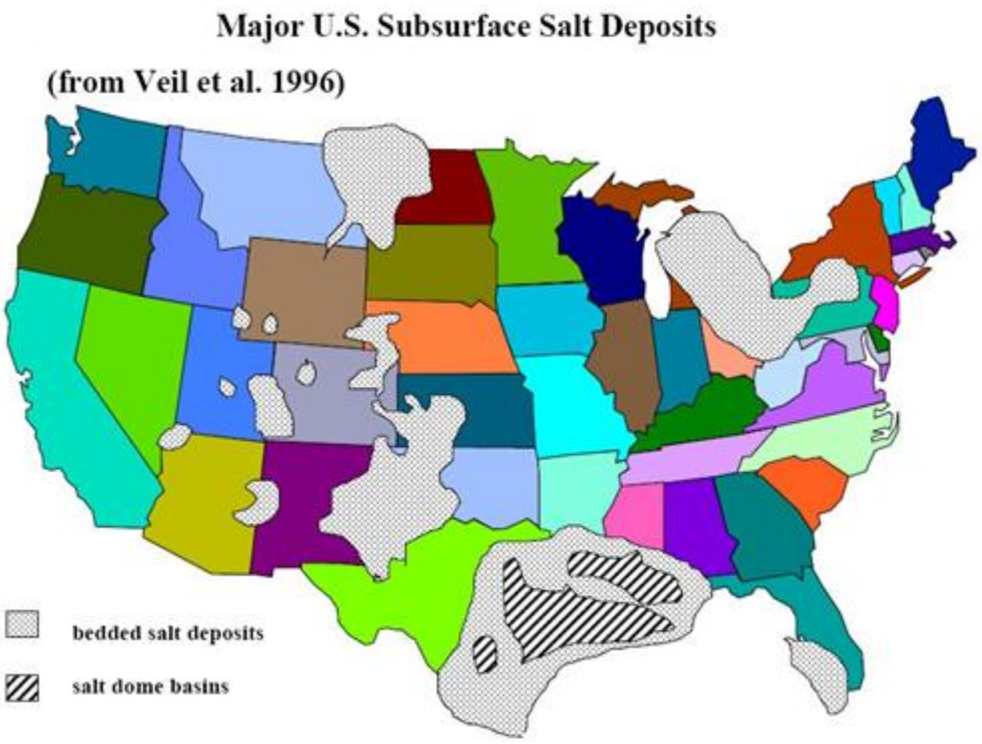


Figure 8

Salt cavern storage facilities are primarily located along the Gulf Coast, as well as in the northern states, and are best suited for peak load storage. Salt caverns are typically much smaller than depleted gas reservoirs and aquifers, in fact underground salt caverns usually take up only one one-hundredth of the acreage taken up by a depleted gas reservoir, see Figure 9 for an overview of likely salt caverns.


Major U.S. Subsurface Salt Deposits

(from Veil et al. 1996)

Figure 9

Underground Rock Caverns

Underground rock caverns created by excavating comparatively hard and impervious rock formations (either through new excavation for the CAES plant or in existing hard-rock mines.)

The geology of many regions of the country does not include sandstone, limestone, or salt formations suitable for conversion to storage. These regions include the entire eastern seaboard, upper mid-west states such as Minnesota and Wisconsin, and many western states such as Utah, Idaho, Oregon, and Washington.

Similar to salt dome traps are two other forms of structural traps, but these two are found in hard rock formations. They are:

- Anticline Trap
- Fault Trap

An *anticline trap* is an example of rocks which were previously flat, but have been bent into an arch. Oil that finds its way into a reservoir rock that has been bent into an arch will flow to the crest of the arch, and get stuck (provided, of course, that there is a trap rock above the arch to seal the oil in place). Once the oil is removed, the trap can be used for compressed air storage.

Figure 10 shows a cross section of the Earth showing typical Anticline Traps. Reservoir rock that isn't completely filled with oil also contains large amounts of salt water.

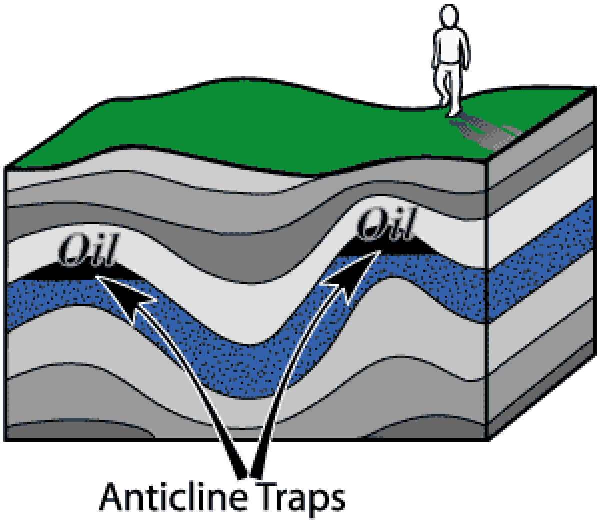


Figure 10

Fault traps are formed by movement of rock along a fault line. In some cases, the reservoir rock has moved opposite a layer of impermeable rock. The impermeable rock thus prevents the oil from escaping. In other cases, the fault itself can be a very effective trap. Clays within the fault zone are smeared as the layers of rock slip past one another. This is known as *fault gouge*.

Figure 11 shows a cross section of rock showing a fault trap - in this case, an example of *gouge*. This is because the reservoir rock on both sides of the fault would be connected, if not for the fault separating the two. In this example, it is the fault itself that is trapping the oil.

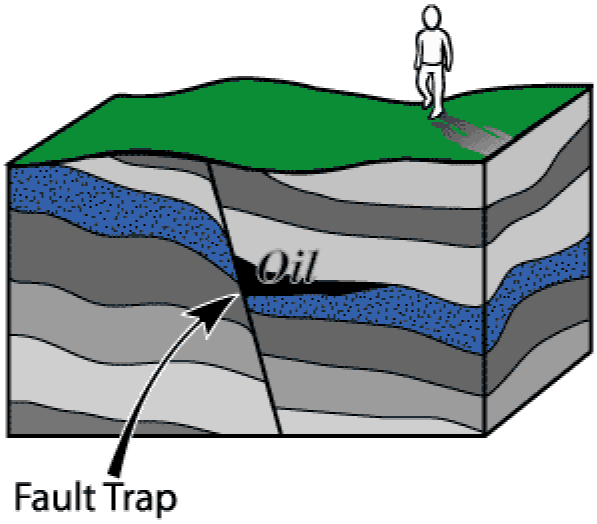


Figure 11

Porous Rock Formations

At depths of 1,500 feet or more, the free pore space of a suitable rock formation can be often used for storage of natural gas or compressed air. The rock formation layer must be adequately porous or fissured with good permeability and have an impermeable overburden which will not let the stored gas escape either vertically or laterally. Generally speaking, sandstones, dolomites, porous limestones or fractured rocks are suitable for such storage. Storage space in an aquifer is created by injected gas under pressure to displace free water. Depleted oil or gas reservoirs represent a particular type of porous storage.

Abandoned Mines

Abandoned limestone or coal mines have the potential to be excellent storage sites. These locations can evaluated, in situ, since the sites already exist. In addition, the sites have a history of operating conditions that can be reviewed. They generally have excellent permeability. The site is likely to have good infrastructure in place, including electrical supply. CAES can be a good use for an exhausted limestone or coal mines; however, there is a very limited supply of sites available.

Deep underground caverns may be operated with or without hydraulic compensation. *With hydraulic compensation*, water at the bottom of the storage cavern is connected to a surface reservoir. Thus, the storage pressure is always at or near the hydrostatic pressure of the water column to the surface.

For caverns operated *without hydraulic compensation* (e.g., salt caverns), the air pressure varies between the two design pressure levels associated with the CAES plant. In addition, it is generally better to operate the surface turbo-machinery at a constant pressure that is slightly lower than the lowest pressure in the cavern.

The first instance of natural gas successfully being stored underground occurred in Weland County, Ontario, Canada, in 1915. This storage facility used a depleted natural gas well that had been reconditioned into a storage field. In the United States, the first storage facility was developed just south of Buffalo, New York. By 1930, there were nine storage facilities in six different states. Prior to 1950, virtually all natural gas storage facilities were in depleted reservoirs.

The most prominent and common form of underground storage consists of depleted gas reservoirs. Depleted reservoirs are those formations that have already been tapped of all their recoverable natural gas. This leaves an underground formation, geologically capable of holding compressed air. Depleted reservoirs are also attractive because their geological characteristics are already well known. Of the three types of underground storage, depleted reservoirs, on average, are the cheapest and easiest to develop, operate, and maintain.

The factors that determine whether or not a depleted reservoir will make a suitable storage facility are both geographic and geologic. Geographically, depleted reservoirs must be relatively close to consuming regions.

Geologically, depleted reservoir formations must have high permeability and porosity. The porosity of the formation determines the amount of compressed air that it may hold, while its permeability determines the rate at which compressed air flows through the formation, which in turn determines the rate of injection and withdrawal of working gas. In certain instances, the formation may be stimulated to increase permeability.

Aquifers

Aquifers are underground porous, permeable rock formations that act as natural water reservoirs. However, in certain situations, these water containing formations may be reconditioned and used as CAES storage facilities. As they are more expensive to develop than depleted reservoirs, these types of storage facilities are usually used only in areas where there are no nearby depleted reservoirs. Underground aquifers may already have significant underground volumes available that require only minimal site preparation. They have the advantage of being a ‘natural’ storage site.

Aquifers are the least desirable and most expensive type of storage facility for a number of reasons. First, the geological characteristics of aquifer formations are not as thoroughly known, as with depleted reservoirs. A significant amount of time and money goes into discovering the geological characteristics of an aquifer, and determining its suitability as a storage facility. Seismic testing must be performed; much like is done for the exploration of potential natural gas formations. The area of the formation, the composition and porosity of the formation itself, and the existing formation pressure must all be discovered prior to development of the formation. In addition, the capacity of the reservoir is unknown, and may only be determined once the formation is further developed.

In order to develop a natural aquifer into an effective storage facility, all of the associated infrastructure must also be developed. Since aquifers are naturally full of water, in some instances powerful injection equipment must be used, to allow sufficient injection pressure to push down the resident water and replace it compressed air.

Developing an aquifer formation as a storage facility can be time consuming and expensive. In some instances, aquifer development can take several years and perhaps more than twice the time it takes to develop depleted reservoirs as storage facilities.

Lake or ocean storage

In addition to underground storage, deep water in lakes and the ocean can provide pressure without requiring high-pressure vessels or drilling into salt caverns or aquifers. The air goes into inexpensive, flexible containers such as plastic bags below in deep lakes or off sea coasts with steep drop-offs. Obstacles include the limited number of suitable locations and the need for high-pressure pipelines between the surface and the containers. Since the containers would be very inexpensive, the need for great pressure (and great depth) may not be as important. A key benefit of systems built on this concept is that charge and discharge pressures are a constant function of depth. Inefficiencies can thereby be reduced in the power plant. Efficiency can be increased by using multiple charge and discharge stages and using inexpensive heat sources and sinks such as cold water from rivers or hot water from solar ponds.

A nearly isobaric (i.e., constant pressure) solution is possible if the compressed gas is used to drive a hydroelectric system. However, this solution requires large pressure tanks located on land (as well as the underwater air bags). Also, hydrogen gas is the preferred fluid, since other gases suffer from substantial hydrostatic pressures at even relatively modest depths.

Chapter 3
Compressed Air Storage System Designs

Compressed air energy storage (CAES) offers a method to store low-cost off-peak energy in the form of stored compressed air (in an underground reservoir or an aboveground piping or vessel system) and to generate on-peak electricity by:

- Releasing the compressed air from the storage reservoir,
- Preheating the cool, high-pressure air, and
- Directing the preheated air into an expansion turbine driving an electric generator.

Since the compressor and expander operate independently and at different times, CAES offers significant advantages over a conventional simple-cycle combustion turbine system, where approximately 55-70% of the expander power is used to drive the compressor.

Gas Compression and Expansion

Compression of air generates a lot of heat. The air is warmer after compression. Decompression requires heat. If no extra heat is added, the air will be much colder after decompression. If the heat generated during compression can be stored and used again during decompression, the efficiency of the storage improves considerably. Additional heat can be supplied by burning fuel. One of the confusing aspects of the CAES is the requirement for additional fuel in the expansion process. The reasons lie in the fundamental physics of gas compression and expansion. When a gas is compressed, it gets warmer. This is why air compressors have cooling fins. Conversely, when it expands, it gets cold. This is why frost builds up on the space shuttle fueling lines. The magnitude of expansion envisioned in the CAES expander systems is such that the outflow of the turbine without heat being added would be nearly cryogenic in nature, making the design of the turbines problematic.

A highly efficient arrangement uses high, medium and low pressure pistons in series, with each stage followed by an air-blast venturi that draws ambient air over an air-to-air heat exchanger. This warms the exhaust of the preceding stage and admits this preheated air to the following stage. The only exhaust gas from each stage is cold air which can be as cold as −15C.

There are three ways in which a CAES system can deal with the heat. Air storage can be adiabatic, diabatic, or isothermic:

- *Adiabatic storage* retains the heat produced by compression and returns it to the air when the air is expanded to generate power. Its theoretical efficiency approaches 100% for large and/or rapidly cycled devices and/or perfect thermal insulation, but in practice round trip efficiency is expected to be 70%. Under adiabatic compression, some of the compression work goes into heating the gas. If this heat is then lost to the surroundings, and the same quantity of heat is not added to the gas upon expansion, efficiency is reduced. Energy storage systems often use large underground caverns. This is the preferred system design, due to the very large volume, and thus the large quantity of energy that can be stored with only a small pressure change. The cavern space can be compressed adiabatically with little temperature change and heat loss.

- *Diabatic storage* dissipates the extra heat with intercoolers into the atmosphere as waste. Upon removal from storage, the air must be re-heated prior to expansion in the turbine to power a generator which can be accomplished with a natural gas fired burner for utility grade storage. The lost heat degrades efficiency, but this approach is simpler.

- *Isothermal compression* and expansion approaches attempt to maintain operating temperature by constant heat exchange to the environment. They are only practical for low power levels, without very effective heat exchangers. The theoretical efficiency of isothermal energy storage approaches 100% for small and/or slowly cycled devices and/or perfect heat transfer to the environment. In practice neither of these perfect thermodynamic cycles is obtainable, as some heat losses are unavoidable. The isothermal process maintains constant temperature. The heat that compression generates must flow to the environment for the temperature to remain constant. In practice this is often not the case, because proper intercooling requires a compact internal heat exchanger that is optimized for high heat transfer and low pressure drop. Without an internal heat exchanger, isothermal compression can be approximated only at low flow rates, particularly for small systems. Small compressors have higher inherent heat exchange, due to a higher ratio of surface area to volume.

Compression can be done with electrically powered turbo-compressors and expansion with *turbo- expanders* or air engines driving electrical generators to produce electricity. A conventional gas turbine is a compressor-turbine combination, as seen in Figure 12.

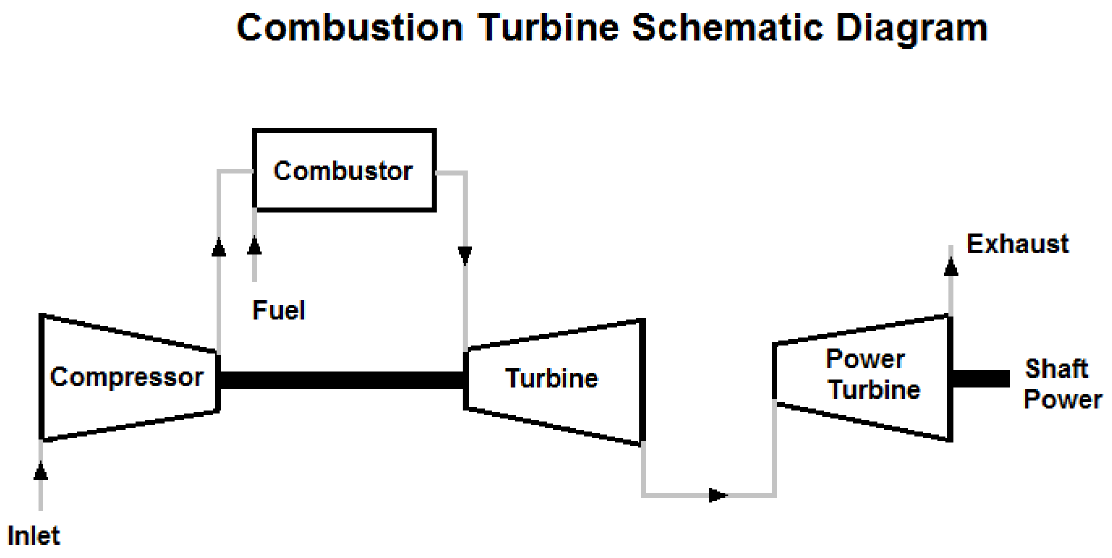


Figure 12

This particular turbine design uses a compressor to compress the air into the unit and the turbine stage expands the gas to power the turbine. The first stage of which is dedicated to running the two-stage compressor. None of the energy extracted in the first stage goes to generating electricity. In fact, nearly two-thirds of the mechanical energy generated in a conventional gas turbine is used to run the compressor sections of the turbine.

When a CAES system is used, the air is already compressed so the expander does not drive the compressor. Therefore, the net yield of the expander goes up by a factor of three.

Various concepts have been proposed to reduce the amount of gas required during expansion. The McIntosh Plant recovers waste heat from the compression cycles, reducing natural gas consumption up to 25% as compared to the Huntorf Plant. Other proposed cycles may further reduce gas consumption, and one concept proposes eliminating fuel altogether by capturing, storing and re-using the heat of compression.

Compressed Air Energy Cycles

A variety of different thermodynamic cycles may be applied to the CAES plant design. The selection of any of the following cycles is driven by specific site conditions and operating requirements and has a significant impact on the plant costs, selection of plant components, and overall plant operating/performance characteristics.

The most common types of compressed air energy cycles are:

- Conventional cycle
- Recuperator cycle
- Combined cycle
- Steam-injected cycle
- Compressed air with humidification
- Adiabatic cycle

Each of these cycles is described in detail below.

Conventional Cycle

For a conventional CAES plant cycle the major components include:

- A motor/generator with clutches on both ends (to engage/disengage it to/from the compressor train, the expander train, or both)
- Multi-stage air compressors with intercoolers to reduce the power requirements needed during the compression cycle, and with an aftercooler to reduce the storage volume requirements
- An expander train consisting of high- and low-pressure turboexpanders with combustors between stages
- Control system (to regulate and control the off-peak energy storage and peak power supply, to switch from the compressed air storage mode to the electric power generation mode, or to operate the plant as a synchronous condenser to regulate VARS on the grid)
- Auxiliary equipment (fuel storage and handling, cooling system, mechanical systems, electrical systems, heat exchangers)
- Underground or aboveground compressed air storage, including piping and fittings

Figure 13 is a schematic diagram of a conventional cycle compressed-air storage system.

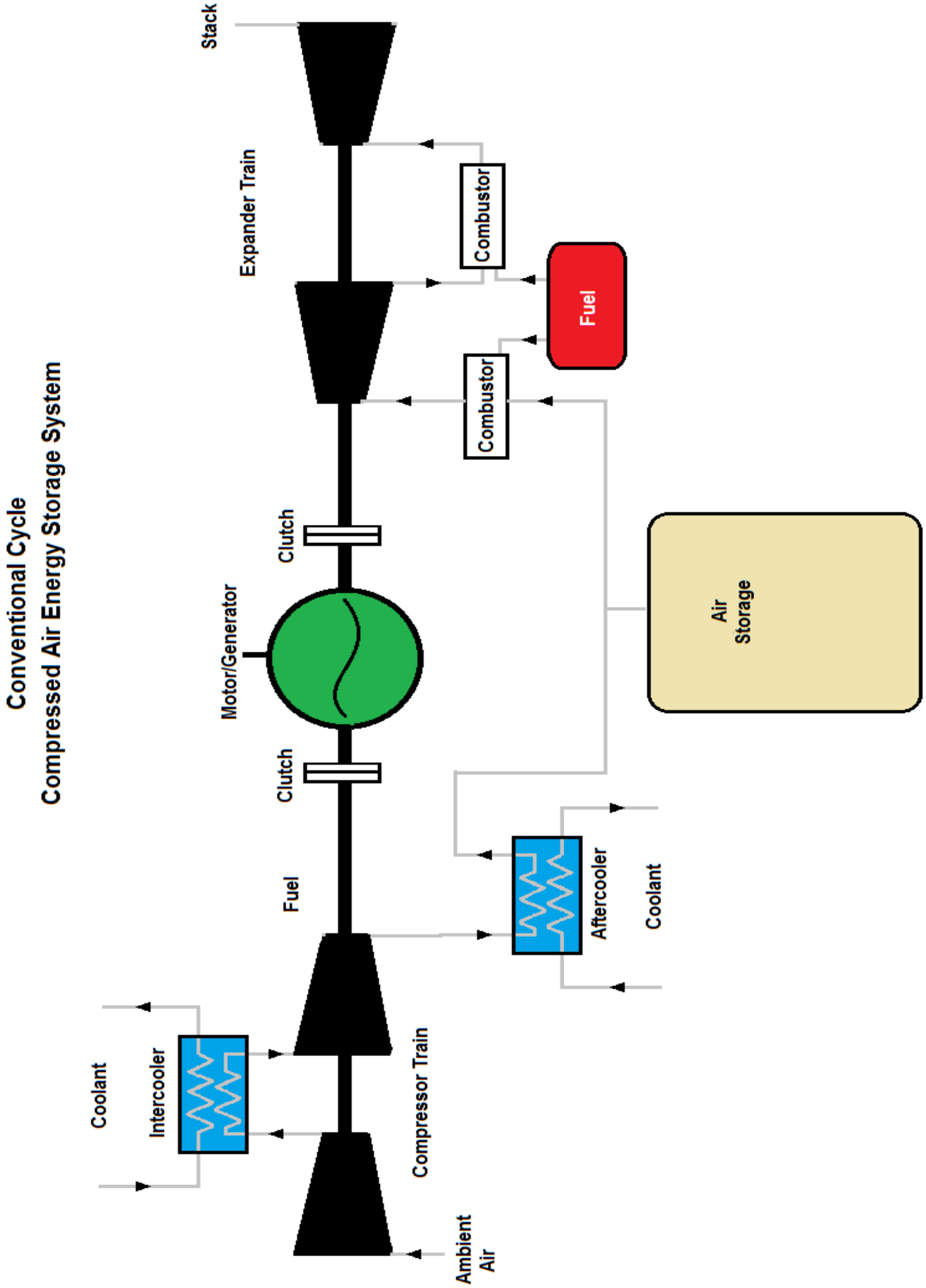

Conventional Cycle
Compressed Air Energy Storage System
Ambient Air
Coolant
Intercooler
Compressor Train
Fuel
Clutch
Motor/Generator
Clutch
Aftercooler
Coolant
Air Storage
Combustor
Fuel
Combustor
Expander Train
Stack

Figure 13

In the compressed air storage mode, the low cost off-peak electricity from the grid is used to operate the motor-driven compressor train to compress the air and to send it into a storage facility. In single-shaft CAES plant configurations, the shaft power to start the compressor may be supplied partially or completely by the expander. In the power generation mode, the compressed air is withdrawn from the storage reservoir, preheated in the recuperator, sometimes heated further via fuel burning in a combustor, and then expanded through the reheat turbo-expander train to drive the generator to provide peak power to the grid. It should be noted that the compression and generation power ratings for the overall plant can be different values, to meet the power available during off-peak time periods versus the power needed during on-peak time periods.

While combustion turbines use standardized power plant equipment, CAES plants are optimized for specific site conditions such as the availability and price of off-peak energy, cost of fuel, storage type (and the local geology if underground storage is used), load management requirements, peaking power requirements and capital cost of the facility. By converting off-peak energy from the grid to compressed air and storing it for electric power generation during peak periods, utilities can defer or avoid higher capital-intensive generation, transmission, and distribution upgrades, yet they can still meet the peak electricity demand from their load centers.

The combustor can be designed to operate on a variety of fuels, including natural gas, oil, and hydrogen. Since CAES plants use a fuel to heat air during the discharge generation cycle, a CAES plant is not truly a “pure” energy storage plant such as pumped hydro, battery, and flywheel storage systems. In general, since fuel is used during a CAES plant’s generation cycle, a CAES plant provides approximately 25-60% more energy to the grid during on-peak times than it uses for compression during off-peak times (the exact value of this percentage is determined by the specific CAES plant design). In addition, as was mentioned above, the power output of an expansion turbine used in a CAES plant provides two to three times more power to the grid than the same expansion turbine would provide to the grid if it were a part of a simple-cycle combustion turbine plant. This explains the exceptionally low specific fuel consumption (heat rate) of a CAES plant as compared to a combustion turbine. For example, if the expansion turbine element from a 100 MW simple cycle combustion turbine were used in a CAES plant configuration, it would provide 250 to 300 MW to the grid.

The conventional cycle illustrated in Figure 13 consists of the intercooled compressor train, reheat expander train, motor/generator, control system, and the air storage along with auxiliary equipment (fuel storage and handling, heat exchangers, mechanical systems, and electrical systems). The stored air is expanded through a reheat turbo-expander train where the air is heated (via combustion of fuel) sequentially in the high pressure and low-pressure combustors before entering the corresponding high-pressure and low-pressure expansion turbines. Such a configuration is used by the German Huntorf plant and is characterized by relatively high heat rate (approximately 5,500 Btu/kWh) compared to more recent CAES plant designs, as described below. This type of plant is best suited for peaking and spinning reserve duty applications.

Recuperated Cycle

A recuperated cycle plant is the conventional CAES thermal cycle with an additional component (the recuperator), is shown in Figure 14. A *recuperator* recovers the low pressure turbine waste heat to preheat the stored air before it goes into the high-pressure combustor. This reduces the fuel consumption of the plant (as compared to the conventional plant above) by about 25%. This configuration is used in the Alabama McIntosh plant that was designed for primary operation as a source of peak power and as a load-management storage plant. Since the recuperator reduces the plant heat rate during generation by about 25%, it reduces the cost of the plants' peak power supply.

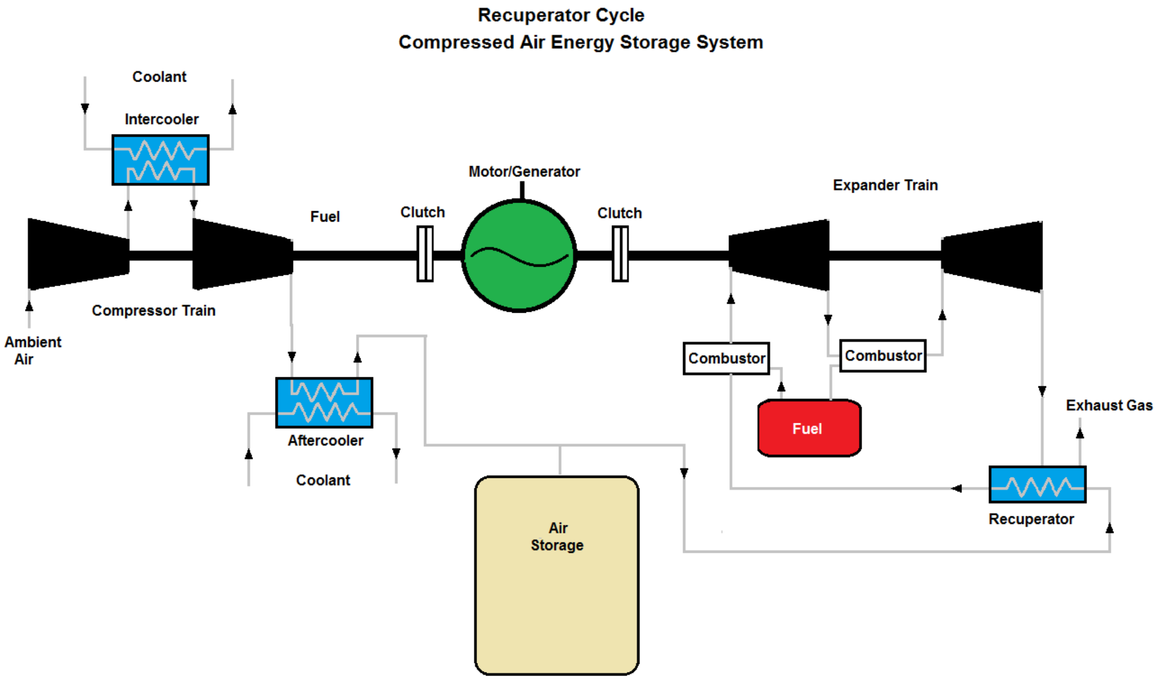


Figure 14

Combined Cycle

A combined cycle plant is the conventional cycle with addition of a Heat Recovery Steam Generator (HRSG) and steam turbine, as shown in Figure 15. The exhaust heat from the low-pressure expander is recovered in the HRSG to produce steam, which in turn drives a steam turbine and provides additional power from the plant. Due to the thermodynamic inertia of the bottoming cycle equipment, the additional power generated by the bottoming steam cycle will reach full capacity in approximately one hour after the CAES plant start-up.

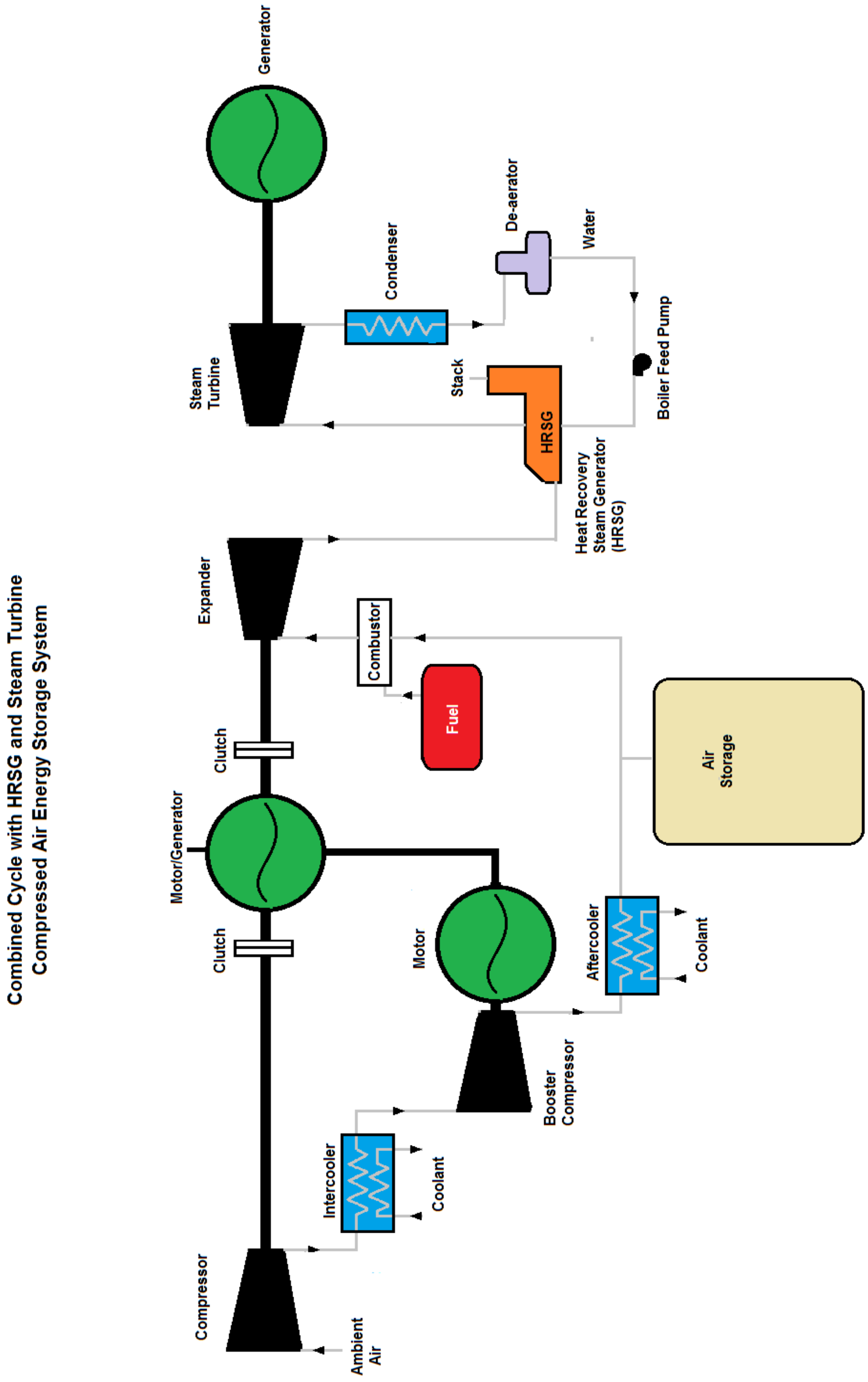

Combined Cycle with HRSG and Steam Turbine
Compressed Air Energy Storage System
Generator
Condenser
De-aerator
Water
Steam Turbine
Stack
Boiler Feed Pump
HRSG
Heat Recovery Steam Generator (HRSG)
Expander
Combustor
Fuel
Clutch
Air Storage
Motor/Generator
Clutch
Motor
Aftercooler
Coolant
Booster Compressor
Intercooler
Coolant
Compressor
Ambient Air

Figure 15

Therefore, this concept is applicable for cases that need additional peak power for continuous long-term operations. Compared to the conventional cycle, this cycle reduces specific storage volume per kWh produced with a corresponding reduction in the storage reservoir costs.

Steam-injected Cycle

A steam-injected cycle plant is the conventional cycle adapted to use the HRSG to recover waste heat for steam production, as illustrated in Figure 16. The steam is added to the airflow from the storage reservoir to increase the mass flow through the expansion turbine during the generation cycle, thereby increasing the output power level from the plant.

The mass of air needed to be stored per unit of power output is significantly reduced due to steam injection with corresponding reduction of the storage volume and costs. Similar to combined cycle gas turbine plants with steam injection, the additional power associated with steam injection in this CAES cycle follows the power level produced by the air expansion turbine. Like any steam-injected system, this concept uses de-mineralized water; thus, the cost of this type of water has to be included in economic feasibility studies for this type of plant.

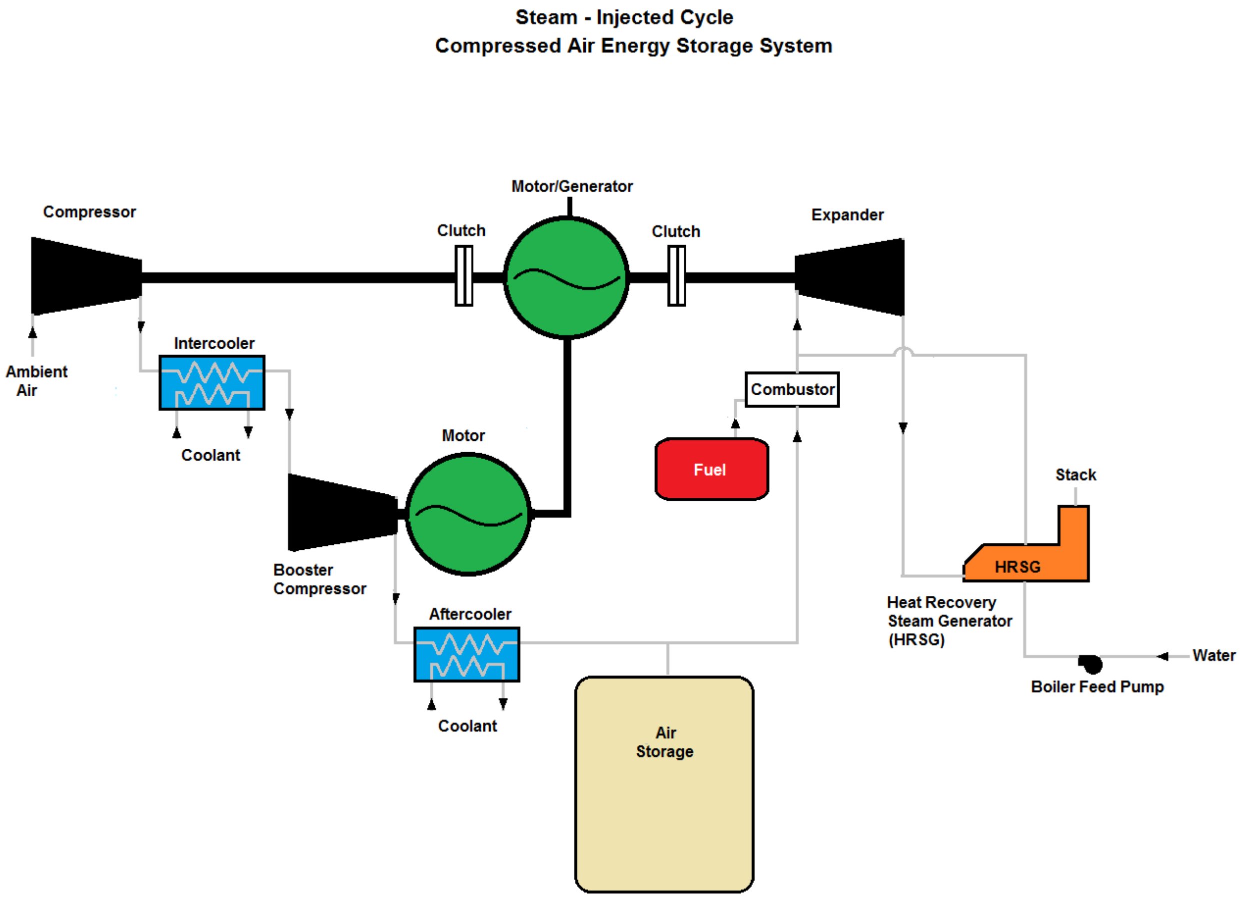


Figure 16

Compressed Air Storage with Humidification (CASH)

As shown in Figure 17, the stored air is humidified in an *air saturator* before being injected into the combustion turbine. The mass of air needed to be stored per unit of power output is significantly reduced due to humidification. Thus, the size of the air storage reservoir required is much smaller than other types of CAES cycles. The dynamics of this concept are better than those for the combined cycle and steam injection concepts. This concept also uses water, although this water does not require demineralization.

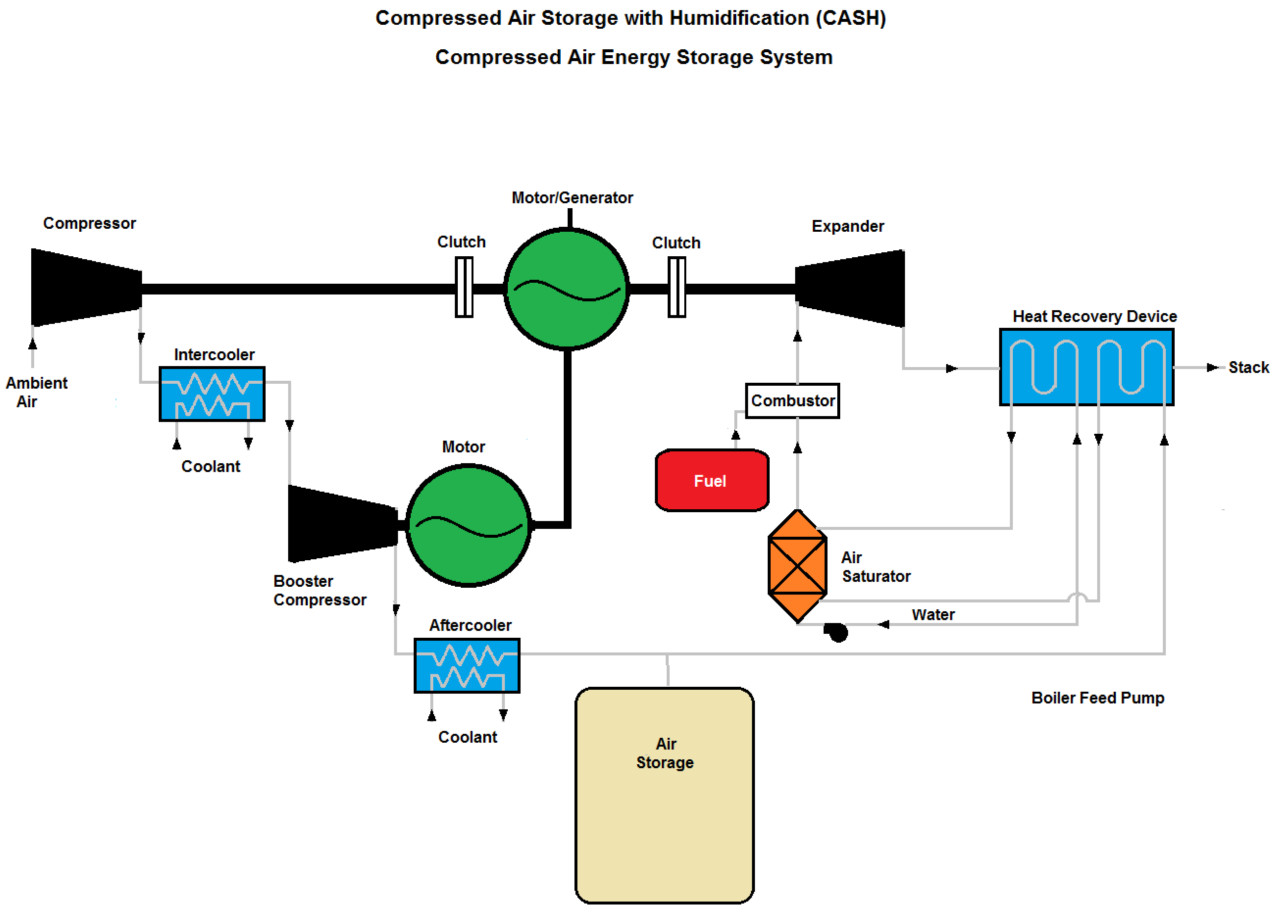


Figure 17

Adiabatic CAES Cycle

In the adiabatic cycle the thermal energy recovered during the compression cycle is stored and used later to reheat the stored air during the generation cycle to reduce or even eliminate any fuel consumption. As illustrated in Figure 18, this type of cycle uses sensible or latent heat storage and recovery materials (e.g., basalt stone/thermal oils and phase change salts, respectively).

The result is called an *adiabatic* CAES plant where no fuel is used during the plant's generation cycle. The round trip efficiency for this type of plant has been estimated to be 65%.

Adiabatic Cycle

Compressed Air Energy Storage System

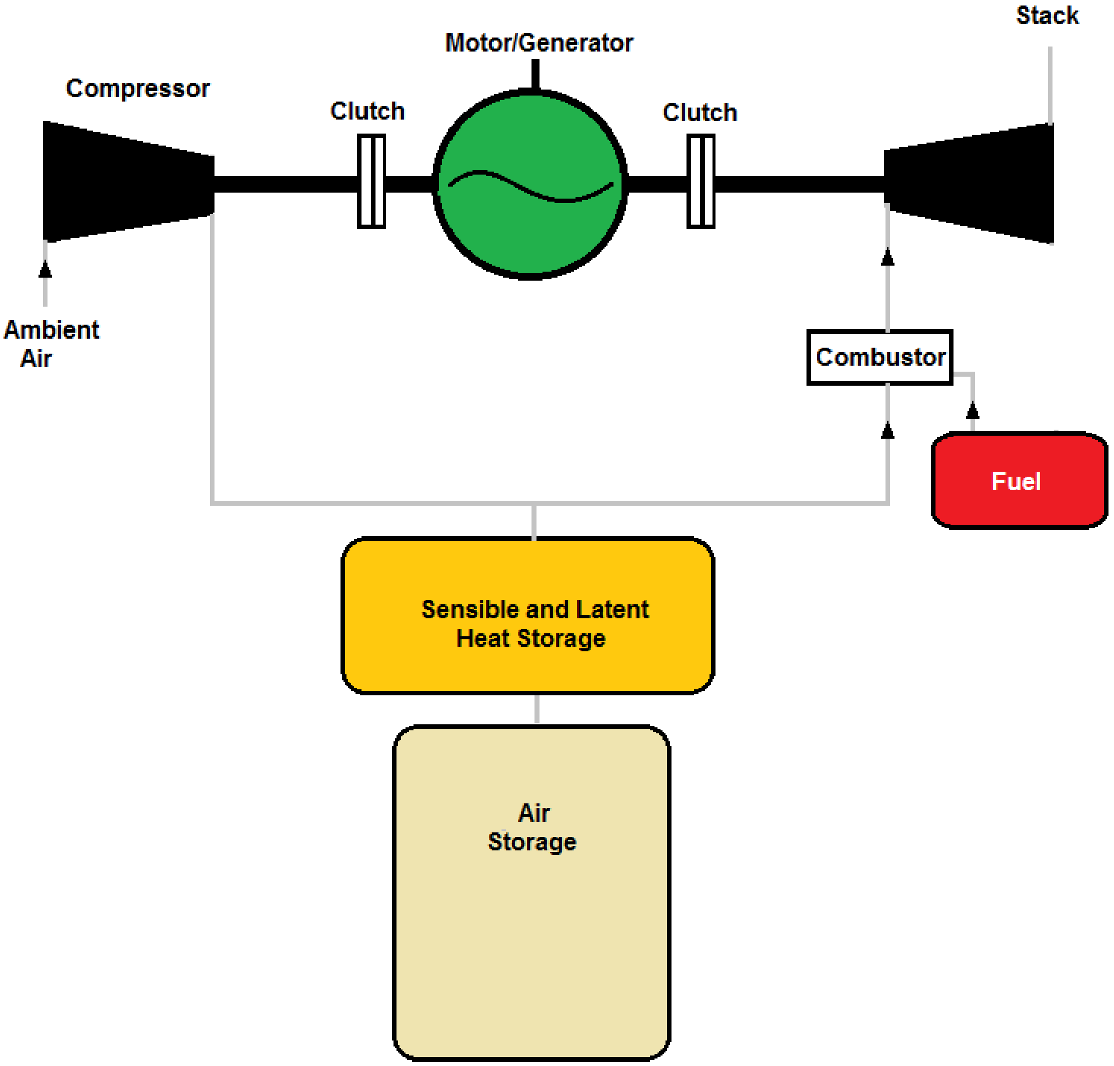


Figure 18

Hybrid Compressed-Air Energy Storage Concept

A hybrid CAES plant allows the plant to operate continuously as a base-load combustion turbine and, when necessary, to operate at increased power during peak hours to supply intermediate/maximum peak power as needed. This plant concept is particularly well suited for distributed power generation applications. The following is a brief description of the major operating modes of a conceptual 4.8 MW hybrid CAES plant:

- Base load operation – The plant is operated as a conventional combustion turbine with 100% of the expander flow provided by the compressor. The turbine supplies a net power output of 4.8 MW at 11,700 Btu/kWh.

- Intermediate peak load operation - The expander flow and power are increased because the expander receives compressed air flow from the storage reservoir in addition to the full airflow from the main compressor. It is estimated that when 20% additional airflow comes from the storage reservoir, the net output power will be 7.9 MW for three hours at 8,300 Btu/kWh.

- Maximum peak load operation - The compressor is disengaged, and the full flow of the compressed air from the storage reservoir goes into the expander. The power output is approximately 16 MW at a heat rate of approximately 4,000 Btu/kWh.

- Storage-charging mode of operation - The off-peak power feeds both the motor-driven main compressor and the separate motor-driven boost compressor. Approximately 12 MW of off-peak power is required to drive the compressors.

- Self-charging operation - 78% of the main compressor’s flow is sent to the expander to generate electric power to drive the booster compressor to fill the storage reservoir. This requires about 3.5 hours of charging time, with no power going to or from the grid.

- Synchronous condenser mode of operation – By opening the clutch between the compressor and the motor/generator, and between the expander and the motor/generator, the motor/generator is synchronized to the grid and is operated as a synchronous condenser, providing VARS support. In this mode, the motor/generator works to stabilize line voltage and frequency, ease grid power transitions, and provides reactive power to assist in providing high quality electrical power to the grid.

New Concepts in CAES Design

A conventional single-shaft configuration was used for the McIntosh and Huntorf plants. The compressors, motor/generator, and expanders are all on the same shaft, separated by clutches. This low initial capital cost concept requires only a single motor / generator that supports both the compression and power generation cycles. The expanders can be used to start the compressor train. The advanced recuperator used in the McIntosh plant is a necessary component to reduce the heat rate.

CAES developers are proposing several innovative CAES plant concepts; the innovation lies in the use of present day turbo-expanders, compressors, new thermal cycles, different turbo-machinery configurations, and different component selection. These concepts are summarized in Table 2 and described in the text below.

Concept One is a multi-shaft arrangement that includes a reheat expander train (with a recuperator) driving the electric generator for peak power generation and a number of parallel independently operating motor-driven intercooled compressors trains for charging the underground storage. This concept has higher capital costs but provides significant operating flexibility. This concept is currently under consideration for a number of projects.

In *Concept Two*, a high-pressure recuperator is used instead of the high-pressure combustor in the expansion train. The only combustor is a conventional low pressure combustor installed upstream of the low-pressure turbine. This concept eliminates the high-pressure combustor, which is a relatively new and a technically challenging component. Alstom is promoting this concept for 300-400 MW CAES plants.

With *Concept Three* an air turbine is added upstream of the combustion turbines. A recuperator recovers the heat in the low-pressure expander exhaust and preheats the compressed air from the cavern to approximately 500C. The preheated compressed air is expanded through an air turbine to drive a generator in addition to the power generated by a combustion turbine. The combustion turbine and the air turbine can generate more power than the combustion turbine alone. The compressor train consists of a number of motor-driven intercooled compressors operating in parallel to charge the underground storage. This concept has the advantages of high peak power, proven components, excellent operating flexibility, reliability, and availability, and competitive costs.

There are a number of studies investigating the integration of wind farms with small capacity CAES plants. *Concept Four* is a plan to use the wind power (primarily during night hours) to compress the air for storage in above ground piping and/or other pressure vessels. During peak hours of electric demand, the compressed air supplies a combustion turbine to generate electric power for sale at premium prices. Since the compression is independent of the power generation, this hybrid plant can operate continuously to provide base load power in addition to the intermittent peak load.

See Table 2 for more information about these innovative concepts.

Table 2

New Concepts in CAES Design

Characteristic	Concept 1	Concept 2	Concept 3	Concept 4
Feature	Multiple independent compressor trains	High-pressure Recuperator	Preheat air upstream of combustion turbine	Compress air using wind power
Status	Available	Available	Design is being marketed	Under consideration
Market	Plants requiring flexibility	300-400MW plants requiring high reliability	Plants requiring high peak power and operating flexibility	Wind farms
Development	Operational flexibility	Produces lower emissions	Provides high peak power	Integrated with wind energy
Issues	High initial cost	Reliability of high-pressure recuperator	System control and heat balance	Power fluctuation from wind, cost of above ground compressed air storage

Chapter 4
Advantages and Disadvantages of CAES

The primary benefits of implementing a CAES system are ancillary services provided to the grid. Applications include: peak shaving; spinning reserve; VAR support; and arbitrage. By utilizing CAES, the energy from a variety of sources (including wind, solar and the grid itself) can be temporarily stored to be recovered at a later time, presumably when it is more needed and, perhaps, more valuable.

Although CAES systems which use underground storage are inherently site specific, it is estimated that more than 80% of the U.S. territory, has geology suitable for such underground storage. CAES utilizes proven technology that can be optimized for specific site conditions and competitively delivered by various suppliers.

Listed below are a few other advantages and disadvantages of CAES.

Advantages

CAES plants designed for specific applications can provide economic benefit to owners and/or operators of power generation facilities. The benefits of using a CAES plant to support power generation include the following:

- Increase use of generation facilities during off-peak hours (i.e., during the storage plant charging cycle.)
- Provide ramping, intermediate, and peaking power during the day.
- Store nighttime wind energy for delivery during the higher priced daytime.
- Provide frequency regulation (CAES can provide much better frequency control than a base load power plant).
- Provide VAR support (e.g., by operating the CAES plant to supply reactive power in the synchronous condenser mode). A CAES plant can be operated 24 hours a day in the synchronous condenser mode, since it does not require any air from the storage reservoir.
- Provide off-peak to on-peak arbitrage.

- Absorb excess generating capacity with its compressor during times of rapidly decreasing demand. This application is particularly useful when base nuclear, hydro, or fossil capacity is available at very low prices during off peak time periods.

- The CAES plant is the only technology that can provide significant energy storage (in the thousands of MWh's) at relatively low costs. The plant has practically unlimited flexibility for providing significant load management at the utility or regional levels.

- CAES plants are capable of black start. Both the Huntorf and McIntosh plants have blackstart capability that is occasionally required.

- CAES plants have fast startup time. If a CAES plant is operated as a hot spinning reserve, it can reach the maximum capacity within a few minutes. The emergency startup times from cold conditions at the Huntorf and McIntosh plants are about 5 minutes. Their normal startup times are about 10 to 12 minutes.

- CAES plants have a ramp rate of about 30% of maximum load per minute.

- The nominal heat rate of a CAES plant at maximum load is about three times lower than the heat rate of a comparable combustion turbine plant using the same turbine expander. CAES plants also excel at part load. Their heat rate at 20% of maximum load is 80% of the nominal heat rate at maximum load. This is very good and unique, since all other oil, gas, and coal power plants have poor efficiency at 20% load, making them uneconomical for operation at part load for normal duty. This characteristic of CAES plants make them very useful (and efficient) for ramping, part load, and regulation duty.

Disadvantages

Given all these advantages, one could ask, “Why there are so few CAES plants in operation?” A few of the potential reasons are listed below.

- The underground geology is likely perceived as a risk issue by utilities, even though oil and gas companies have been storing hydrocarbon-based fuels in similar underground reservoirs for over 80 years.

- Site selection is somewhat limited since one needs the presence of mines, caverns, and certain geological formations.

- As is the case with any energy conversion, certain losses are inevitable. Less energy eventually makes it to the grid if it passes through the CAES system than in a similar system without storage.

- The requirement for additional heating in the expansion process is the most significant disadvantage. By some estimates, 1 kWh worth of natural gas will be needed for every 3 kWh generated from a CAES system. This is particularly problematic if fossil fuels are used for the heat addition. As natural gas prices increase, the economics of CAES, marginal at present, could fail.

Summary

Based on the experience gained with the operation of the McIntosh and Huntorf plants, the industry has found that:

- CAES plants can be built within estimated costs and schedule,
- The plants confirmed the expected high efficiency, reliability, availability,
- The plants have competitive economics,
- The underground storage caverns can be developed using well-established techniques,
- Underground storage reservoirs can achieve negligible leak rates. In fact, no air leakage has been measured at either the Huntorf or McIntosh plants since they were commissioned, and
- CAES plants can be constructed using commercially available equipment; mainly components developed for the combustion turbine and oil/gas industries over that last 50 years.

Compressed Air Energy Storage systems are well suited as a companion to intermit energy sources such as wind and solar. They also complement large base-load nuclear plants and offer an effective method to store vast amounts of power for later consumption.

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