

# A MODULAR, THERMALLY CLOSED, ADSORPTION-ENHANCED COMPRESSED AIR ENERGY STORAGE SYSTEM

Timothy F. Havel<sup>1</sup>

<sup>1</sup>Energy Compression Inc., Boston MA, USA

Adsorption-Enhanced Compressed Air Energy Storage (AE-CAES) is a means of reducing the cost of the pressure vessels needed by CAES facilities that do not rely on subterranean geological formations to confine their air. It does this by adsorbing the air in nano-porous crystalline materials such as zeolites, which take up many times their volume in air at pressures that are quite low compared to other forms of CAES. This approach allows the temperature of the zeolite or other adsorbent to be used to control how much air is in the tank, since the amount of air adsorbed depends exponentially on the inverse absolute temperature. In order to implement such a temperature-swing storage cycle with reasonable round-trip efficiency, the heat and cold needed must be stored and largely reused over multiple cycles. Here we describe a modular AE-CAES system that can achieve this and promises to be extremely durable, in that the bulk of the system should last many decades with daily cycling. By using caisson boring and trenchless construction techniques to build it largely underground, the proposed system can also be made unobtrusive even in suburban settings, and it is inherently safe even against an act of terrorism. Engineering firms interested in collaborating on a demonstration project are invited to contact the author for additional information.

**Keywords:** adsorption, CAES, compressed air, energy storage, zeolite

## BACKGROUND AND INTRODUCTION

Adsorption-Enhanced Compressed Air Energy Storage (AE-CAES) was first introduced at EESAT 2009 [1]. Like the contemporaneous “isothermal” approaches to CAES, it can be located anywhere using artificial pressure vessels, can use low-grade waste or solar thermal heat to compensate for losses over the storage cycle, does not require fossil fuels for its operation and is generally environmentally benign. Unlike isothermal CAES, however, it uses only low pressures (about 10 bar) and near-adiabatic compression and expansion using only off-the-shelf hardware. Even more distinctively, it regulates the amount of air in the tank by cooling the adsorbent therein to make it take up air and heating it to discharge the air again, all at the same modest pressure. This in turn makes AE-CAES extraordinarily safe, since even if the tank were ruptured the majority of the air would only slowly be released as the adsorbent warmed to ambient temperatures. Finally, although commonplace zeolite adsorbents can greatly lower the cost of the pressure vessels needed for AE-CAES today, significant improvements can be expected either by modifying them in various well-established ways or by taking advantage of some of the new kinds of nanoporous materials that have recently been developed, such as metal-organic frameworks.

The most important question to be decided in designing an AE-CAES system is whether to make it thermally open or closed (see Fig. 1). In the former

case, the heat or cold needed to cycle the system is taken from an external source, and delivered to a thermal load when charging it or discharging it, respectively. Thus a thermally open system provides thermal energy storage in concert with mechanical or, by conversion, electrical. Using zeolite adsorbents, the value of the heat and cold stored will be comparable, in terms of the cost of electricity needed to produce it, to the value of the stored mechanical energy. An excellent example of the use of a thermally open system would be at a cold storage warehouse. To prevent the formation of crystals in ice cream due to sublimation, these typically operate near  $-30^{\circ}\text{C}$ , which is cold enough to charge a zeolite-based AE-CAES system with air at 10 bar. When the facility needs to shed load, it can keep the warehouse cold by pumping heat energy from it to the zeolite. This in turn warms the zeolite and releases the air, which can then be used to drive a generator to power the lights or other equipment.

In contrast, a thermally closed AE-CAES system includes a thermal reservoir in addition to the zeolite or other adsorbent, which gets hot when the zeolite gets cold and vice versa. This allows most of the heat and cold needed for the temperature swing to be reused over multiple cycles. Thermal losses over each cycle are of course inevitable and must be compensated for with heat and cold from external sources, quite possibly electrically powered. In that case these would constitute parasitic loads that must be deducted in calculating the round-trip efficiency. Experience with similar designs

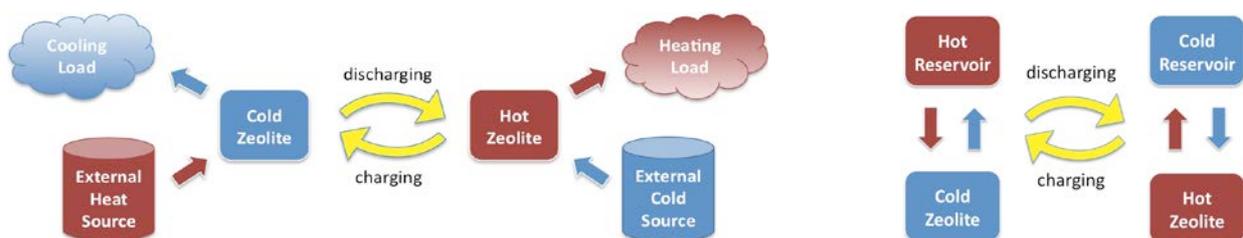


Fig. 1. Flows of heat and cold while charging and discharging a thermally open AE-CAES system (left) and a thermally closed AE-CAES system (right).

nevertheless implies that a thermal energy storage efficiency in excess of 85% should be achievable [2]. More importantly, the heat required with zeolite adsorbents is only at a temperature near 100°C, which can often be obtained from a waste stream or from non-concentrated solar thermal panels. Energy from these sources would not add to the operating cost of the system, so this would improve its economical if not physical efficiency. Similarly, a thermochemical refrigeration technology powered by low-grade heat, such as adsorption refrigeration, could be used for the cooling needed to make up for lost cold. Such a thermally closed system could be used for many of the same applications as batteries are today.

It should be noted that there are several ways to blend features of thermally closed and open systems together, which could enhance the value of AE-CAES in specific situations. For example, the cold needed could be stored and reused while the heat is taken from a waste stream and not reused. The purpose of this paper is to introduce a general approach to designing AE-CAES systems which is simple enough to keep the additional upfront costs of the thermal energy storage subsystem needed for thermally closed systems under control. A modular, fully thermally closed AE-CAES system will be given as an example.

### Related work

The thermal energy storage subsystem proposed for use in AE-CAES is known as a regenerative heat exchanger or regenerator. It can be as simple as a tube packed with gravel, as in Fig. 2. Regenerators have been in widespread use for nearly two centuries, playing for example an important role in Sterling engines. They have also been used for both thermal and, by conversion, mechanical or electrical energy storage, as exemplified by the work of Jonathan Howes & James Macnaghten at Isentropic Ltd. in the UK [2]. Their use as a means of improving the coefficient of performance of adsorption refrigerators has been explored by Robert Critoph & Roger Thorpe at the University of Warwick, again in the UK [3]. This last example is of particular note here because it demonstrates that a particulate bed packed with an adsorbent for the gas passing through it can itself function as a regenerator.

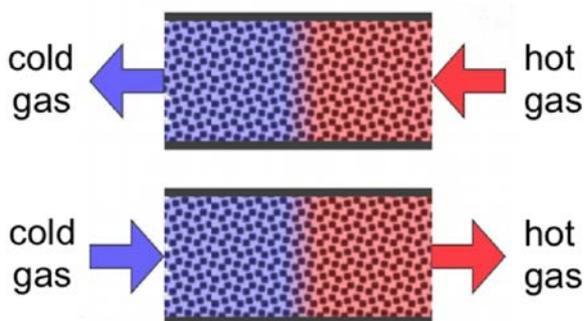


Fig. 2. Operation of a regenerator while charging it with heat and/or discharging its stored cold (top), and operation while charging it with cold and/or discharging its stored heat (bottom). Note the well-defined thermal fronts pass through the packed beds therein much more slowly than the carrier gas itself.

## AE-CAES SYSTEM DESCRIPTION

### The energy storage module

The AE-CAES system described in the following consists of modules, which operate independently and can be added to the system in any number depending on the amount of energy storage desired. Each module contains a pair of tanks open at their ends, which will serve as regenerators for thermal energy storage. One of these tanks is filled with a zeolite particulate while the other is filled with an inert particulate. The latter should be composed of a stable material which has a high volumetric heat capacity, but is otherwise not important. A cutaway view of proposed module is shown in Fig. 3, which will be used as the basis for the ensuing discussion.

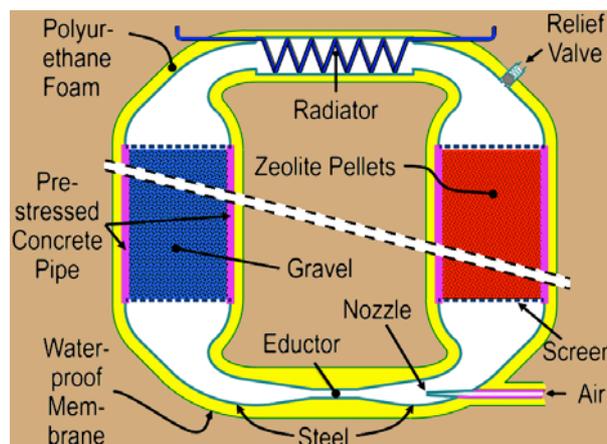


Fig. 3. Cutaway view of the AE-CAES energy storage module. Only the lower & upper portions are shown, separated by a pair of diagonal dashed lines through the center.

The regenerators are formed from vertical lengths of cylindrical pipe. One of the pipe lengths is packed with a bed of the zeolite particulate, while the other holds a packed bed of the inert particulate. These pipes must be able to withstand the pressures needed for zeolite-based AE-CAES, or about 10 bar gauge. They must also be made of a material that does not soften at temperatures up to the 100°C needed to desorb most of the air from the zeolite, nor become embrittled down to the -40°C needed to fully load the zeolite with air. Prestressed cylindrical concrete pipe similar to that widely used for water transport fulfills these requirements. It is more durable than comparable steel pipes, costs less, and is most often rated to the desired pressure of 150 psig. These particulate beds are held in place by screens at the tops and bottoms of the pipe lengths. The two lengths are connected at their tops and bottoms by steel fixtures, as indicated in Fig. 3. The entire module is thermally insulated, in our example by a layer of polyurethane foam, which in turn is covered by a membrane to protect it from moisture and abrasion.

In its discharged state, the zeolite bed is hot while the inert bed is cold. In order to charge the module, hot compressed air is blown into it through the nozzle seen on the lower right of Fig. 3. As the resulting jet enters a constriction in the lower fitting often called an eductor, it

increases in velocity according to Bernoulli's principle and entrains the compressed air around it in the flow. This flow then enters a diffuser beneath the cold inert bed, increasing the pressure and forcing the air through the bed. The porosity and particulate geometry of the bed are designed to result in a turbulent flow through it. This ensures that the rate of heat transfer from the hot air to the particulate occurs rapidly compared to the time it takes the air to pass through the bed. The result is a well-defined thermal front which passes slowly from the lower end of the bed to the upper, while the air emerges from the top of the bed at the initial temperature of the bed the whole time.

The now cold compressed air continues through a radiator cooled by a circulating refrigerant to the desired temperature of the zeolite in the fully charged module. This compensates for any cold lost from the inert particulate while the system was in its discharged state. The air then flows into a diffuser above the hot zeolite bed, wherein the porosity and particulate geometry have likewise been designed to ensure a turbulent flow through it. As the zeolite cools, a portion of the air will be adsorbed, releasing additional latent heat that adds to the effective heat capacity of the zeolite. The remainder of the air will continue through the bed and emerge from its bottom at the initial temperature of the zeolite. This air will then be entrained by the jet for another pass around the module. The volumes of the inert bed and the zeolite bed are designed so that the total heat capacity of the inert bed and the total effective heat capacity of the zeolite bed are equal. Thus the cold front passing through the zeolite bed reaches the bottom of the bed at the same time as the hot front passing through the inert bed reaches the top of that bed. When this happens, the system is fully charged.

In order to keep tank volumes hence costs down, the volumetric heat capacity of the inert bed should be larger than the effective volumetric capacity of the zeolite bed, which will be about  $1 \text{ kJ} / (\text{K-L})$ . The review

of the heat capacities of minerals found in Ref. [4] shows there are a number of common minerals available with volumetric heat capacities exceeding  $3 \text{ kJ} / (\text{K-L})$ . Another, issue worth mentioning is that, since nitrogen is adsorbed more strongly by zeolites than oxygen, the hot air emerging from the zeolite bed will be enriched with oxygen. Although diluted by the new air coming in from the nozzle, the air reaching the top of the zeolite bed will still be significantly enriched. In the steady state, the equilibrium reached between the enriched air and the zeolite will have more oxygen adsorbed than would be the case with unenriched air. Because the amount of free gas in the module is small compared to the amount adsorbed in the fully charged state, the adsorbed phase should ultimately consist of nearly 21% oxygen, as in atmospheric air.

To discharge the module, one simply reverses the charging process. Thus instead of blowing air in from the nozzle, one sucks air out through it. The resulting suction lowers the pressure around the nozzle and causes the air in the module to circulate in the opposite direction to that while charging it (counterclockwise in Fig. 3). This causes a cold thermal front to pass downwards through the inert bed and a hot front to pass upwards through the zeolite bed. Once these break through their respective beds, the module has been discharged. The radiator in the top fitting of Fig. 3 can also be used to compensate for any cold lost between charging and discharging. In contrast, heat lost during the quiescent periods between charging and discharging or vice versa can only be made up for with the heat carried by the compressed air as it enters through the nozzle during the charging process. This simple approach should be adequate, although more complicated designs are possible which also allow heat to be added during the discharging process. The air exiting the module during the discharging process will at first be enriched with oxygen, but once a steady state has been reached we expect that the emerging air will have very nearly its normal composition.

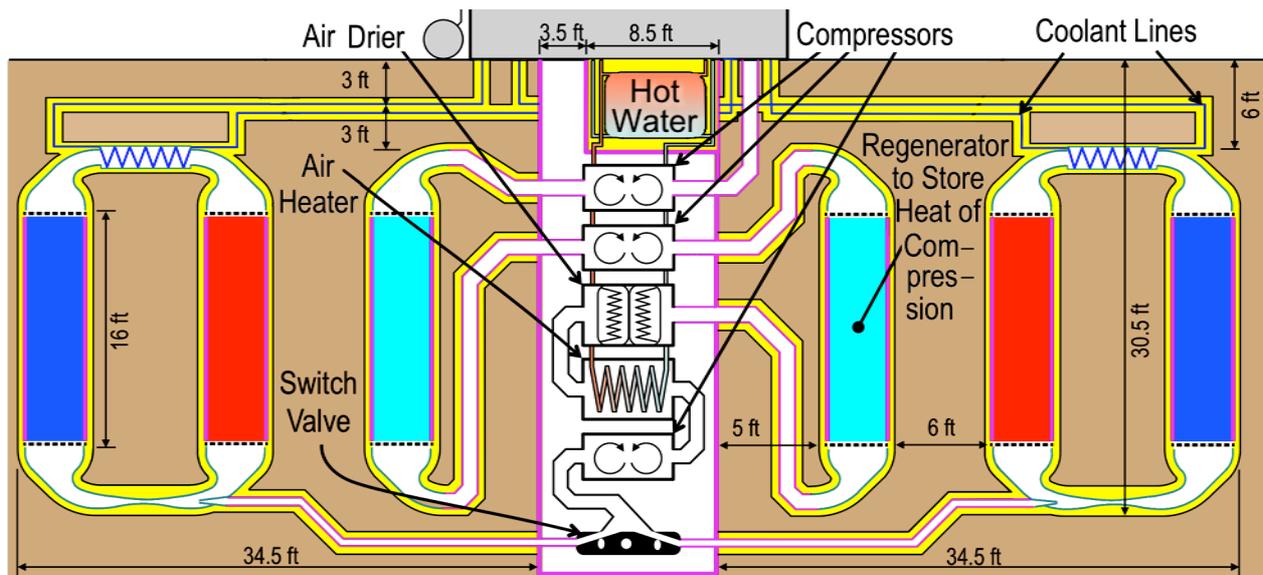


Fig. 4. Cross-sectional view of the underground portion of an AE-CAES system. The dimensions shown are representative but could be varied substantially according to the needs of any particular application.



hours will be needed to fully charge or discharge the system. Each module is expected to take about 2 hours to be charged or discharged, and the switch valve seen at the bottom of the compressor pit will direct the compressed air to 8 of the 24 modules at a time, so that they are charged or discharged in three groups.

Assuming near-adiabatic compression, each stage will heat the air to just over 100°C, after which the air is run through one of the regenerators in the innermost ring. This cools the air back to ambient and stores the heat in the inert particulate therein for recovery during expansion. As the air cools in these regenerators, water will condense and flow downwards with the air to the bottom of the regenerator, where the water collects and is pumped out through a drain to the central equipment facility for disposal. In this way the majority of water in the air will have been removed before the third stage of compression. The remaining water is removed by running the air through a desiccant drier, which uses as its desiccant the same zeolite as is used in the energy storage modules. This ensures that no water or other contaminants will buildup in the modules and reduce their zeolites' capacities over time. The relatively small quantity of zeolite in the drier can readily be regenerated by heating to 300°C, and replaced should its activity decline over time as a result.

Finally, the air is warmed prior to the third stage of compression, so that it comes out of the compressor at approximately 130°C. This additional heat replenishes the heat lost from the modules between charging and discharging them or vice versa. We will now describe how this heat, together with the cold needed to make up for its losses in the modules, is obtained in our illustrative AE-CAES system.

### Heating and cooling apparatus

The amount of thermal energy needed to make up for lost heat and cold between charging and discharging the system, and between discharging and charging it, will likely amount to a significant fraction of the mechanical energy that it stores. Thus in order for the system to attain a reasonable roundtrip efficiency, either (a) heat pumps with a coefficient of performance much better than unity must be used, or (b) the heat and cold must be freely available from the environment. Whereas heat at the modest temperatures of ca. 100°C is often available either from a waste stream or from solar thermal panels, cold at the requisite deep freeze temperatures is seldom found in abundance save at extreme latitudes in the winter.

Fortunately thermochemical refrigeration techniques such as absorption or adsorption refrigeration can be used to generate cold from low-grade heat. Because temperatures much below freezing are not commonly achieved by these techniques, the AE-CAES system presented here will only use them to chill water to ca. 4°C. This chilled water will then be used as a heat sink for an electrically driven vapor-compression heat pump, thereby giving this second stage a higher coefficient of performance and reducing its parasitic electrical load.

The resulting heating and cooling apparatus is shown schematically in Fig. 6. It is housed in a shed on top of the compressor pit, completing the central equip-

ment facility. Mounted on the roof of the shed are one or more solar thermal panels, which produce near-boiling water on a sunny day. A propane backup is included so that hot water will always be available. The hot water is stored above the thermocline of a water tank under the shed and above the compressor pit. This hot water is used to heat the air prior to the third stage of compression, as previously explained. It is also used to drive a thermochemical water chiller, which in the present system is taken to be an adsorption refrigerator based on the silica gel / water pair. Its efficiency is improved by using an evaporative cooling tower to dissipate the heat of adsorption.

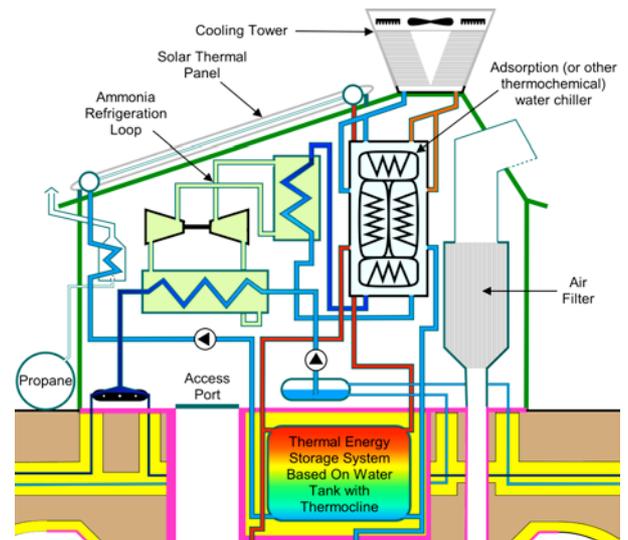


Fig. 6. Schematic diagram of the heating and cooling apparatus for the AE-CAES system, which is housed in a shed above the compressor pit.

The chilled water passes through the condenser of an electrically driven ammonia-based refrigerator, which in turn cools a water-glycol mixture down to -40°C. By using an expansion turbine coupled to the ammonia compressor, as indicated in the diagram, we expect this refrigerator to achieve a coefficient of performance in excess of 5. The water-glycol mixture is then pumped to the radiators of the active modules, using a switch valve similar to that used to determine which bank of 8 modules each is being charged or discharged with air at any point in time. We expect this two-stage refrigeration process to give the AE-CAES system a roundtrip electrical efficiency in the range of 60-80%.

Further improvements in efficiency are possible. First, Rebound Technologies LLC has recently developed a thermochemical refrigeration method that is capable of going from water ice down to -40°C using only low-grade waste heat [7]. Ice in turn can be produced by a number of other thermochemical refrigeration systems, for example an adsorption chiller based on the activated carbon / methanol pair [8]. Another way to improve the effective efficiency would be to use the hot water to heat the air prior to the first and second stages of compression, in addition to the third. This additional heat would be stored in the regenerators and recovered prior to expansion, upon which a portion of it would be converted into electrical energy. Such a

system would also be harvesting energy in addition to storing it, but since solar heat is free, from an economic perspective the result is the same as a higher storage efficiency.

## DISCUSSION AND FUTURE WORK

We have given a complete and precise description of a thermally closed AE-CAES system that makes use of regenerative thermal energy storage and thermochemical refrigeration techniques. There are many open questions regarding the performance and costs of such a system, but some significant advantages over other many other forms of energy storage are already clear.

First, the system will be environmentally benign, in that it contains no toxic, caustic or otherwise dangerous materials that could not safely be disposed of in a landfill. If charged with electricity from renewable sources and provided with a biofuel backup in place of propane, it could also be operated in a entirely carbon-neutral fashion. Second, it will be at least as safe as any form of energy storage available today, since the cold zeolite will only release its air slowly as it warms, so that a simple pressure relief valve ensures that it discharges safely even if everything else fails. The fact that the system is largely underground adds to its safety and makes sabotage difficult, in addition to freeing up the land above it for other uses. These features makes it highly suitable for use in populated areas near to the load centers, where energy storage is generally most valuable.

Third, zeolites do not degrade under pressurized air unless heated to temperatures above 400°C when wet or 500°C when dry. Since we do not need to go above 100°C in normal operation and the modules will be fed dry air, the zeolite will last essentially forever under the intended operating conditions. The modules also contain no moving parts that could wear out, and nothing that could corrode unless the membrane fails and moisture reaches the steel components. Such membranes are very durable, being used to waterproof basements and other subterranean structures that would be difficult to service. Therefore it seems safe to say our modules will need no maintenance and have a mean time to failure on the order a century – considerably longer than any energy storage technology of which we are aware that does not rely on geological formations and hence may be deployed freely. This should result in a low life-cycle cost per unit of energy stored and released over the system's lifetime, as well as with respect to the Barnhart and Benson metric [9].

The upfront and operating costs per unit power will also be quite favorable, since it will be dominated by the cost of the twin-screw compressors that are also used for electricity generation. At 50 kW these run about \$500 / kW (lower at larger scales), which is considerably less than electrochemical technologies such as flow batteries. Well designed and maintained compressors with the modest compression ratios required for AE-CAES will also be better than 95% efficient in both compression and expansion. Of course they will need to be maintained and replaced every decade or two, but as a rule the cost of ownership of such compressors is 75% electricity and only 25% maintenance and capital costs.

Given the efficiency of compression and expansion, the main sources of efficiency losses that remain to be quantified are (1) the mechanical energy lost due to friction as the air passes through the packed beds, and (2) the thermal energy lost from the modules and other regenerators over the storage cycle. The first of these can be estimated by numerical simulations for any given regenerator and particulate geometry, but finding the geometries that minimize frictional losses while still obtaining the desired performance characteristics is a nontrivial problem. Chemical engineering software like that available from Aspen Technologies™ can solve such optimization problems, but their cost has precluded our doing up to this time. Even so, the results of such simulations must always be confirmed by building and analyzing actual prototypes.

Because of the large number of potential sources of thermal energy losses, it will probably not be possible to give a meaningful estimate of their magnitudes until the resources needed to build full-scale prototypes have been summoned. What we can say at this time is that the work by Isentropic Ltd. [2] and nearly two centuries of engineering experience with regenerators indicates that these losses can be managed. By this we mean that they can be reduced to a level at which they can be compensated for by a reasonably small solar thermal or other low-cost sources of low-grade heat, together with a reasonably small refrigeration system driven, at least in part, by such low-grade heat. Until this has been demonstrated in practice, however, thermally open AE-CAES systems may be a more saleable value proposition, albeit one with a smaller market potential.

In summary, we have given a detailed design for a thermally closed AE-CAES system, and described some of its advantages over batteries. AE-CAES is not, of course, a perfect substitute for batteries, which can respond much faster and are considerably more compact. AE-CAES is nevertheless very suitable for diurnal load shifting in a distributed setting, because it is very safe, capable of long durations, and its thermal losses are minimized by daily cycling. Thermally open AE-CAES systems also promise to be useful in matching thermal and mechanical loads in microgrids powered by some subset of gas-fired turbines, internal combustion engines, wind turbines, photovoltaics or solar water heaters. Perhaps the most important difference between AE-CAES and batteries, however, is the following. Rather than being a device which is assembled in a factory and then shipped ready-for-use to its destination, AE-CAES facilities are expected to be construction projects that are built to-order onsite out of standardized components, and then become part of the locality's basic infrastructure. This is of course much closer to how electric utilities have traditionally thought about their investment strategy.

In order to realize the promise of AE-CAES, Energy Compression is currently seeking to partner with a well-established engineering firm that focuses on energy and other infrastructure projects. This partnership may include an exclusive license to AE-CAES, restricted to a selected geographic region and/or energy storage application, in exchange for developing and marketing a corresponding product tailored to that region or application. Interested companies are invited to contact the author for further discussion.

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## AUTHOR'S BIOGRAPHY



Timothy F. Havel is the Founder and CTO of Energy Compression Inc., an early-stage startup in the Boston area focused on commercializing AE-CAES. Over the last five years his primary activity has been developing the intellectual property and identifying the market opportunities for this technology.

Immediately prior to founding Energy Compression Inc., Tim worked at MIT in its Center for Technology, Policy and Industrial Development, and in its Dept. of Nuclear Science and Engineering. His academic career covers over two decades of research in diverse topics in computational chemical physics, including the ETH in Zürich, the Scripps Research Institute in La Jolla, the Univ. of Michigan in Ann Arbor, the Harvard Medical School in Boston and MIT in Cambridge, MA.

Dr. Havel holds a Bachelors in Chemistry from Reed College in Portland OR (1977), a Doctorate in Biophysics from the Univ. of California Berkeley (1982), and a Masters in the Management of Technology from the MIT Sloan School of Management (2007).