



## Adiabatic Liquid Piston Compressed Air Energy Storage

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Energinet.dk project no. 2011-1-10682

*January 2013*

*Tage Petersen, Danish Technological Institute*

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***Energy & Climate  
Refrigeration and Heat Pump Technology***

## **Preface**

This report is the documentation for the ForskEL-project “Adiabatic Liquid Piston Compressed Air Energy Storage”, funded by Energinet.dk, journal number 2011-1-10682.

The project was performed jointly by a group consisting of the Technical University of Denmark, DONG Energy and KBB Underground Technologies with the Danish Technological Institute as project leader.

The authors would like to thank Fritz Crotogino, KBB Underground Technologies, and Aksel Hauge Pedersen, DONG Energy, for all their contributions in form of background knowledge, hints and advices provided for the project. These contributions have been extremely valuable for the project.

## Resume

This project investigates the potential of a Compressed Air Energy Storage system (CAES system). CAES systems are used to store mechanical energy in the form of compressed air. The systems use electricity to drive the compressor at times of low electricity demand with the purpose of converting the mechanical energy into electricity at times of high electricity demand.

Two such systems are currently in operation; one in Germany (Huntorf) and one in the USA (Macintosh, Alabama). In both cases, an underground cavern is used as a pressure vessel for the storage of the compressed air. Both systems are in the range of 100 MW electrical power output with several hours of production stored as compressed air. In this range, enormous volumes are required, which make underground caverns the only economical way to design the pressure vessel.

Both systems use axial turbine compressors to compress air when charging the system. The compression leads to a significant increase in temperature, and the heat generated is dumped into the ambient. This energy loss results in a low efficiency of the system, and when expanding the air, the expansion leads to a temperature drop reducing the mechanical output of the expansion turbines. To overcome this, fuel is burned to heat up the air prior to expansion. The fuel consumption causes a significant cost for the storage.

Several suggestions have been made to store compression heat for later use during expansion and thereby avoid the use of fuel (so called Adiabatic CAES units), but no such units are in operation at present.

The CAES system investigated in this project uses a different approach to avoid compression heat loss. The system uses a pre-compressed pressure vessel full of air. A liquid is pumped into the bottom of the vessel when charging and the same liquid is withdrawn through a turbine when discharging. In this case, the liquid works effectively as a piston compressing the gas in the vessel, hence the name “Adiabatic Liquid Piston Compressed Air Energy Storage” (ALP-CAES). The compression ratio of the gas in the vessel (ratio between maximum and minimum pressure) is relatively low; typical values would be  $< 1,5$ , whereas the compression ratio in existing CAES systems can be higher than 100, because the air is compressed from atmospheric pressure to the storage pressure.

This investigation leads to the conclusion that:

- The mechanical/electrical efficiency of the ALP-CAES system is significantly higher than existing CAES systems due to a low or nearly absent compression heat loss. Furthermore, pumps/turbines, which use a liquid as a medium, are more efficient than

air/gas compressors/turbines. In addition, the demand for fuel during expansion does not occur.

- The energy density of the ALP-CAES system is much lower than that of existing CAES systems (by a factor of 15-30) leading to a similar increase in investment in pressure vessel volume per stored MWh. Since the pressure vessel constitutes a relatively large fraction of the overall cost of a CAES system, an increase of 15-30 times renders the system economically unfeasible unless the operating conditions and the system design are very carefully selected to compensate the low energy density. Future electricity prices may increase to the extent that the efficiency benefit of ALP-CAES partly compensates the added investment.
- When comparing ALP-CAES to an adiabatic CAES system, where compression heat is stored in thermal oil, the ALP-CAES system is found only to be competitive under a very specific set of operating/design conditions, including very high operation pressure and the use of very large caverns.
- New systems are under development, which show an interesting trend in that they use near-isothermal compression and expansion of air (compression/expansion at almost constant temperature), eliminate compression heat loss and still maintain nearly the same level of energy density as existing CAES systems. This combination of features may make these systems superior to the ALP-CAES solution. The new systems are delivered by companies such as LightSail Energy and General Compression. Apparently, these new systems use piston compressors/expanders, at least for the prototypes. However, for large scale systems, piston mechanisms are not the most economical solution. In terms of large scale systems, turbo machinery is the only economical solution.
- Even adiabatic CAES systems seem to add more cost to the electricity than can be accepted in the Danish power system. This added cost is primarily due to the investment in turbine/generator, heat exchangers, and a large quantity of thermal oil. To improve the economy, it would be relevant to investigate the possibility of replacing the thermal oil by water, for example by injecting the water directly into the air flow between the different compression stages to get a direct heat exchange between water and air. This investigation would focus on direct heat exchange in combination with turbo machinery.

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## **1. Background**

The Danish electricity grid will in the future receive more and more power from intermittent sources such as wind turbines and photovoltaics. In periods with low wind and/or low solar radiation, backup power is required. This backup power can come from ordinary power plants fired by fuels or power plants in other countries, and it can come from power stored in local energy storages, which are charged in periods of excess wind or solar power.

For bulk storage of large quantities of mechanical energy, one of the most economical solutions is a Compressed Air Energy Storage (CAES). In this type of system, energy is stored in the form of compressed air in large underground caverns and is converted to electricity by running the compressed air through a turbine expanding it to atmospheric pressure.

With the present variations in electricity prices in Denmark, conventional CAES systems are not economically feasible, partly because of the rather large investment required, and partly because the systems involve energy losses that affect the operation economy.<sup>[4]</sup>

Future increases in wind and solar power are expected to bring larger variations in electricity prices, which may render CAES systems economically and/or politically attractive.

This project investigates an alternative type of CAES system, which would be expected to have an improved operation economy (fewer losses) and might therefore be more competitive.



## 2. Principle of Existing CAES Systems

Existing CAES systems use off-peak electricity to compress air. The compression typically takes place in several stages with air-cooling heat exchangers between the stages to remove compression heat, which is dumped into the ambient. Compressors and heat exchangers are located around label “1” in figure 1. The compressors are driven by a motor/generator, label “2”, which uses electricity from the grid. After compression, the compressed air is entered into one or more underground caverns, label “4”. In principle, the compressed air could be stored in tanks at ground level, but for bulk storage, underground caverns are much more economical.

During peak hours, compressed air from the caverns is fed into the turbine, label “3”, which drives the motor/generator, label “2”, and delivers electricity to the grid. Before entering the turbine, the air is heated by natural gas in a burner.

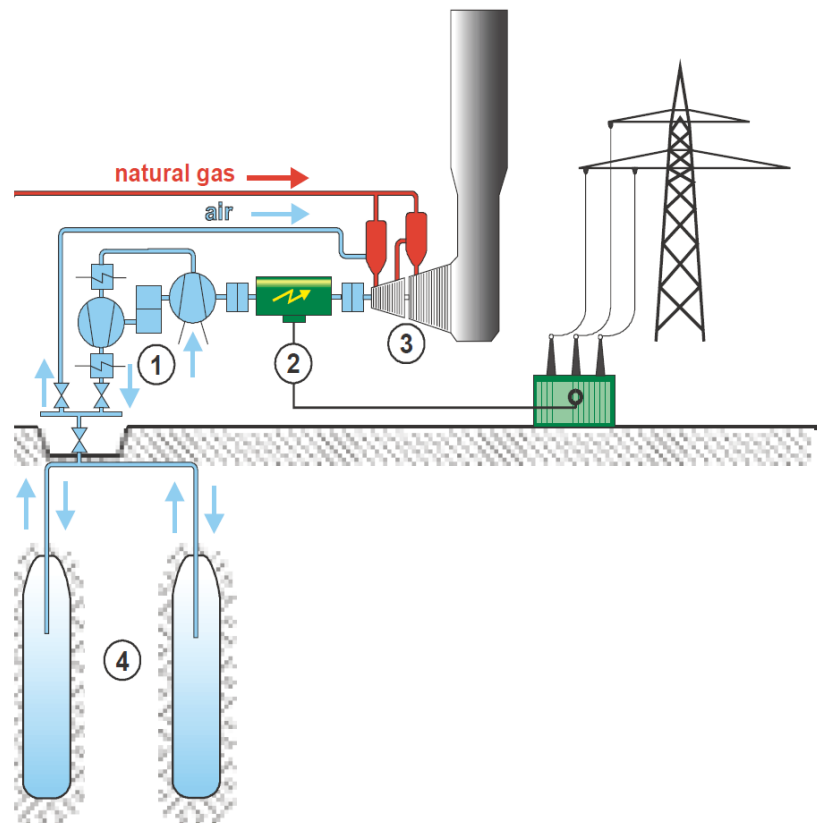


Figure1: CAES system at Huntorf, Germany.[2]

The expansion in the turbine typically takes place in several stages, and as shown in figure 1, burners may be placed between the different stages. The reasons for heating up the air are mainly:

- Hot air fed into the turbine increases the amount of power delivered.
- Air cools down during expansion, and if not heated, it eventually leads to condensation or frost build up, which results in poor turbine performance.
- The expanders are conventional machines designed for high turbine inlet temperatures.

Moreover, as indicated in figure 1, clutches are placed on both sides of the motor/generator to ensure engagement or disengagement depending on the two operating modes.

Depending on viewpoint, the system could be considered to be an “energy storage” or a “gas turbine, where compression and expansion take place at different times”, and thus allowing a decrease of 40-60% in the need for natural gas and a reduction of 40-60% in CO<sub>2</sub> emissions. The latter is probably the best description of why the existing CAES systems were built.<sup>[2]</sup> Gas turbines are often used for peak electricity production, because they can be built at a relatively low cost per MW power. The energy efficiency is typically lower than other power plants, but this is not that important in that a gas turbine only will be running a few hours per day. When performing the compression process at off-peak hours, the energy efficiency does not improve, but it will ensure a better economy in that the power used for compression is cheap. At the same time, the power production during peak hours will increase, because the turbine does not have to drive the compressor. In other words, turbine investment cost per MW power is even lower than with a normal gas turbine (apart from the cost of the cavern).

Figure 2 shows the CAES system at Macintosh, Alabama, which is very similar to the Huntorf facility apart from the fact that the Macintosh facility only has one cavern and the air coming from the cavern is preheated by an exhaust gas recuperator before entering the turbine/burner. Several other variants have been proposed with various heat exchangers and other details added for efficiency improvement, but so far none of these have been built. [4][6]

Figure 2: CAES system at Macintosh, Alabama, USA.[6]

Viewing the CAES system as “energy Storage” only and with the intention of using it in a future without consumption of fossil fuels, the use of natural gas (or other fossil fuels) should of course be avoided. If we disregard the option of using non-fossil fuels, the only ways to effectively run a CAES system would be:

Figure 3 shows a system where compression heat from the two stages is stored by heat exchange with oil. The hot oil is kept in an insulated tank for later use. Hot oil storage is a well-known technology from solar power plants.[7] The oil is physically separated from the compressed air, so that the oil tanks can maintain a relatively low pressure.

Compared to a traditional CAES system, the fuel consumption is 0 (zero), but the insulated tanks and oil require an additional investment. Depending on the type of oil used, a 100 MW system using the temperatures shown in figure 3 might require oil quantities of 800 tons/operating hour. For example, assuming three operating hours per day, the system would need to be charged with 2400 tons of oil meaning an investment of at least Dkr 30-40 million for the oil.

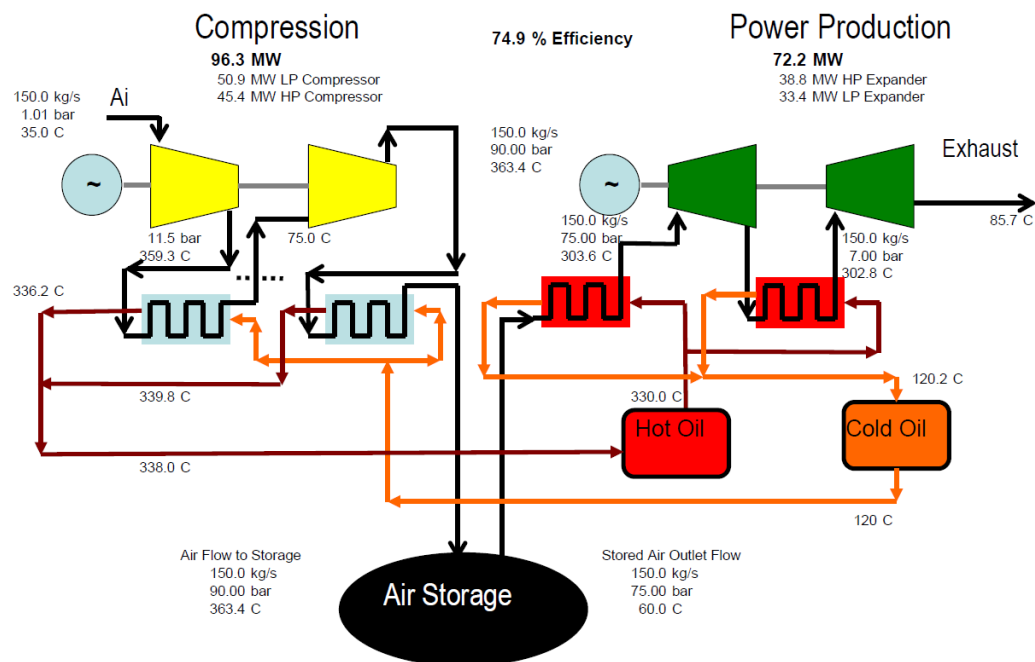
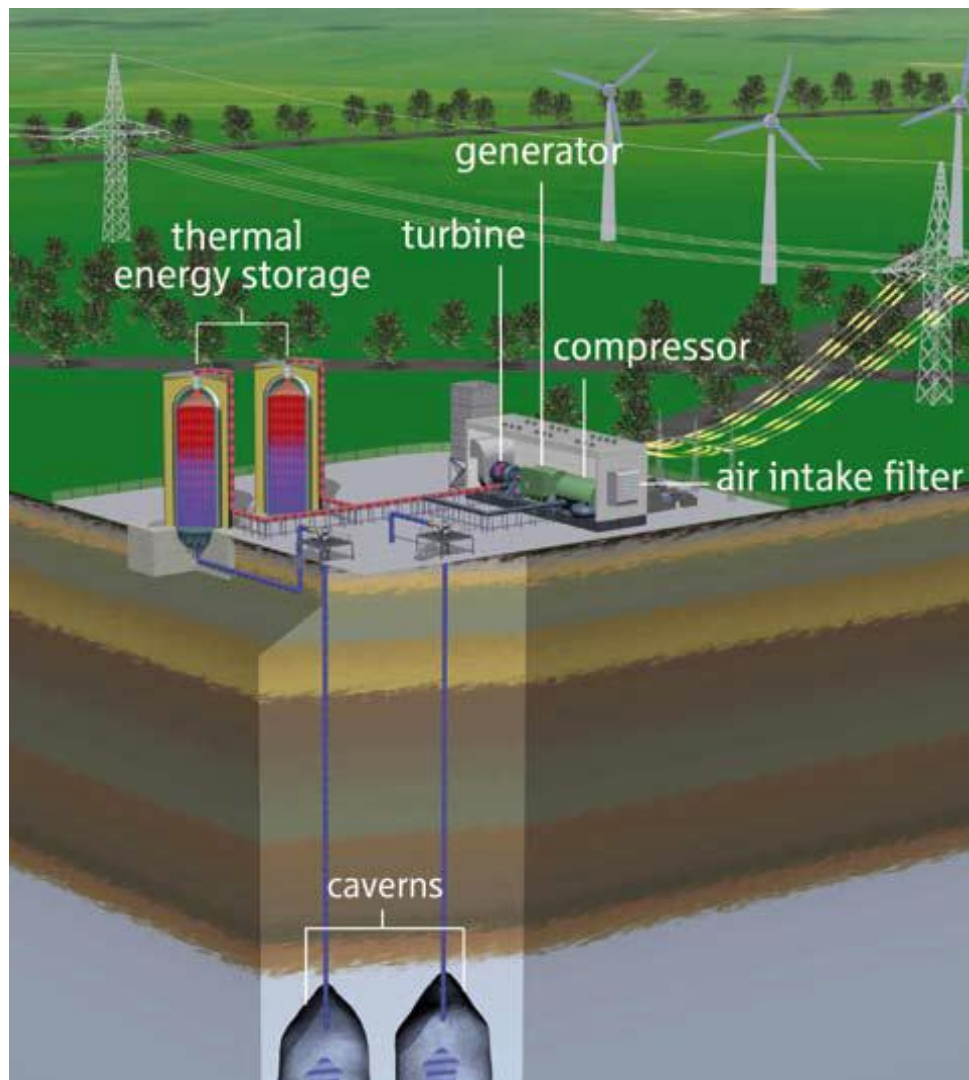


Figure 3: CAES system using hot oil as thermal storage.[6]

Figure 4 shows an approach, where compression heat is stored in a porous solid. In this case, the compressed (hot) air is fed into an insulated tank filled with a porous solid. The air exchanges heat with the solid and enters the cavern at near ambient temperature. At discharge, the air is fed from the cavern into the insulated tanks and is heated before entering the turbine.[8]



*Figure 4: The “ADELE” project with thermal storage in tanks with porous solids.*

The main benefit of this system is that the porous solid might be cheaper than the hot oil in the previous example. However, the pressure in the porous solid is the same as the cavern pressure, which means that the porous solid must be contained in insulated high pressure tanks adding further to the cost.

## 2.2. ALP-CAES: a Different Approach

The ALP-CAES system uses a different approach to avoid heat loss. In this system, an underground cavern is filled with air and pre-compressed to for example 200 bar. By using a motor/pump, water (or another suitable fluid) is pumped into the cavern against the air pressure. The water is taken from a pond at ground level and at atmospheric pressure.

The pressure ratio of the storage between charged and discharged conditions is low, close to unity. Even in fully charged condition, only a small fraction of the cavern volume is filled with water, and the air pressure is not much higher than the starting pressure. Consequently, the air temperature is not much higher than the start temperature.

The temperature increase by pressurization of liquid water is insignificant, which is why cooling is not required.

In addition, it is expected that the cost and efficiency of a pump/turbine using a liquid as a medium is favourable compared to compressors/turbines using air as a medium.

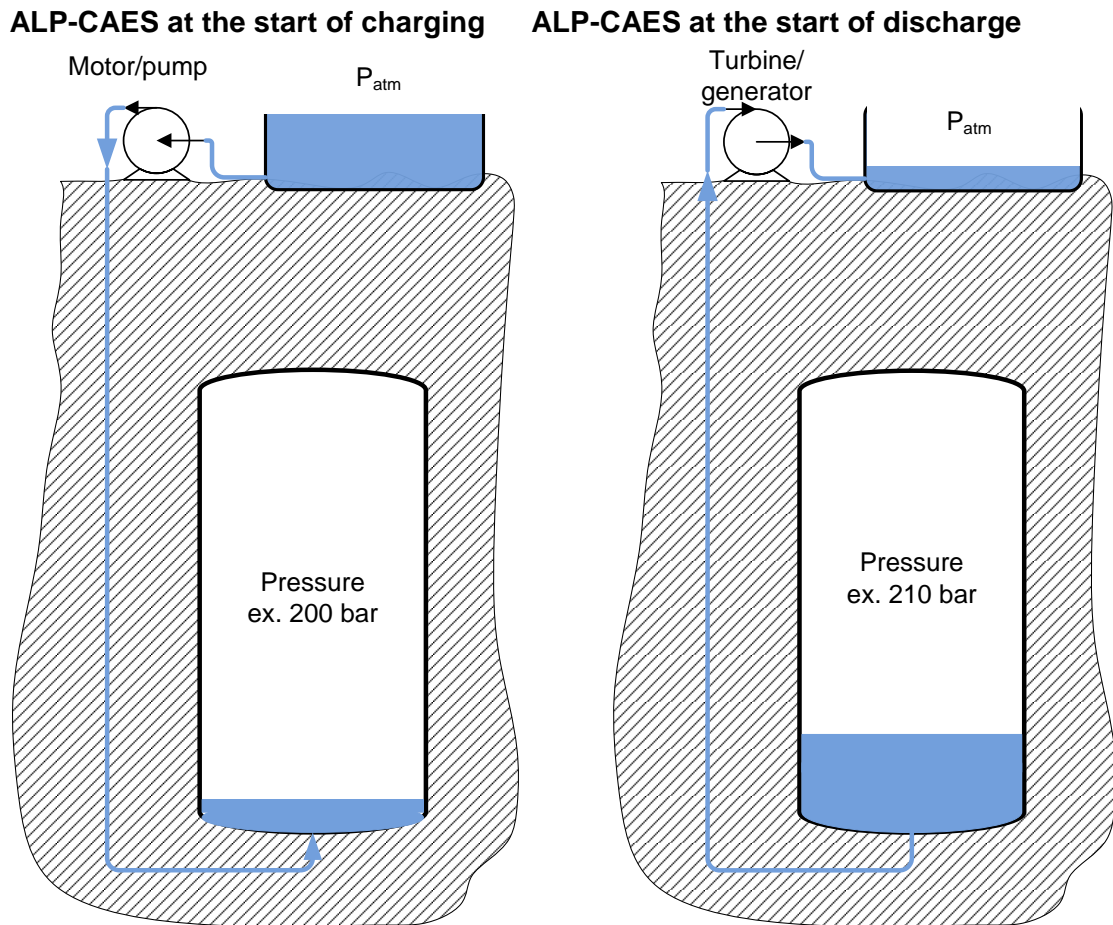


Figure 5: Basic ALP-CAES system.

In principle, the system could be built in small scale using high pressure tanks at ground level. However, since the background of this project is a wish for large scale bulk storage, underground cavern designs are the primary scope of this report.

### **3. Cavern Considerations**

Underground caverns are mostly produced by solution mining, which means that a hole is drilled into an underground salt dome. Water is pumped into the salt dome to dissolve some of the salt and the saturated salt brine is dumped into the ocean, sometimes after diluting the salt brine to contain an appropriate salt concentration. A long flushing/dissolution process follows, which creates a cavity in the salt dome, and after finally removing the remaining salt brine, the cavern is ready to be used as compressed air/gas storage. The process of dissolving the salt may take several years for a large cavern. Still, solution mining is one of the most economical ways to produce large underground reservoirs, partly because the construction material (the salt dome) is almost free of cost, and partly because all operations are done from ground level. Thus, there is no need for sinking shafts or having personnel or machinery operate at great depths.

When using an underground cavern in a salt dome as pressure vessel, there are a number of considerations to be made concerning maximum and minimum pressure, cavern depth etc.

For example, a cavern may not be able to withstand the pressure of the rock on top of it, if the gas pressure inside the cavern is too low. Rock salt is viscoplastic, and it will slowly creep leaving a large trough at ground level. Likewise, a cavern will not be able to withstand a pressure higher than the pressure corresponding to the weight of the rock on top of it, and if a higher gas pressure is used, the rock around the cavern may fracture, and it will not be able to hold the air pressure.

The graph in figure 6<sup>1</sup> shows the normally used relationship between pressure and depth (of the cavern top).

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<sup>1</sup> Courtesy of KBB Underground Technologies[2]

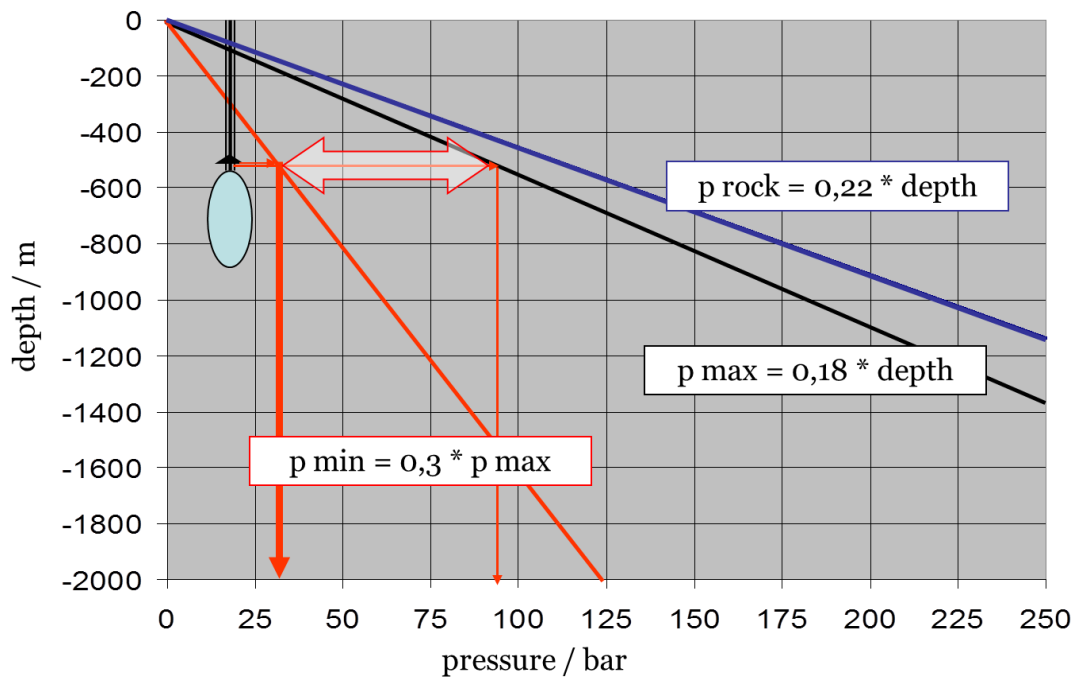


Figure 6: “Thumb rule” of the relationship between depth of cavern top and pressure.

For example, if a maximum cavern pressure of 200 bars is anticipated, the depth of the cavern top must be at least 1100 meters. In the ALP-CAES case, the pressure of the ground level turbine is smaller than the pressure of the cavern due to the weight of the liquid column in the piping that runs from the cavern to the turbine. When neglecting the height of the cavern and by using water as a medium, the weight of the column of water reduces the pressure by 110 bars, which leaves a difference of only 90 bars in pressure for the power production. This equals a pressure ratio of about 2.

When using air as a medium, as in a conventional CAES system, and taking the air from the top of the cavern, the reduction in pressure will be 22 bars in that the density of air at 200 bars is approximately  $200 \text{ kg/m}^3$ . Thus, air density at ground level is approximately  $180 \text{ kg/m}^3$ , which means that the average density in the piping is approximately  $190 \text{ kg/m}^3$ . This means an actual reduction in pressure of 20 bars. In other words, it is a good approximation that the energy density of a conventional CAES system using air as a medium is reduced by 10 % due to the weight of the air column.



### 3.1. Alternative Pressure Vessels

For small scale CAES systems, ground level steel tanks or piping systems might be considered. The price depends heavily on type, as seen in figure 7. Standard 40-litre nitrogen flasks and other industrial gases are mass-produced in large quantities, which means a relatively low price of approximately Dkr 10,000/m<sup>3</sup>. Large high pressure tanks are typically made to order, which means a higher price per m<sup>3</sup>.<sup>[5]</sup>

According to Nyserda<sup>2</sup><sup>[6]</sup>, a large scale tank system at ground level, which is composed by stacks of long and large diameter pipes with domed ends, can be built at roughly five times the price of an underground cavern. For small volume systems (volume < 40.000 m<sup>3</sup>), ground level pipe systems seem to be competitive to caverns.

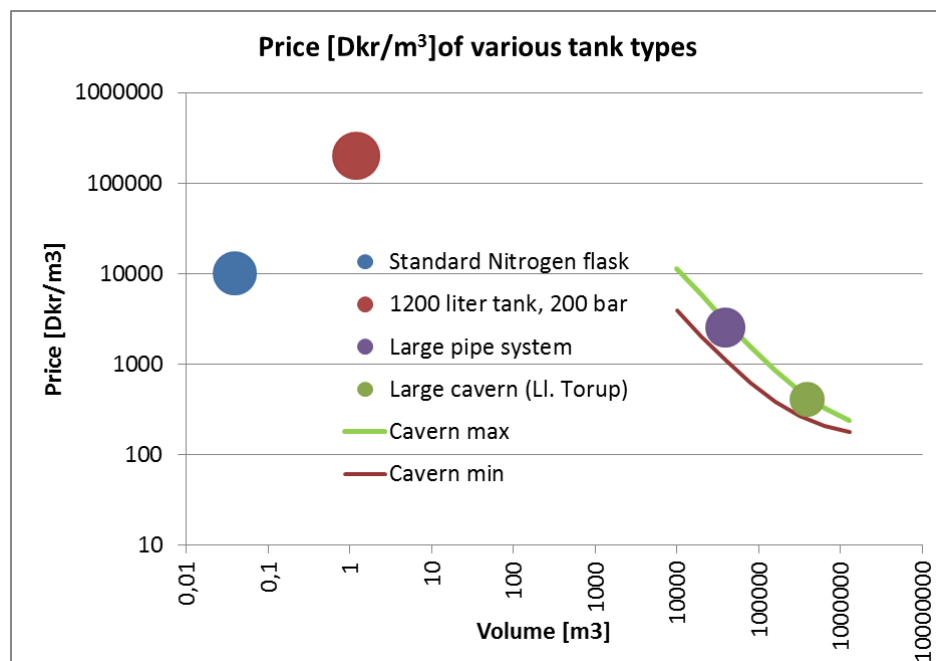


Figure 7: Price of various high pressure tanks types.

The price of a cavern similar to the caves in the natural gas storage (500.000 m<sup>3</sup>) at Lille Torup, Denmark, is approximately Dkr 200 million. According to DONG<sup>[3]</sup> and KBB Underground Technologies<sup>[2]</sup>, this price is equivalent to Dkr 400/m<sup>3</sup>. The caverns at Lille Torup are quite large and in the same scale range as the cavern at the Macintosh CAES-unit, USA. Smaller caverns tend to have a higher price per m<sup>3</sup>.

<sup>2</sup> New York State Energy Research and Development Authority.

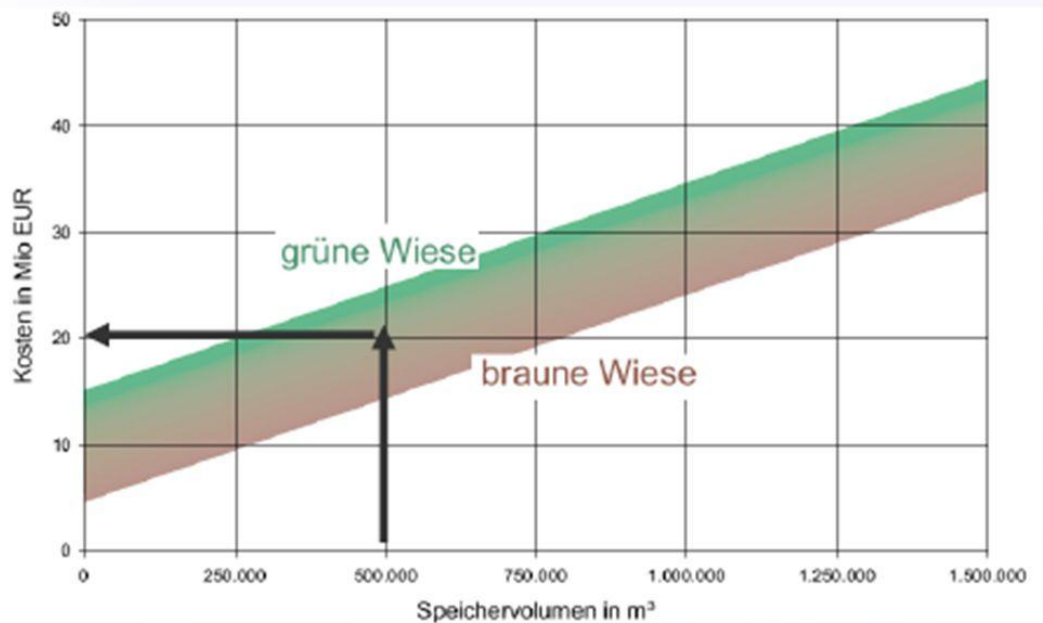


Figure 8: Price range of solution mined caverns.[2]

Abandoned mines have been suggested for the use as pressure vessels for CAES systems. This idea has been discarded after corresponding with KBB Underground Technologies[2] due to the following reasons:

- Most rocks such as coal or granite are fractured and do not allow containment of liquids or even gases under pressure.
- In many cases, mines only provide limited amounts of open – not backfilled – volumes (compared to caverns), which means that the usable volume is limited.
- Even if the volume is large enough and a generally tight host rock such as salt is available, it is very difficult to prove the tightness of the entire mine before air has been filled into the mine.
- The cost for sealing the large access shafts is very expensive.

Because of these reasons, there is only one minor gas storage in an abandoned mine in Europe. Even though there are many mines.

An underground aquifer has equally been suggested as pressure vessel. An aquifer consists of a porous mass (e.g. sandstone) originally filled with saline water with a gastight layer (seal) on top of it. This technology is well-known from the natural gas storage at Stenlille, Denmark.

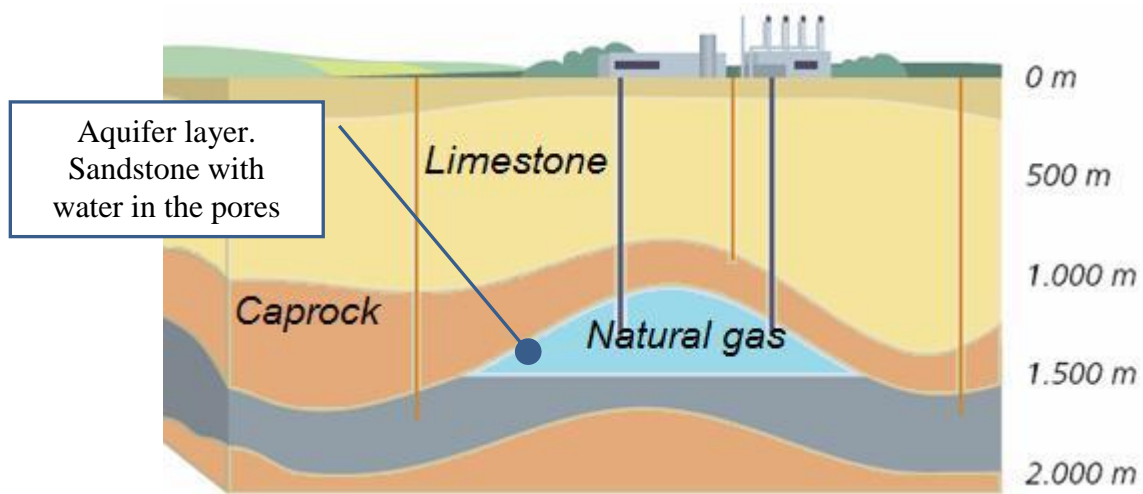


Figure 9: The aquifer natural gas storage at Stenlille, Denmark.

This idea was also discarded by KBB Underground Technologies<sup>[2]</sup> because of these reasons:

- An aquifer used as gas storage can only be filled/emptied on a monthly basis. This is the reason why porous reservoir storages are mainly used for seasonal natural gas storage.
- An aquifer used as flexible CAES-storage means much higher flow rates, for example because emptying/filling happen on a daily basis. The pressure drop through the porous layer is also high leading to a very poor round trip efficiency.
- Oxygen may react with the host rock and lead to oxygen depletion, or clog the tiny pore spaces.

#### 4. Energy Density for ALP-CAES vs. Other CAES Types

The investment costs are a relatively large part of the total operating cost of a CAES system, especially when considering a system *without* gas/oil burners. The investment costs depend on type of CAES system, size, power output, maximum pressure etc.

If disregarding the efficiency of the turbine/generator, the main factors determining the amount of energy that can be stored are the CAES type, the operating pressures, and the size

of the pressure vessel. When comparing ALP-CAES to other CAES systems, the cost of the tank/vessel/cavern needed for the desired amount of electricity stored should be evaluated as part of the economic analysis. This is done by calculating the energy density (e.g. expressed in kWh/m<sup>3</sup>) for a tank used in the different CAES systems.

When calculating the energy density of a tank in an ALP-CAES system, the compression (or expansion) of the air may be calculated as isothermal (taking place at constant temperature) or adiabatic (taking place with no heat exchange). Since the pressure ratio is relatively low, even in the adiabatic case, the temperature increase is small, which means that the difference between the calculations is minimal. For the sake of simplicity, the calculations in the following assume isothermal compression/expansion.

The same calculation may be more complex for an unfuelled “standard” CAES system. In a “standard” CAES system, air is compressed from atmospheric pressure to the pressure in the tank/vessel/cavern, which may be as high as 200 bar. If compression is done in one step without heat transfer, the air temperature coming out of the compressor would be more than 1000°C. Likewise, if the compressed air is stored in a cavern at ambient temperature, and it is expanded in one step without heat transfer, the air temperature coming out of the turbine would be lower than -200°C.

Clearly, this would be impractical (and inefficient). Therefore, a realistic process would either be:

A: Compression in multiple steps with heat exchange between the steps. Heat is dumped to the ambient. Expansion in multiple steps with heat exchange between the steps. Heat is taken from the ambient.

Or

B: Compression in multiple steps with heat exchange between the steps. Heat is stored in a fluid or another medium. Expansion in multiple steps with heat exchange between the steps. Heat is taken from the storage medium.

In case A, the average air temperature during expansion is below, but close to ambient temperature, and in case B, the average air temperature is above, but close to ambient.

Therefore, instead of making elaborate calculations for each possible combination of pressure levels and steps, it is assumed in the calculations throughout the rest of this report that compression and expansion are isothermal and take place at or near ambient temperature.

It should be kept in mind that the calculation is only done to get an impression of the amount of energy stored in one  $\text{m}^3$  of tank, and it does *not* say anything about system efficiency.

The results of the calculations prove that it is well justified to use these rather rough assumptions for the calculations.

#### 4.1 Pressure Vessel Energy Density

The term “pressure vessel” is used to designate a system, where air is compressed from atmospheric pressure to a high pressure (= the pressure inside the vessel) and then fed into the pressure vessel. This is the system used in an unfuelled near-isothermal CAES system such as the ADELE-system, and the thermal oil storage system described in section 2.1.

The graph in figure 10 shows the energy density of a pressure vessel as function of pressure ratio (minimum pressure/maximum pressure) with the maximum pressure as a parameter. Calculation procedure is described in appendix 1, and it is based on isothermal compression/expansion.

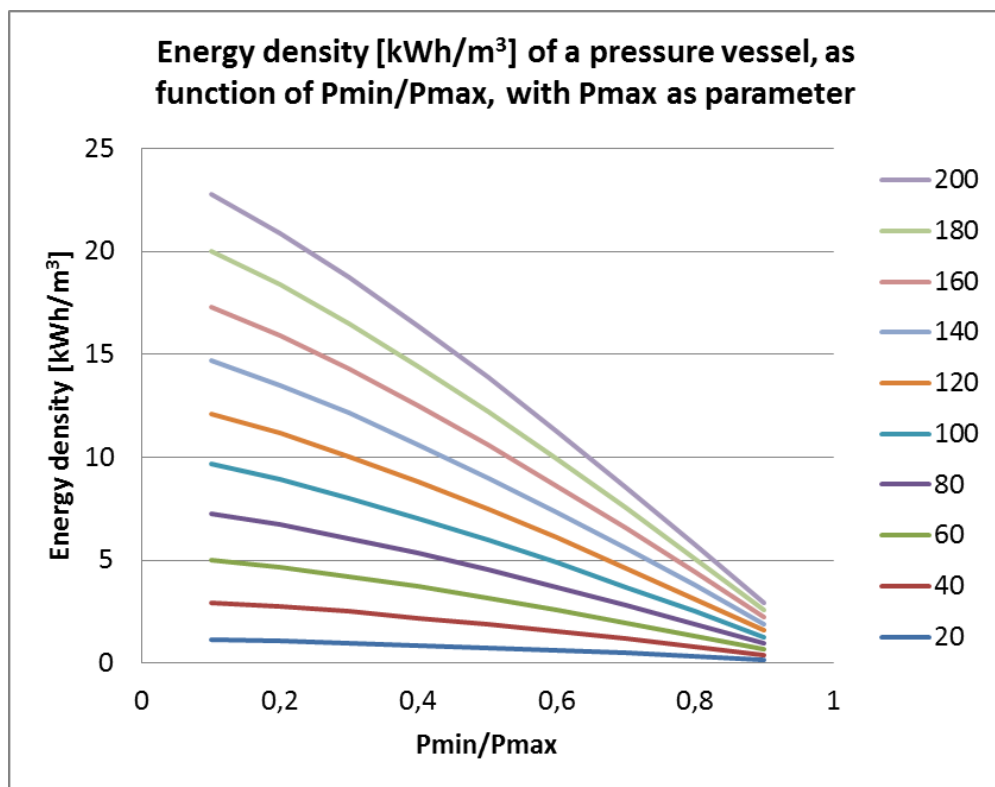


Figure 10: Energy density of a pressure vessel.

For example, when using a maximum pressure of 200 bar and a minimum pressure of 60 bar (which equals  $0.3 \cdot \text{maximum pressure}$ ) based on the normal operating limits of a cavern, the energy density is  $18 \text{ kWh/m}^3$ . As described earlier, the energy density would be 10%

lower if an underground cavern is used due to the weight of the compressed air column between ground level and cavern top. A realistic value would therefore be  $16 \text{ kWh/m}^3$ .

The CAES units at Huntorf, Germany, and Macintosh, Alabama, both run at a pressure ratio of approximately 0,6, which may be due to limitations in operating range of the gas turbines. Moreover, the maximum pressure is below 100 bar, and when using these values, the energy density of a pressure vessel is  $5 \text{ kWh/m}^3$ . At high pressures, the energy density seems to increase almost linearly with pressure.

## 4.2 Hydrophore Energy Density (Ground Level)

The term “hydrophore” is used to designate a system, where a liquid (e.g. water, oil) is pumped from atmospheric pressure into a tank containing air at high pressure (such a tank is called a hydrophore, and it is used for small domestic water systems). This system is used in ALP-CAES systems.

The graph in figure 11 shows the energy density of a hydrophore as function of pressure ratio (minimum pressure/maximum pressure) with the maximum pressure as parameter. Calculation procedure is described in appendix 1, and it is based on isothermal compression/expansion.

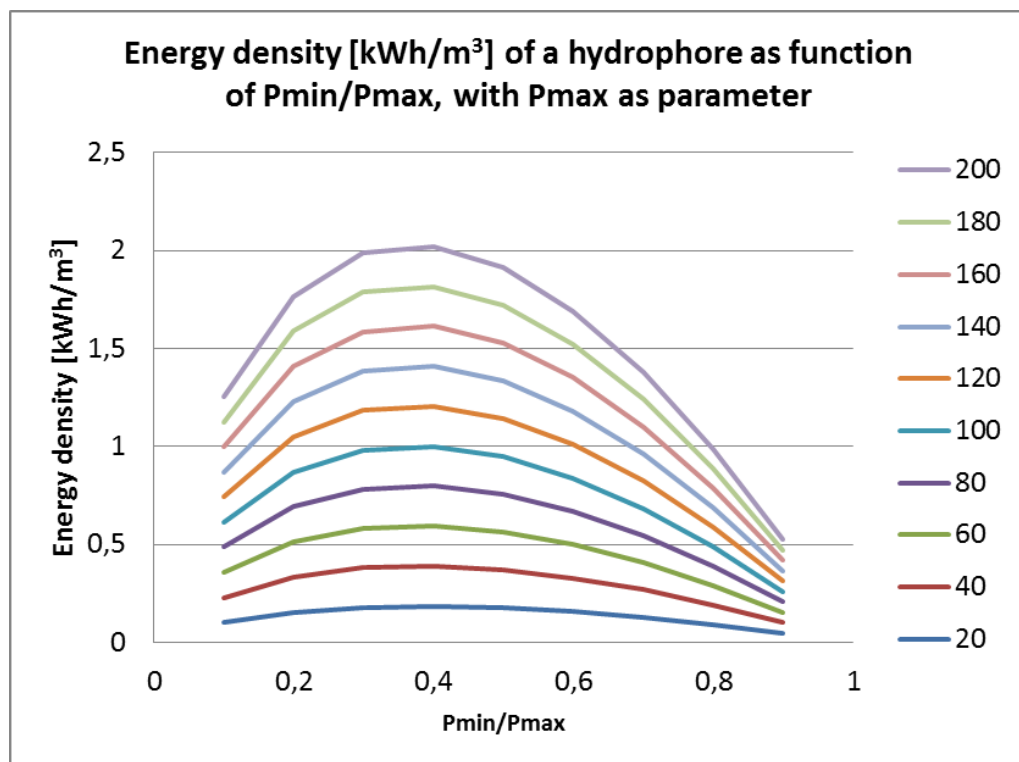


Figure 11: Energy density of a hydrophore at ground level.

If using 200 bar as the maximum pressure, the maximum energy density is 2 kWh/m<sup>3</sup>. This value is reached at a pressure ratio of 0,4 (maximum pressure = 2,5 \* minimum pressure), which may not be realistic in the scope of the ALP-CAES idea (pressure ratio close to 1 and small temperature variation). With an air temperature starting at 300 K, the end temperature after compression would be approximately 390 K.

However, the pressure ratio can be increased without reducing the energy density much. For example, by using a pressure ratio of 0,65, the energy density only drops to 1,5 kWh/m<sup>3</sup>, and if assuming a start temperature of 300 K, the end temperature after compression would be approximately 340 K.

When using the operating values from Huntorf and Macintosh, the energy density is 0,8 kWh/m<sup>3</sup>.

It should be noted that the graph in figure 11 describes the energy density of an ALP-CAES system with the compressed air tank at ground level, and *not* an ALP-CAES system using an underground cavern.

### 4.3 Hydrophore Energy Density (Underground Cavern)

When using an underground cavern as compressed air tank, the “useful” pressure is reduced due to the weight of the column of liquid between ground level and the cavern. This detail can be included in the calculations by assuming that the maximum cavern pressure and depth are proportional, as described in section 3. The graph in figure 12 shows the energy density of a hydrophore using an underground cavern.

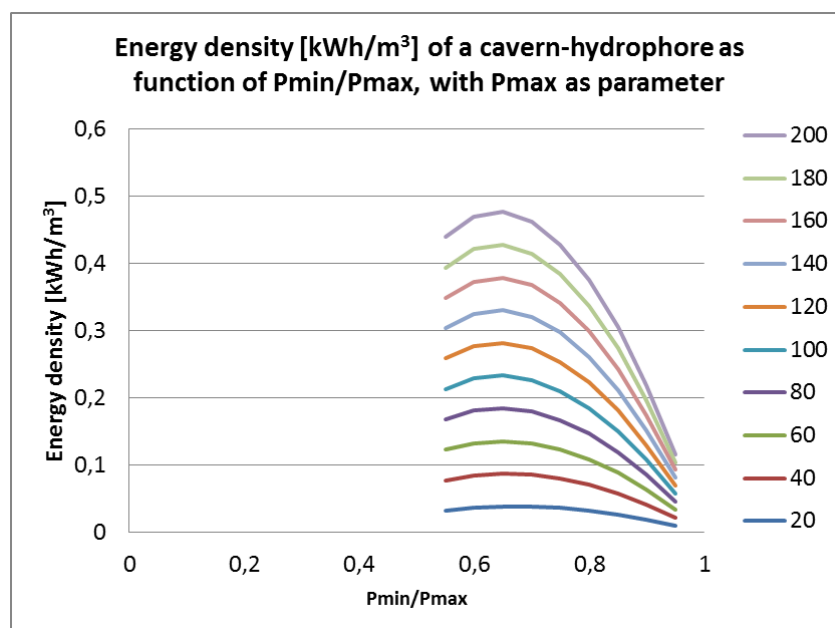


Figure 12: Energy density of a cavern-hydrophore.

It should be noted that values of  $P_{min}/P_{max}$  below 0,55 do not make sense in that pressures below 0,55 times the maximum pressure will not be able to support the column of liquid between cavern and ground level (Assuming the liquid is water with a density of  $1000 \text{ kg/m}^3$ . Saturated salt water would have a density of  $1030 \text{ kg/m}^3$ , giving nearly the same result). Attempting to use a lower pressure would result in a vacuum in the piping at ground level.

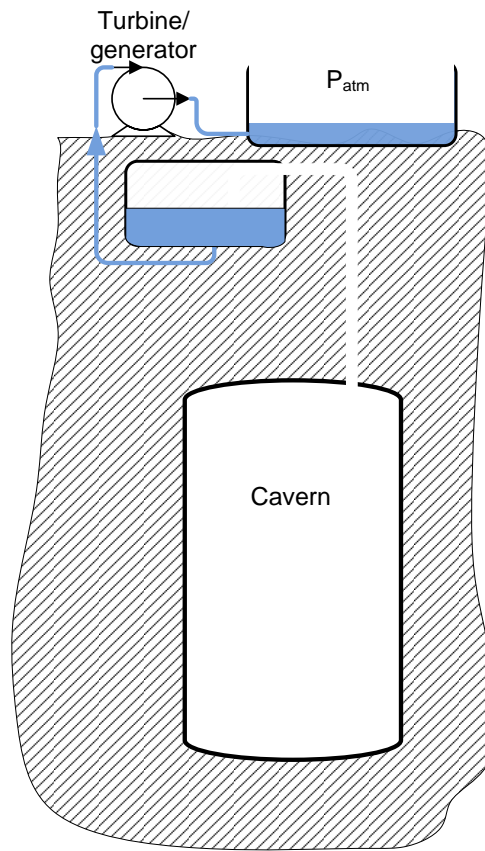
When using 200 bar as a maximum pressure, the energy density is slightly below  $0,5 \text{ kWh/m}^3$ . This value is reached at a pressure ratio of 0,65, which is closer to the basic idea of ALP-CAES. With an air temperature starting at 300 K, the end temperature after compression would be 340 K. Moreover, when using the operating data from Huntorf and Macintosh, the energy density is  $0,23 \text{ kWh/m}^3$ .

When compared with a hydrophore at ground level, this system has a slightly better economy as the price of a ground level tank system is approximately five times the price of a cavern. However, the energy density is only four times smaller. From the calculations, it can be concluded that a large scale ALP-CAES system has an energy density which is at least 20 times lower than the energy density of an unfuelled near-isothermal CAES system. This means that for each kWh stored, an ALP-CAES system would need 20 times more storage volume. Economically, this means that ALP-CAES can only be competitive if the cheapest storage possible is chosen, for example large underground caverns or pressure vessels that are no longer in use.

#### **4.4 Avoiding the Liquid Column - Additional Tank**

To avoid problems related to the liquid column, it has been suggested that a smaller tank could be placed near ground level with the purpose of only filling this tank with the liquid. Then, the large underground cavern would only contain air. As the smaller tank is close to ground level, and it is exposed to the same internal pressure as the cavern, it has to be built of a material that can withstand the pressure in itself. According to Nyserda[6], this means that each  $\text{m}^3$  in the smaller tank is at least five times more expensive than one  $\text{m}^3$  of the cavern. On the other hand, removing the liquid column may increase the energy density up to a factor of 4 depending on pressure and pressure ratio.





*Figure 13: Cavern with additional tank at ground level.*

The energy density of this solution is identical to the energy density of a “hydrophore at ground level”, if neglecting the height of the additional tank. However, the investment cost will be slightly higher than the cost for a cavern with the same total volume. In order to compare the economy of this solution with the economy of the “pressure vessel” - without entering any actual prices, the term “adjusted energy density” has to be defined.

The idea is that since the price per  $\text{m}^3$  of the additional tank is approximately five times higher than the price per  $\text{m}^3$  of a cavern, the energy density of a combination of a cavern and an additional tank should be adjusted according to the extra price to reflect the energy density measured in value for money.

For example, assume that the “Cavern with the additional tank” has an energy density of  $XX \text{ kWh/m}^3$  at some maximum pressure, and at a pressure ratio of 0,9. Pressure ratio 0,9 also means that 90% of the total volume is in the cavern and 10 % of the volume is in the additional tank (neglecting any necessary overhead volume). The price of the cavern and the additional tank will then be  $0,9 * 1 + 0,1 * 5 = 1,4$  times the price of an ordinary cavern. Consequently, the adjusted energy density would be  $XX/1,4 \text{ kWh/m}^3$  (energy density measured in value for money).

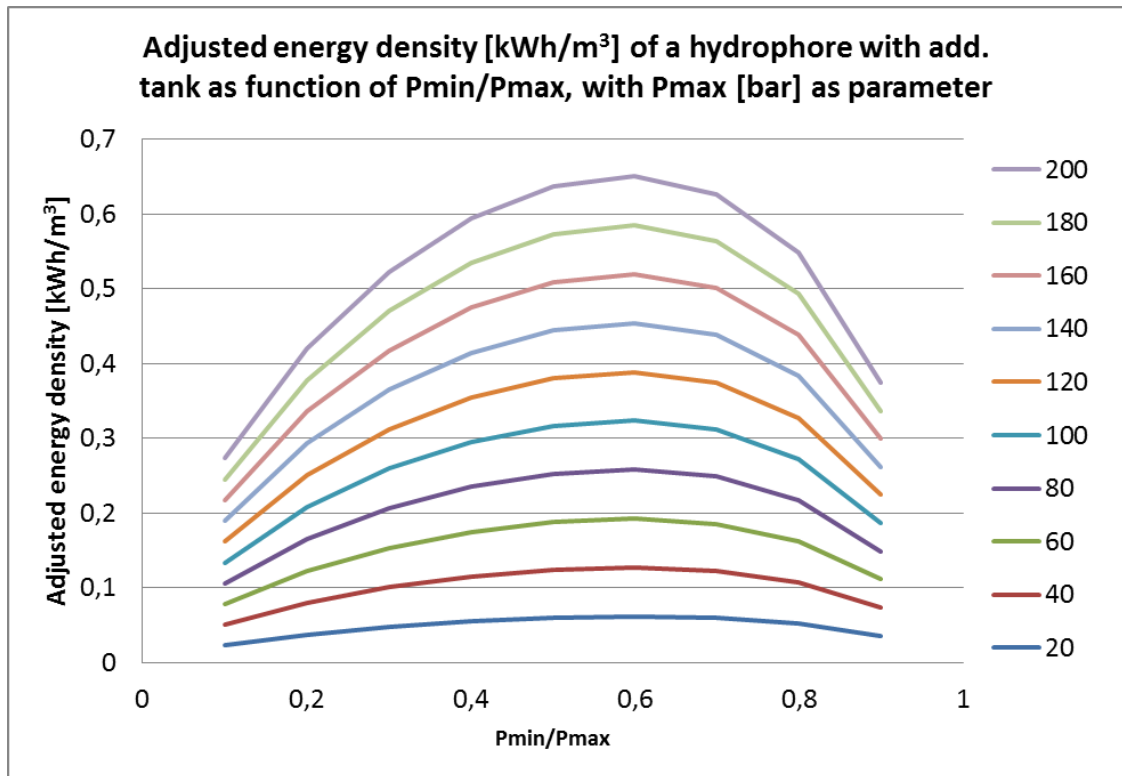


Figure 14: Energy density of hydrophore with additional tank.

As seen in the graph in figure 14, the hydrophore with an additional tank has an optimum configuration at a pressure ratio of 0,6, but the energy density expressed in value for money is not much higher than a cavern-hydrophore. Given the additional complexity of the system, the overall economy is most likely similar to that of a cavern-hydrophore.

#### 4.5 Underground Turbine/Generator and Pond

Another way to avoid the problem of the liquid column between cavern and ground level could be to locate the turbine/generator and the pond at the same depth as the cavern.

For the turbine/generator and pond to be at atmospheric pressure, they would have to be located in a reinforced cavity with service access through a large elevator shaft.

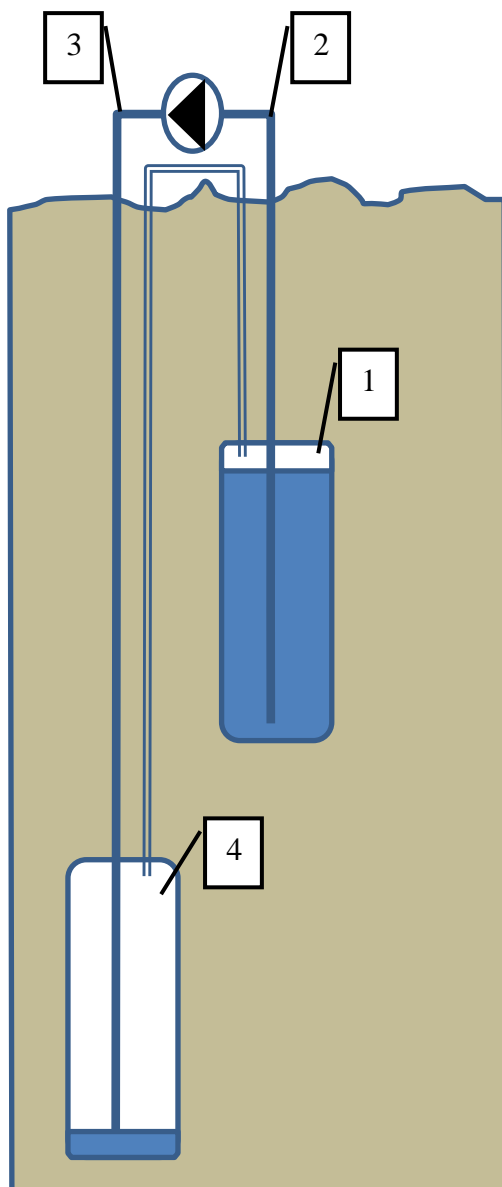
According to KBB Underground Technologies<sup>[2]</sup>, the additional price of these features would render the setup economically uninteresting.

#### 4.6 Double Cavern Storage

As yet another alternative, it has been suggested that an energy storage system composed by two caverns at different depths is made with a liquid cycling between the two caverns.

The system would in principle be a pumped hydro storage with a pressurised air/gas cushion at the top of the caverns to ensure a positive pressure in the liquid piping, even at ground level.

In the setup shown in figure 15, the air/gas pressure is the same in both caverns ensured by a transfer pipe. This allows the top cavern to be completely filled with liquid (brine) providing the maximum quantity of liquid possible and a high energy density in the system.



The gas pressure at “1” is chosen to be the allowed maximum pressure for the depth of cavern 1. The pressure at “2” can be calculated as: the pressure at “1” minus the pressure of the brine column from “1” to ground level.

To allow the maximum work output from the turbine, the pressure at “3” is (theoretically) set at atmospheric pressure. Pressure “4” is equal to pressure “1” due to the transfer pipe, but pressure “4” must also be equal to the pressure of the brine column from “3” to “4” (plus atmospheric pressure).

At the end of the discharge process, the bottom cavern is almost filled, and the top cavern is almost empty. In this case, the driving pressure is equal to the driving pressure at the beginning minus two times the brine pressure of the cavern height.

The average driving pressure can be calculated as the start driving pressure plus the end driving pressure divided by two.

By doing so, the various pressures and energy densities can be calculated as shown in figure 16.

Figure 15: Double Cavern Storage.

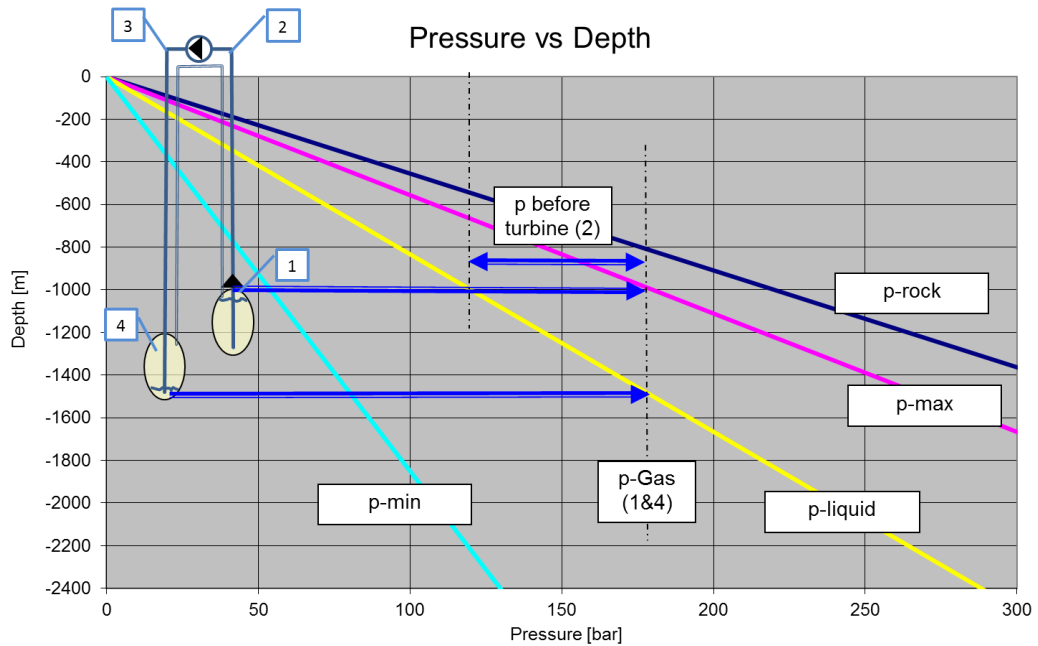


Figure 16: Pressures in Double Cavern Storage.

Moreover, by looking at energy density, the following relationship will occur:

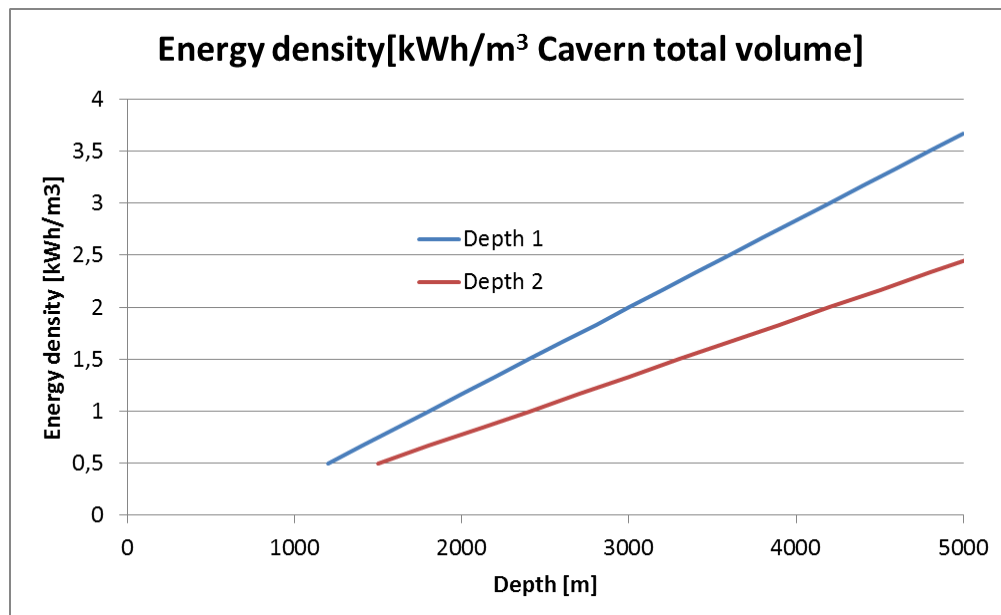


Figure 17: Energy Density of Double Cavern Storage.

As indicated in figure 17, it appears that within the preferred cavern depths (<2000 m), the energy density will be less than 1 kWh/m³, which is a factor of 10 less than the outcome of a simple compressed air cavern, which is assumed to be close to isothermal expansion.

## 5 Economy of CAES Systems

If we look at a CAES system as energy storage only, i.e. only systems without oil/gas burners, the CAES system does not have any net energy production. Thus, the business case would be as follows:

Electricity is purchased at times of low demand/low prices, and it is stored in the form of compressed air. In theory, the same amount of electricity is sold again at times of high demand/higher prices.

The income generated would then be:

$$\text{Income} = \text{Amount of Electricity} * (\text{Sales price} - \text{Purchase price})$$

Furthermore, building and operating a CAES storage facility involves expenses that depend on different factors:

A: Investment cost for air storage tank/vessel/cavern. This investment typically depends on storage type, pressure, size etc. For many types of tanks/vessels, the price of storage is roughly proportional to the amount of energy stored. For caverns, prices are slightly more complex as shown in figure 7, and they have an initial price, which is independent of volume.

B: Investment cost for turbines/pumps/compressors, and motor/generator, i.e. the cost of the energy consuming and producing units. These costs depend off course on type, pressure, size (in MW power), but are independent of the storage tank size.

C: Efficiency losses. Turbines/pumps/generators and so on are not perfect, which means that the amount of electricity sold is smaller than the amount of electricity purchased, thereby reducing the income.

D: Manpower and maintenance costs. Since this report is mainly concerned with comparing ALP-CAES with other possible CAES-technologies and not the absolute size of costs, it will be assumed that manpower and maintenance costs are roughly the same for all technologies, and will not be estimated here.

E: In the ALP-CAES case, a large pond must be built at ground level, which contains concentrated salt water or another operating fluid. The cost of this has not been evaluated, since it must be highly dependent on local conditions. Given the right geological formations, it may be relatively simple and economically sound to build such a pond. On the other hand,

there may be several locations, where it may be impossible to get a permission to build such a pond due to the risk of leakage, pollution etc.

When trying to evaluate these costs, it may be practical to convert the actual costs into “added cost per MWh purchased” in order to have a common unit. This unit is the cost that is added to the purchase price due to the above mentioned expenses, and it is easily comparable to actual electricity prices. Moreover, it is more informative than for example: “A 100 MW Pelton turbine costs approximately US\$ 15 million”.

To establish the “added cost per MWh purchased”, it is, however, necessary to define an operating mode. In other words, since the costs must be spread out over the electricity turnover, the expected turnover must be defined. As a reasonable example, it is assumed that the compressed air tank/vessel/cavern is filled and emptied completely (within the normal operating range) two days out of three. This accounts for the fact that storage is most likely not needed during weekends, holidays and a few workdays now and then. The Huntorf facility is at present down to less than 100 starts per year, whereas in the early years of operation, the average number of starts per year was close to 250.

## 5.1 Investment in Tank/Vessel/Cavern

As stated in section 3, the price per m<sup>3</sup> of a tank varies considerably according to size. For micro-units, the most economical solution might be the use of standard nitrogen flasks at Dkr 10.000/m<sup>3</sup>. For larger units such as a large above ground piping system could be built at Dkr 2000/m<sup>3</sup>, and a large cavern would cost Dkr 400/m<sup>3</sup>.

Assuming that the annual investment cost is 10% of the cost price (interest + repayment), the “added cost per MWh purchased” can be calculated as (neglecting efficiency of compressor/pump):

$$\text{Added Cost per MWh} = \frac{\text{Annual Investment Cost}}{\text{Annual purchase of electricity}} = \frac{\text{Price} \left[ \frac{\text{Dkr}}{\text{m}^3} \right] * 0,10}{\text{Energy density} \left[ \frac{\text{Mwh}}{\text{m}^3} \right] * 365 * 2/3}$$

The following values for the “added cost per MWh purchased” in Dkr/MWh are calculated using values of 0,25 kWh/m<sup>3</sup> for ALP-CAES and 5 kWh/m<sup>3</sup> for an unfuelled CAES system:

	Nitrogen flask	Large pipe system	Large cavern
ALP-CAES	16400	3300	660
Unfuelled CAES	820	165	33

The average spot price for West Denmark has in 2012 been very close to Dkr 300/MWh,

which means that an ALP-CAES system as a minimum triples the price, solely due to the investment cost for the cavern.

The values for energy density used above are based on a maximum air pressure of 100 bar and a pressure ratio of 0,6; similar to the operation data of the Huntorf/Macintosh units.

## 5.2 Investment in Turbine/Motor/Generator etc.

The investments in pumps/turbines and motor/generator may vary considerably depending on system setup, size (in MW power), pressure etc. To convert the investment cost into an “added cost per MWh purchased”, it is necessary to define the daily average operating hours, since the annual investment costs must be spread out on the annual production of MWh.

In the case of a system using a liquid as medium, such as ALP-CAES, relatively good price data are available. César Adolfo Alvarado-Ancieta<sup>[1]</sup> has collected price data from 140 hydropower plants and published the results in the magazine “Wasserkraft & Energie, 3/2012” under the title: “Kostenschätzung 2012 für die elektrische und mechanische Ausrüstung des Krafthauses in Wasserkraft- und Pumpspeicher-Projekten”.

For a CAES system using a liquid as medium, the most economical setup is a Francis pump turbine. In this setup, the turbine can be used as a pump simply by inverting the direction of the rotation. The generator can also be used as a motor.

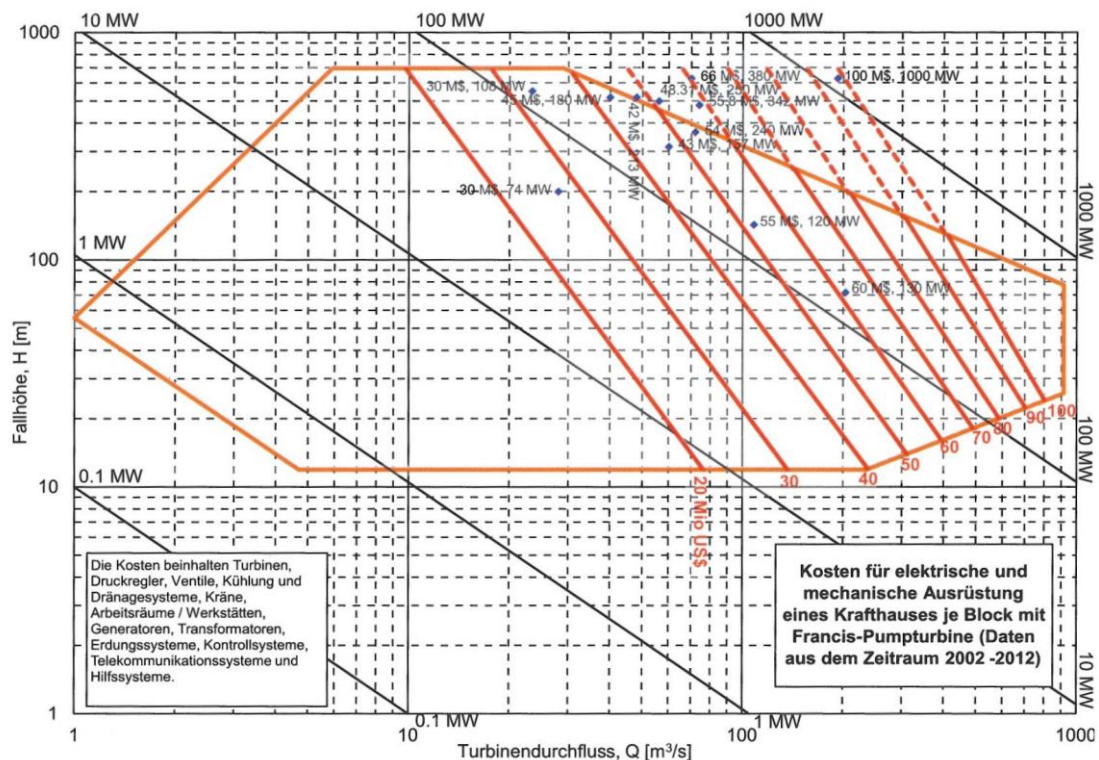


Figure 18: Price indication for Francis pump turbine.



In general, the price of the Francis pump turbine decreases with increasing pressure, and the price per MW power decreases with increasing size. A typical size for CAES systems would be approximately 100 MW, and the use of a maximum cavern pressure of 100 bar, i.e. a 45 bar max pressure at inlet of the turbine due to the liquid column, leads to a price of US\$ 30 million ( $\approx$  Dkr 175 million).

According to the same author, a Pelton turbine with the same power and pressure would cost approximately US\$ 20 million, but would require a separate pump in that Pelton turbines cannot be reversed and used as pumps. Although data for separate pumps have not been found, it is assumed here that a Pelton turbine with a separate pump will not be more economical than a Francis pump turbine.

Data for an adiabatic unfuelled CAES system (see figure 3) have been provided by Nyserda<sup>[6]</sup> for comparison. The data given here deal with a 72 MW system and excluding the price of the cavern the cost of the system is US\$ 66 million. Assuming that the hardware price is a relatively linear function of size, whereas the cost of labour and materials are a fixed price, a 100 MW unit would cost US\$ 54 million for hardware and US\$ 27 million for materials and labour, which equals US\$ 81 million ( $\approx$  Dkr 470 million).

Assuming that the annual investment cost is 10% of the cost price (interest + repayment), the “added cost per MWh purchased” can be calculated as function of the number of daily operating hours:

Daily operating hours	3	4	5	6	7	8	9	10	11	12
ALP-CAES	160	120	96	80	68	60	53	48	44	40
Adiabatic CAES	429	322	258	215	184	161	143	129	117	107

*Added cost per MWh purchased [Dkr/MWh] as function of average daily operating hours.*

### 5.3 Efficiency Losses

Pumps and turbines have efficiencies below 100%, which means that there are energy losses when charging and discharging the compressed air storage. These losses can be converted into an “added cost per MWh purchased”.

If we set the efficiency of the pump (including the electric motor driving it) to  $\eta_{\text{pump}}$  and the efficiency of the turbine (including the generator producing the electricity) to  $\eta_{\text{Turb}}$ , the added cost will be:

$$\text{Added Cost per MWh} \left[ \frac{\text{DKK}}{\text{MWh}} \right] = \text{Purchase price} \left[ \frac{\text{DKK}}{\text{MWh}} \right] \times \left( \frac{1}{\eta_{\text{pump}} * \eta_{\text{Turb}}} - 1 \right)$$

Electric motors and generators of very large size can have efficiencies up to 98%, and pumps using liquids as a medium can have efficiencies up to 95%. Setting both  $\eta_{\text{pump}}$  and  $\eta_{\text{Turb}}$  to



0,93, the “added cost per MWh purchased” will be at least 0,15 times the purchase price. The purchase price of electricity varies considerably. Figure 19 shows the spot prices for West Denmark from January 2012 to September 2012.

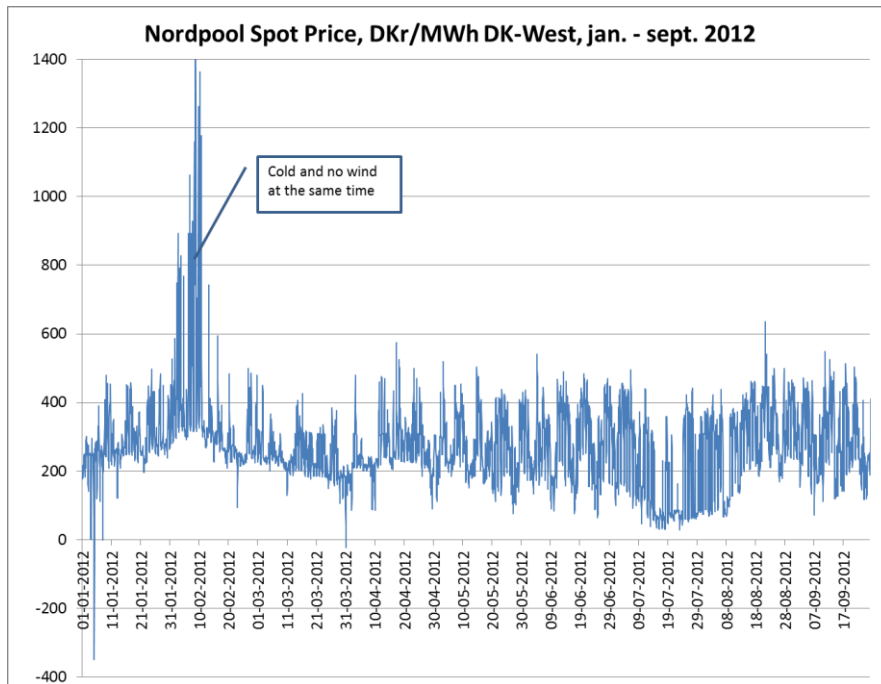


Figure 19: Example of electricity spot prices.

Although the greatest variation seems quite large, ranging from Dkr -350/MWh to more than Dkr 1400/MWh, it is clear that the extremes only occur very few hours per year.

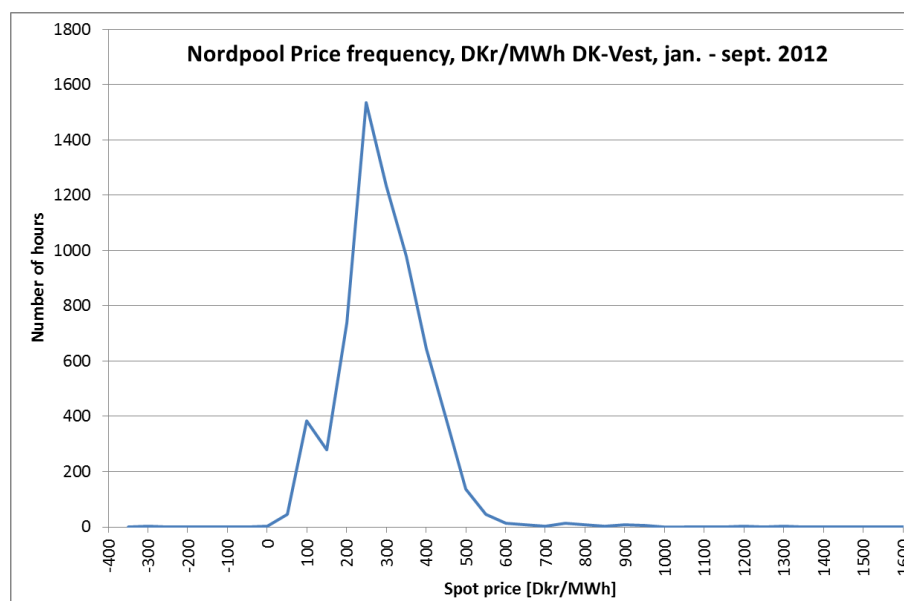


Figure 20: Spot price frequency.

Figure 20 shows a frequency plot of the data from figure 18. This figure clearly shows that the vast majority of production hours are in the range of Dkr 100-500/MWh.

In terms of a typical “off-peak” purchase price of Dkr 200/MWh, the “added cost per MWh purchased” would be Dkr 30/MWh for a system using a liquid as a medium; i.e. an ALP-CAES system.

When using an unfuelled CAES system, which compresses air from atmospheric pressure to tank pressure, the efficiency varies greatly depending on how the compression heat is handled. In principle, the heat can be stored during compression and reused during expansion, which provides a potentially high efficiency. Alternatively, various technologies can be used to create a near-isothermal compression and expansion, where the heat is dumped into the ambient at very low excess temperatures or stored at near ambient temperature in simple, uninsulated ponds.

The efficiency of the compressor/expander is in other words highly dependent on how efficient the heat storage or the near-isothermal processes are handled. Assuming, for example, an efficiency of 85% for the compressor and expander (and still 98% for the motor/generator), which must be considered low for a large scale industrial application, this gives a round-trip efficiency of 69%, which leads to an added price of Dkr 88/MWh.

It should be noticed that if the purchase price for electricity approaches 0 (zero), for example because surplus electricity production becomes more frequent, the added price due to efficiency will also approach 0 (zero) in that the added price is proportional to the purchase price. In other words: If the increase in unpredictable and/or surplus wind power leads to more hours with very low purchase prices, it will be economically more interesting to ensure a high storage energy density than a high efficiency.

## **6 Economic Comparison**

When trying to compare the overall economy of ALP-CAES versus an adiabatic unfuelled CAES, the variables have to be narrowed down to a reasonable quantity, and a maximum/minimum range must be considered. For example, it is well known that small units have a poor economy compared to large scale systems. Small units will therefore not be considered. Furthermore, low pressure units have a low energy density leading to a high cost of storage volume. Thus, only high pressure units should be considered.

### **6.1 CAES Units of Equal Power**

Concerning the size of a unit, a main input given by DONG<sup>[3]</sup> state that: “A suitable unit size would be 100 MW with several hours of operating time”. This statement seems highly reasonable, but as the calculations show, it still provides some challenges.

- In the calculation below, the added cost per MWh has been calculated for an unfuelled CAES system and an ALP-CAES system based on a power of 100 MW with daily operating hours varying from 3 to 12 hours. Cavern maximum pressure is set at 100 bar.
- In each case, the necessary cavern volume has been calculated, and the price of the cavern has been based on the middle price in the graph from KBB Underground Technologies[2] (see figure 8).
- Pumps/turbines using a liquid as medium have been set to an efficiency of 93%. Air compressors and turbines are set to an efficiency of 83%. These values include the motor/generator efficiencies.

Notice that values are cumulative, which means that the lines for “Turb./gen.” are the total costs in each case.

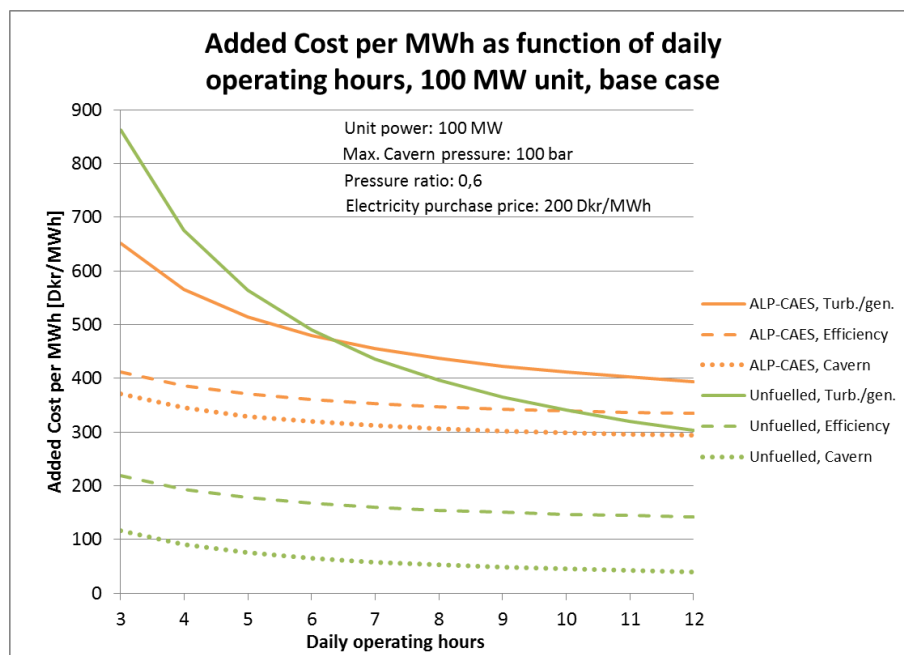


Figure 21: Added Cost per MWh for a 100 MW unit.

According to the calculation, ALP-CAES is competitive at low daily operating hours. However, a closer study of the values behind this will show that the conclusion doesn't hold. When looking at the calculated cavern sizes, it appears that even at low operating hours, the ALP-CAES system would require an enormous cavern, i.e. a cavern larger than most “normal” caverns, due to the much lower energy density of ALP-CAES. In practise, this means that ALP-CAES requires more than one cavern in most cases, which leads to even higher average costs per m<sup>3</sup>.

Furthermore, in connection with low operating hours, the cavern calculated for the unfuelled system is very small and uneconomical. In other words, it would not make sense to build a unit of this type and size.

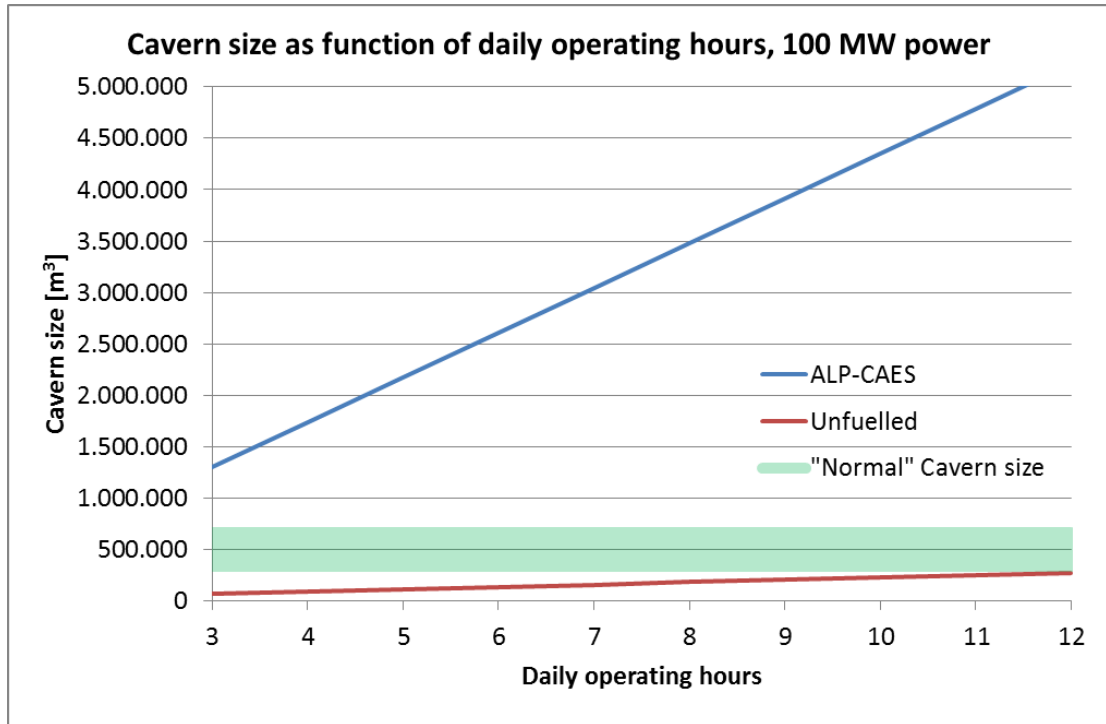


Figure 22: Calculated cavern size for 100 MW power, for different operating hours.

Another detail that should be taken into consideration is the pressure drop in the piping from the cavern to the ground level. Since ALP-CAES has an energy density 20 times lower than the unfuelled CAES, the flow rate would have to be 20 times higher. The density of water is approximately ten times higher than that of air at 100 bar, i.e. the pressure drop would be 200 times higher. This can be compensated by increasing the pipe diameter, and a rough calculation shows that the piping should be minimum 1,5 meters in diameter.

According to KBB Underground Technologies[2], this has never been done before, and a special rig would therefore have to be constructed to support this piping during the cavern construction.

## 6.2 CAES Units of Equal Cavern Size

When setting the cavern size to be constant and an average “normal” size of 500.000 m<sup>3</sup>, a more reasonable calculation can be done under the assumptions that:

- Maximum cavern pressure is set at 100 bar, and pressure ratio is 0,6. This leads to energy storage of 2200 MWh for the unfuelled CAES system (neglecting turbine efficiency) and 110 MWh for the ALP-CAES system.
- Setting the number of daily operating hours to be identical for the two units, power would be proportional to the energy storage. For example, by setting daily operating hours to 11, which could match business hours and the cooking peak, the unfuelled unit would be 200 MW and ALP-CAES would be 10 MW.
- Price of the compressor/turbine unit for the unfuelled CAES would be twice the price of a 100 MW unit, i.e. Dkr 940 million.
- Price of the pump/turbine unit for ALP-CAES would be approximately Dkr 23,4 million.

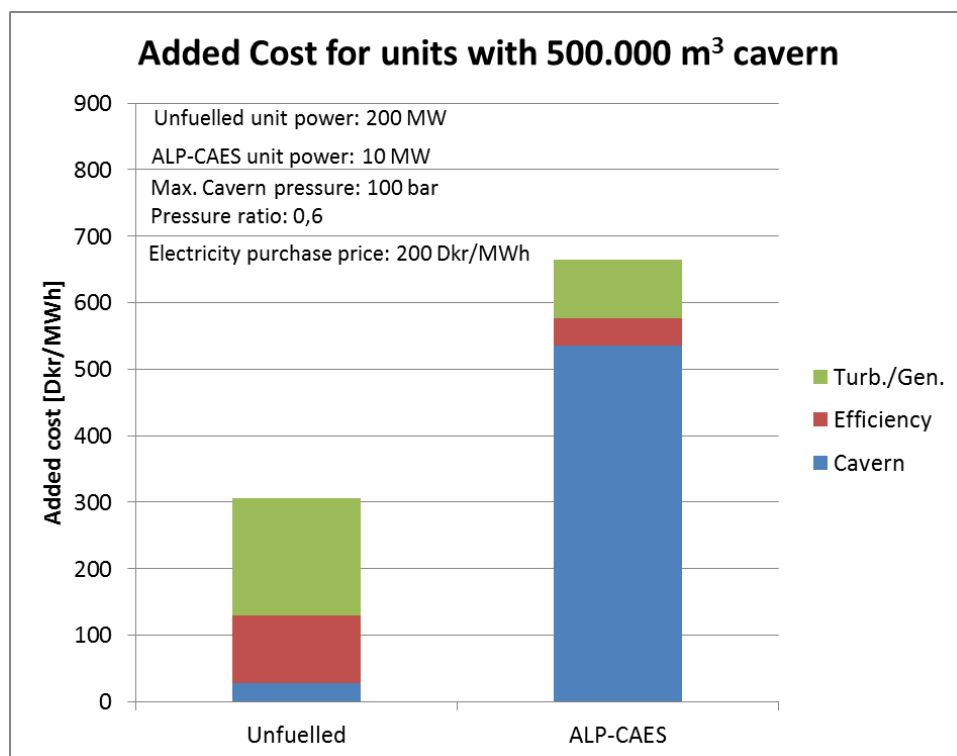


Figure 23: Added Cost per MWh for units with identical cavern size.

As indicated before, the calculation clearly shows that the weakness of the ALP-CAES system is the low energy density, which leads to a high cost of the compressed air storage. Moreover, the main weakness of the unfuelled system is the investment cost in compressor/turbine/generator (including heat exchangers and thermal oil) and the low efficiency.

### 6.3 High Energy Cost

When making the same assumptions as in section 6.2, but with the assumption that energy costs rise considerably, for example to Dkr 1000/MWh, a similar calculation can be made.

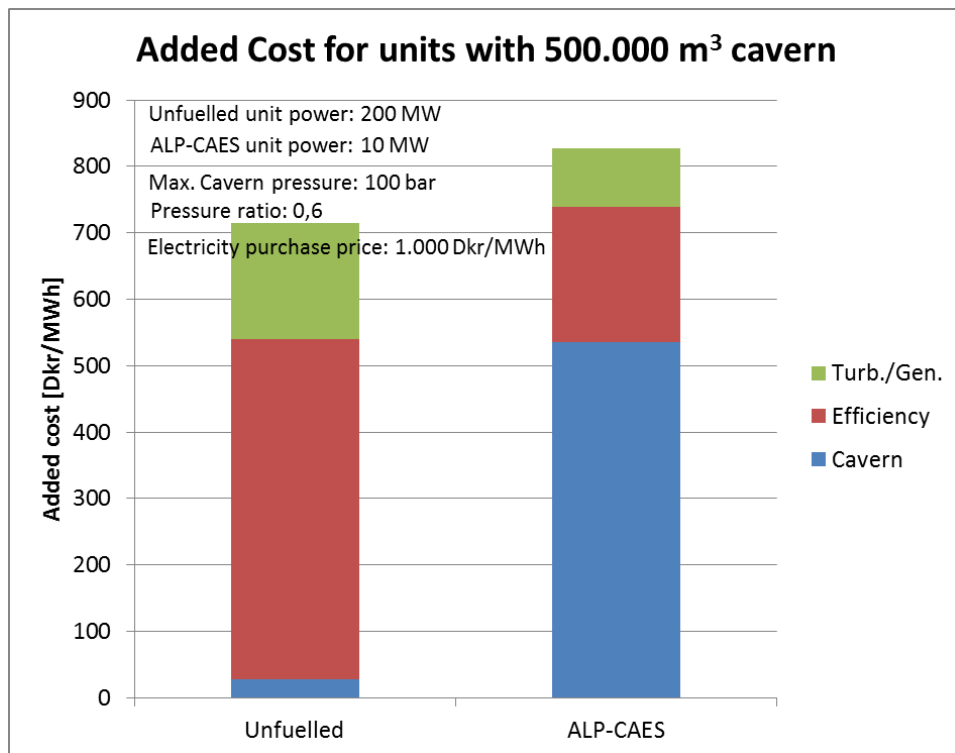
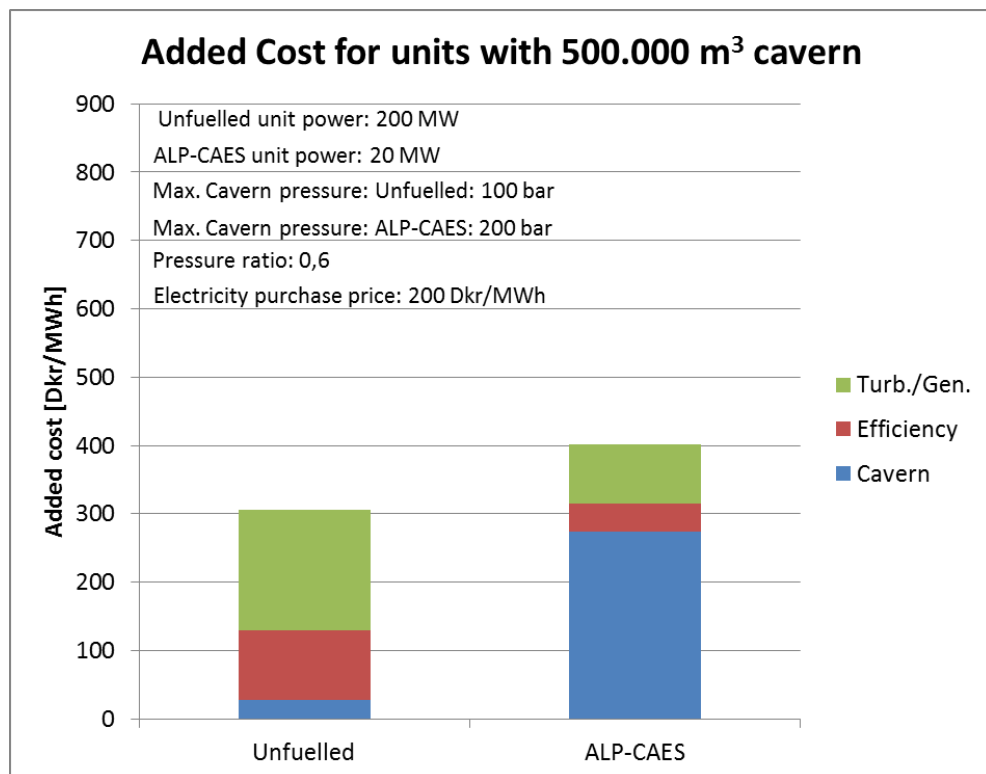


Figure 24: Added Cost per MWh for units with identical cavern size and high energy price.

Although efficiency cost of the unfuelled CAES rises considerably, the overall economy is still better than ALP-CAES. A rough calculation indicates that the “break-even”-point is reached at an electricity price of Dkr 1400/MWh.

## 6.4 High pressure ALP-CAES

In the ALP-CAES system using an underground cavern, the pressure at the turbine inlet will be considerably lower than the air pressure in the cavern, due to the weight of the liquid column. One might argue then, that it could be reasonable to design the ALP-CAES system for a higher cavern pressure. The energy density would then increase, lowering the investment cost for the cavern. For example, using 200 bar maximum cavern pressure, the maximum pressure at the inlet to the turbine would be 90 bars, which is still reasonable for a water turbine. The natural gas facility at Ll. Torup uses pressures of approximately 200 bars. For the unfuelled CAES, cavern pressure is maintained at 100 bars for simplicity and because the unfuelled CAES does not benefit much from an increase in energy density.



*Figure 25: Added Cost per MWh for units with identical cavern size and high pressure in the ALP-CAES case.*

In this case, the ALP-CAES unit approaches the total cost profile of the unfuelled CAES system, and a further calculation shows that if the electricity purchase price increases to 500 Dkr/MWh, the 2 units have identical costs.

## 6.5 ALP-CAES with very large cavern and high pressure

Since a very large fraction of the cost for ALP-CAES systems is in the form of investment in caverns, the economy could be further improved by selecting the most economical cavern size. When combining the use of high pressure with a very large cavern (in this case, a size of 1.500.000 m<sup>3</sup> is selected; the largest size in the graph from KBB Underground Technologies; see figure 8), the economy of ALP-CAES is slightly better than the unfuelled CAES. The ALP-CAES unit would then be of 60 MW power and 11 hours operating time. In the comparison, the unfuelled CAES still uses a 500.000 m<sup>3</sup> cavern, partly because the economy is insensitive to cavern size, and partly because turbine data are not available for larger sizes.

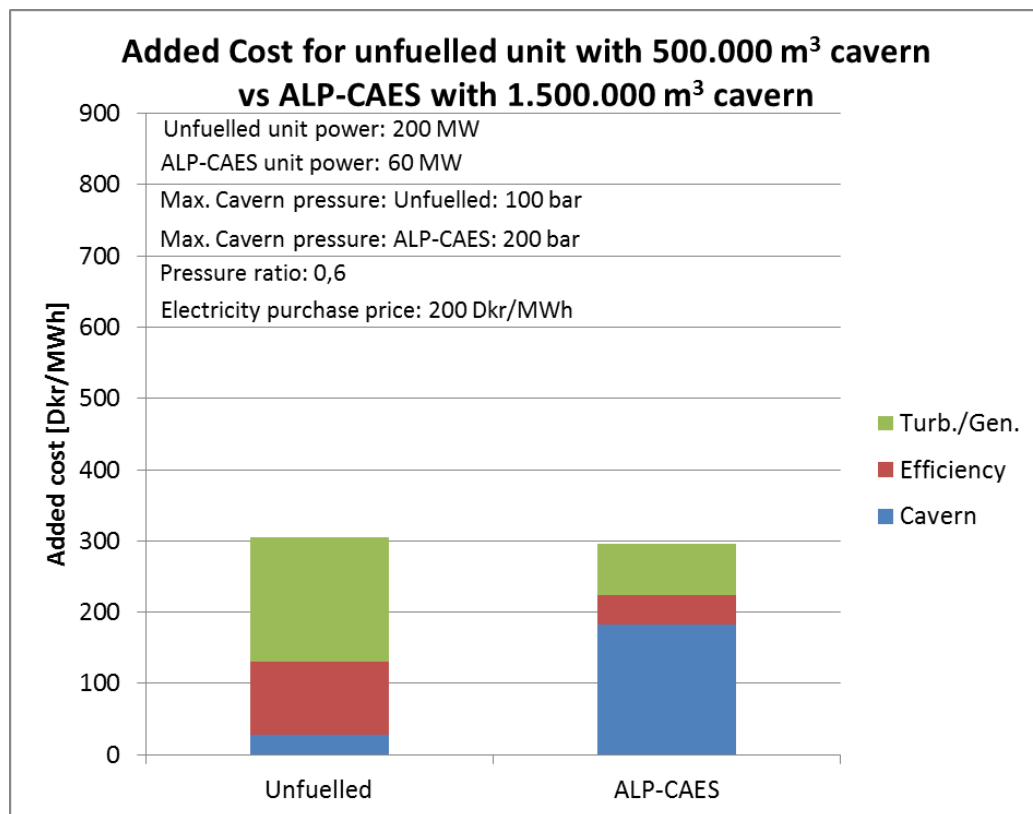


Figure 26: Added Cost per MWh for unfuelled unit with 500.000 m<sup>3</sup> cavern and ALP-CAES unit with 1.500.000 m<sup>3</sup> cavern and high pressure.

With the pressure ratio used, it must be considered that more than 30 % of the cavern volume would be filled with saturated salt water, and that a salt water pond of similar size would be needed at ground level. This corresponds to a pond of 250 m diameter, 10 m deep. The cost for this pond has not been included in figure 26.



## 7 Recommendations for Future Work

Summing up the results of this report, it is evident that:

- ALP-CAES has a superior energy efficiency compared to other CAES systems, and the investment in turbine/pump is low. However, the energy density is low, which results in a very high investment in storage volume. Moreover, ALP-CAES requires a very large ground level pond containing a liquid, which is a potential environmental hazard adding an unknown expense to the system.
- Adiabatic CAES as described has a high energy density, which means a low investment in storage volume. However, the investment in turbine/compressor is much larger than ALP-CAES and the heat exchangers and the thermal energy storage in the form of oil add considerably to the expense. In addition, the energy efficiency of adiabatic CAES will typically be lower than ALP-CAES.

With the present conditions in the Danish energy system, Adiabatic CAES seems to be more favourable than ALP-CAES, but none of the systems are economically viable.

Designing a CAES system viable in the Danish energy system requires that all parts of the system are economically optimized, which means that:

- Energy density should be high, which leads to a system that takes air from atmospheric pressure and compresses it to storage pressure.
- Any thermal energy storage (if necessary) should be in the form of a cheap, safe medium, such as water, concrete, rocks etc., preferably under atmospheric pressure.
- To avoid investment in heat exchangers, water injection should be considered as a way of achieving a near-isothermal compression/expansion. See appendix 2, LightSail Energy technology.
- Compressor/expander should be optimized economically. Machinery, which is reversible, should be used if possible, which means that the same machine can be used as a compressor and an expander.

For systems of this size, it appears that only turbo machinery (axial- or centrifugal compressors/expanders) is competitive. For example, a rough estimate has been made of a system with 100 MW power and max 100 bar pressure, where the high pressure part is

operated by piston machinery performing the compression/expansion between 10 and 100 bar.

There is no machinery of this size available as a single unit, but the piston machinery could be based on three very large MAN-B&W diesel engines (type 12K90MC-S) at a cost of Dkr 175 million, excluding the motor/generator. This is to be compared with the total cost of the air compressor and high pressure expander of the adiabatic CAES system described by Nyserda<sup>[6]</sup>, which is approximately Dkr 135 million, including the motor/generator.

Turbo machinery and water injection are normally considered an unhealthy combination, in that impingement of water drops on the fast rotating turbine parts is known to cause pitting/erosion. However, this error mechanism typically occurs under abnormal operating conditions, where the droplet size is uncontrolled. If it were possible to control the droplet size and create a very fine mist, it might be possible to operate even turbo machinery with water injection and achieve a near-isothermal compression/expansion.

Alternatively, the compression/expansion could be performed in multiple stages, where the direct heat exchange takes place at each stage in separate tanks/scrubbers by injection of water.

## 8 References

### Primary Literature

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- [2] Crotogino, Fritz, KBB Underground Technologies, *Huntorf CAES: More than 20 Years of Successful Operation*, Spring 2001 Meeting, Orlando, Florida, USA, 15-18 April 2001.

Several presentations and excerpts as well as multiple hints and advices.

- [3] Aksel Hauge Pedersen, DONG Energy. Reference to meeting at Dong Energy Headquarters and meeting at Ll. Torup natural gas storage facility.

Supply of background knowledge as well as multiple hints and advices.

- [4] Elmegaard, Brian et al., *Muligheder for anvendelse af Compressed Air Energy Storage (CAES) for ellagring i fremtidens danske elsystem*, PSO-F&U-projekt nr. 2005-1-6567. (Brian Elmegaard, Henrik Lund, Aksel Hauge Petersen).

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- [5] Hanson Tanks, L.A. California, USA (reference based on a quotation from Hanson Tanks, L.A., California, USA.)

- [6] Nysenda (New York State Energy Research and Development Authority), *Compressed Air Energy Storage, Engineering and Economic Study*, Final report 10-09, December 2009.

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[http://www.nrel.gov/csp/troughnet/power\\_plant\\_data.html](http://www.nrel.gov/csp/troughnet/power_plant_data.html)
- [8] <http://www.rwe.com/web/cms/en/365478/rwe/innovation/projects-technologies/energy-storage/project-adele/>
- <http://lightsailenergy.com/>
- <http://www.generalcompression.com/>
- <http://www.sustainx.com>

## Secondary Literature

*CAES - Muligheder for anvendelse af Compressed Air Energy Storage for ellagring i fremtidens danske elsystem - Virkningsgrad og kapacitet af Compressed Air Electricity Storages (CAES), PSO-F&U-projekt nr. 2005-1-6567 - Delrapport II.*

## Appendix 1

### Energy Density Calculations

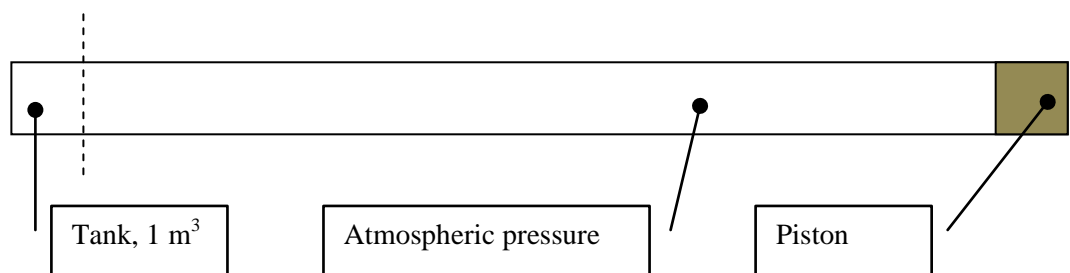
In this chapter, the energy density [ $\text{kWh/m}^3$ ] for a pressure vessel and a hydrophore is evaluated. The efficiency of the energy conversion from mechanical work to pressurised air is set to 100%; meaning that losses are not taken into account, since the purpose is to compare the two storage technologies only.

For both the pressure vessel and the hydrophore it is assumed that they work between a maximum pressure,  $P_{\text{max}}$ , and a minimum pressure,  $P_{\text{min}}$ , and that changes in pressure occur at a constant temperature. The hydrophore is assumed to be emptied of liquid, when  $P_{\text{min}}$  has been reached in order to ensure maximum possible air volume for energy storage.

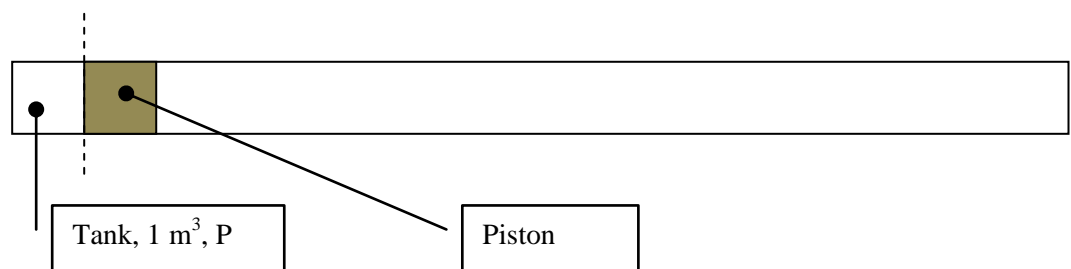
### Pressure Vessel

The energy content of a pressure vessel at pressure  $P$  is the same as the amount of energy it takes to pump the tank up to this pressure. This can be calculated by looking at a very large imaginary cylinder, where a piston compresses the air from atmospheric pressure to the pressure  $P$ , where the cylinder is exactly so big that the end volume is  $1 \text{ m}^3$ . When calculating the work performed by the piston, it equals the energy content in  $1 \text{ m}^3$  of filled pressure vessel.

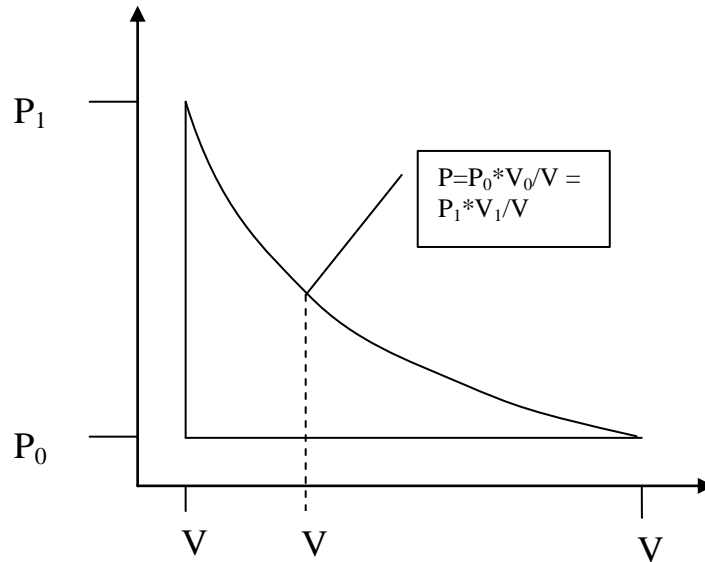
### Start



### End



In a pressure-volume diagram, the work done by the piston is indicated by the area of the figure with  $P_0$  being the atmospheric pressure and  $P_1$  being the maximum pressure. If assuming isothermal compression, pressure and volume are inversely proportional, and with  $V_1$  being  $1 \text{ m}^3$ , it is easy to calculate  $V_0$ .

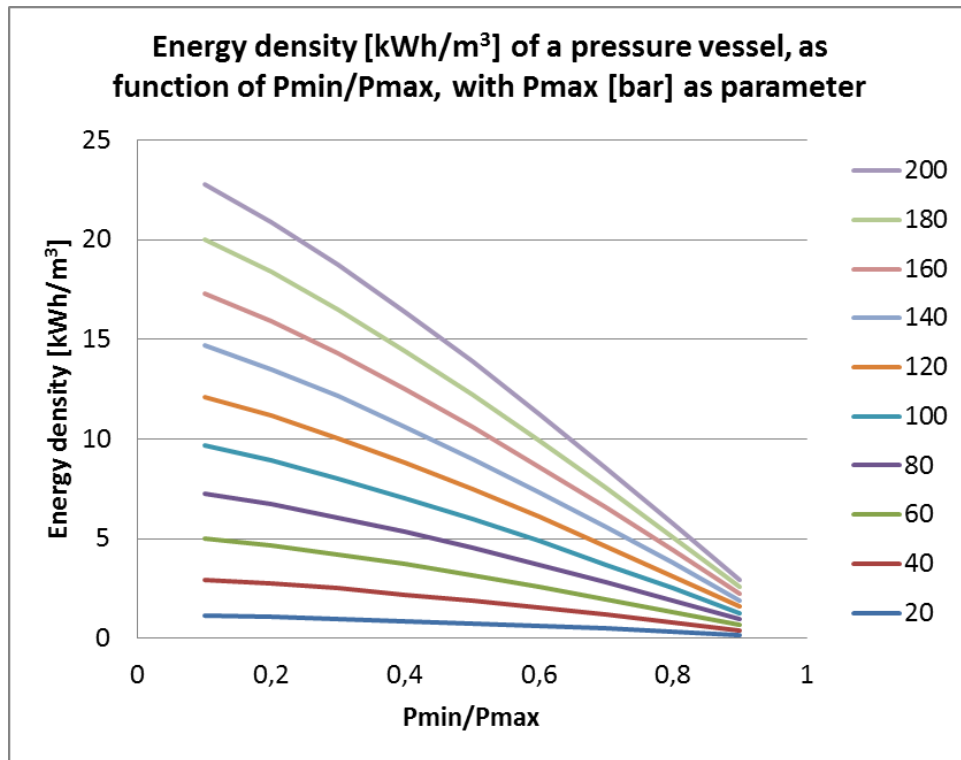


$$\begin{aligned}
 W(P) &= \int_{V_1}^{V_0} (P - P_0) dV = \int_{V_1}^{V_0} P dV - P_0 * (V_0 - V_1) = \int_{V_1}^{V_0} P_1 * V_1 * \frac{1}{V} dV - P_0 * (V_0 - V_1) \\
 &= P_1 * V_1 * (\ln(V_0) - \ln(V_1)) - P_0 * (V_0 - V_1)
 \end{aligned}$$

This can be rearranged to (since  $P_0$ ,  $P_1$  and  $V_1$  are known):

$$W = P_1 * V_1 * \left( \ln\left(\frac{P_1}{P_0} * V_1\right) - \ln(V_1) - 1 + \frac{P_0}{P_1} \right)$$

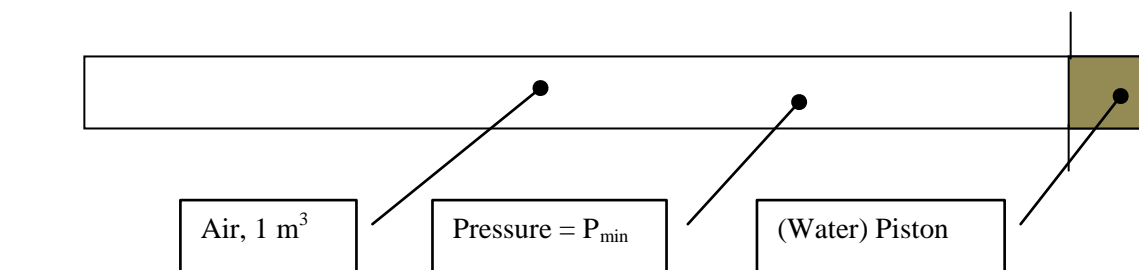
The energy calculated here is the energy content in  $1 \text{ m}^3$  of pressure vessel, when expanding from  $P$  to atmospheric pressure. The energy available from  $P_{\max}$  to  $P_{\min}$  can then be calculated as  $W(P_{\max}) - W(P_{\min})$ , and is shown in the following graph:



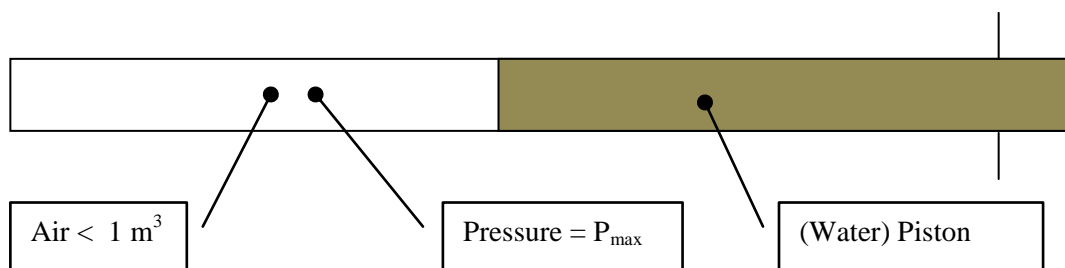
## Hydrophore

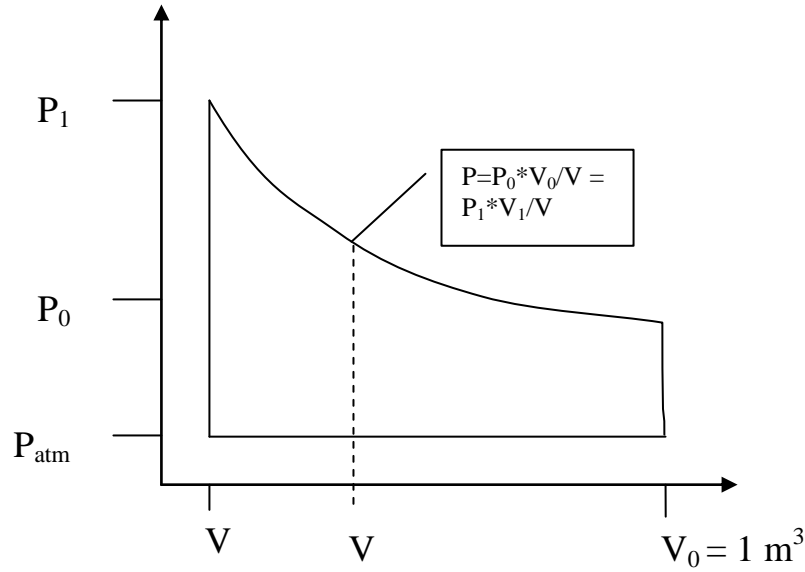
The hydrophore uses a pre-pressurised tank. Water (or any other liquid) is pumped into the tank acting like a piston to compress the air. The energy content of 1 m<sup>3</sup> of the hydrophore can be calculated by looking at an imaginary tank with a start air volume of 1 m<sup>3</sup> and by letting the incoming water compress the air from P<sub>min</sub> to P<sub>max</sub>.

Start



End

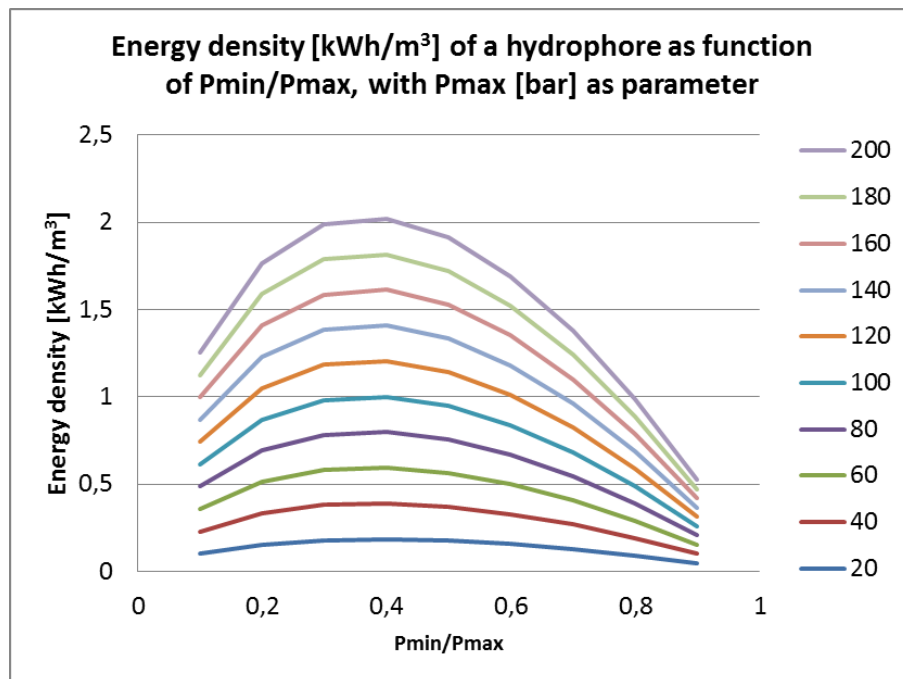




Again, if assuming isothermal compression, pressure and volume are inversely proportional and given the values of  $P_0$  and  $P_1$ , the minimum volume can be calculated.

$$\begin{aligned}
 W(P) &= \int_{V_1}^{V_0} (P - P_{atm}) dV = \int_{V_1}^{V_0} P_0 * V_0 * \frac{1}{V} dV - P_{atm} * (V_0 - V_1) = \\
 &P_0 * V_0 * (\ln(V_0) - \ln(V_1)) - P_{atm} * (V_0 - V_1) \\
 &= P_0 * V_0 * (\ln(V_0) - \ln(V_0 * \frac{P_0}{P_1})) - P_{atm} * (V_0 - V_0 * \frac{P_0}{P_1})
 \end{aligned}$$

The available energy per  $m^3$  is shown in the graph below:





## Hydrophore, Including Water Column

If an underground cavern is used as energy storage, the water column between ground level and the cavern must be taken into account, as the column will reduce the available pressure at the turbine inlet. Based on information from KBB Underground Technologies, the pressure of the water column can be related to the maximum pressure:

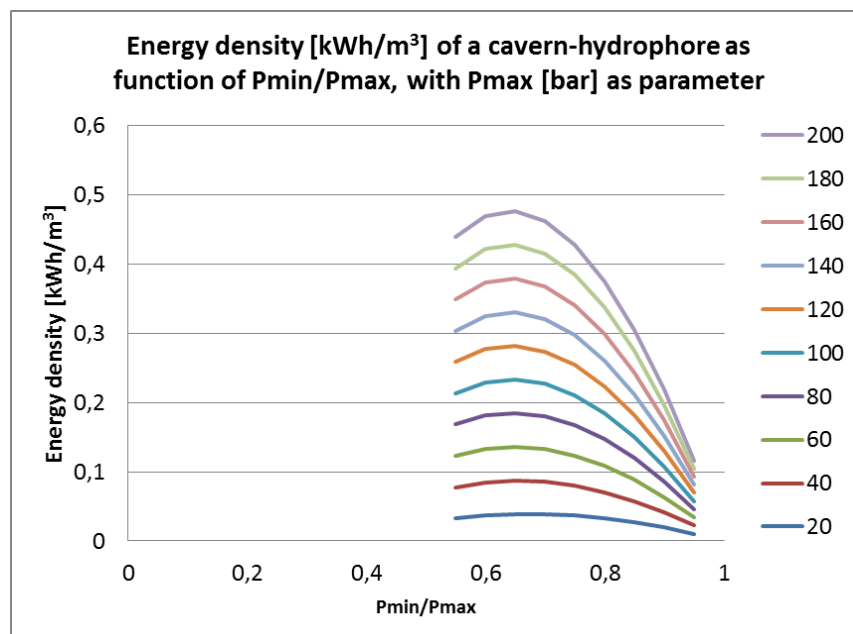
- Maximum pressure [bar] = Depth [m] \* 0,18
- Water column pressure [bar] = Depth [m] \* 0,1 = 0,55\* Maximum pressure {bar}

The energy content in the cavern then changes to (where  $P_{WC}$  is the pressure of the water column):

$$\begin{aligned}
 W &= \int_{V_1}^{V_0} (P - P_{atm} - P_{WC}) dV = \int_{V_1}^{V_0} P_0 * V_0 * \frac{1}{V} dV - (P_{atm} + P_{WC}) * (V_0 - V_1) = \\
 &P_0 * V_0 * (\ln(V_0) - \ln(V_1)) - (P_{atm} + P_{WC}) * (V_0 - V_1) \\
 &= P_0 * V_0 * (\ln(V_0) - \ln(V_0 * \frac{P_0}{P_1})) - (P_{atm} + 0,55 * P_1) * (V_0 - V_0 * \frac{P_0}{P_1})
 \end{aligned}$$

If  $P < (P_{VS} + P_{atm})$ , there will be vacuum at the inlet to the pump/turbine; this range is however irrelevant. When neglecting the atmospheric pressure,  $P_{min}/P_{max}$  must be higher than 0,55.

The graph of energy density as function of pressure ratio is shown in the graph below.

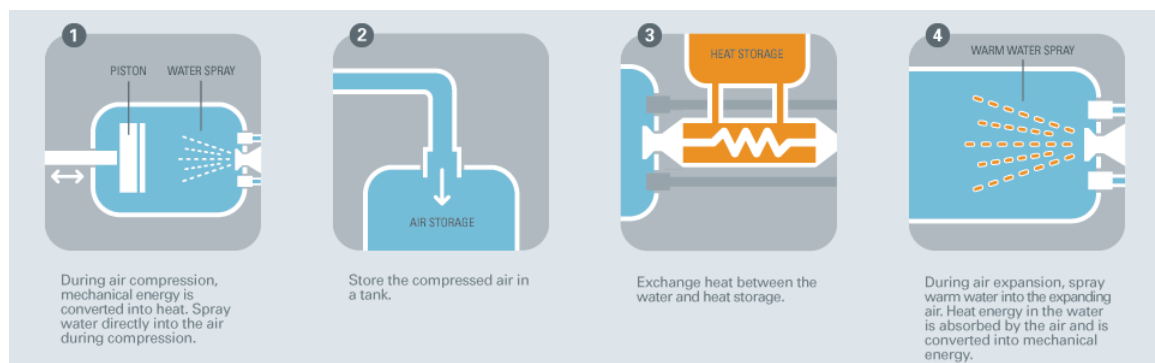


## Appendix 2: Near-isothermal CAES Systems Presently in Development

### LightSail Energy Technology

LightSail Energy<sup>3</sup> is an American company that claims to be close to commercialization of an innovative CAES-technology. In the first versions, the system uses compressed air tanks at ground level for storage. The tanks are made of filament wound composite, not steel, to obtain the most competitive price. The compressors/expanders used are slightly modified natural gas piston compressors (off the shelf items).

The main modification of the compressors is a water spray injection system that allows the compression to be near isothermal. The water is sprayed into the air, while being compressed, as a very fine mist. This allows for a very efficient heat transfer between air and water droplets. The slightly heated water is separated from the air before entering the compressed air into the tank. The warm water is stored for later use, where it is sprayed into the air being expanded during system discharge.



*LightSail Energy system operation.*

LightSail writes on its website that the system has a roundtrip efficiency of 70% (Grid → CAES → Grid). Examples of economy are also provided on the website. If assuming a purchase price for off-peak electricity of \$ 40/MWh, the first system will have an end price of approximately \$ 250/MWh, i.e. the system will multiply the electricity price by a factor of 6. An improved version is under development, which is said to have an end price of approximately \$ 180/MWh (factor of 4,5). Finally, LightSail estimates that the use of an underground cavern instead of tanks could drive the end price down to \$ 120/MWh, which is then three times the purchase price.

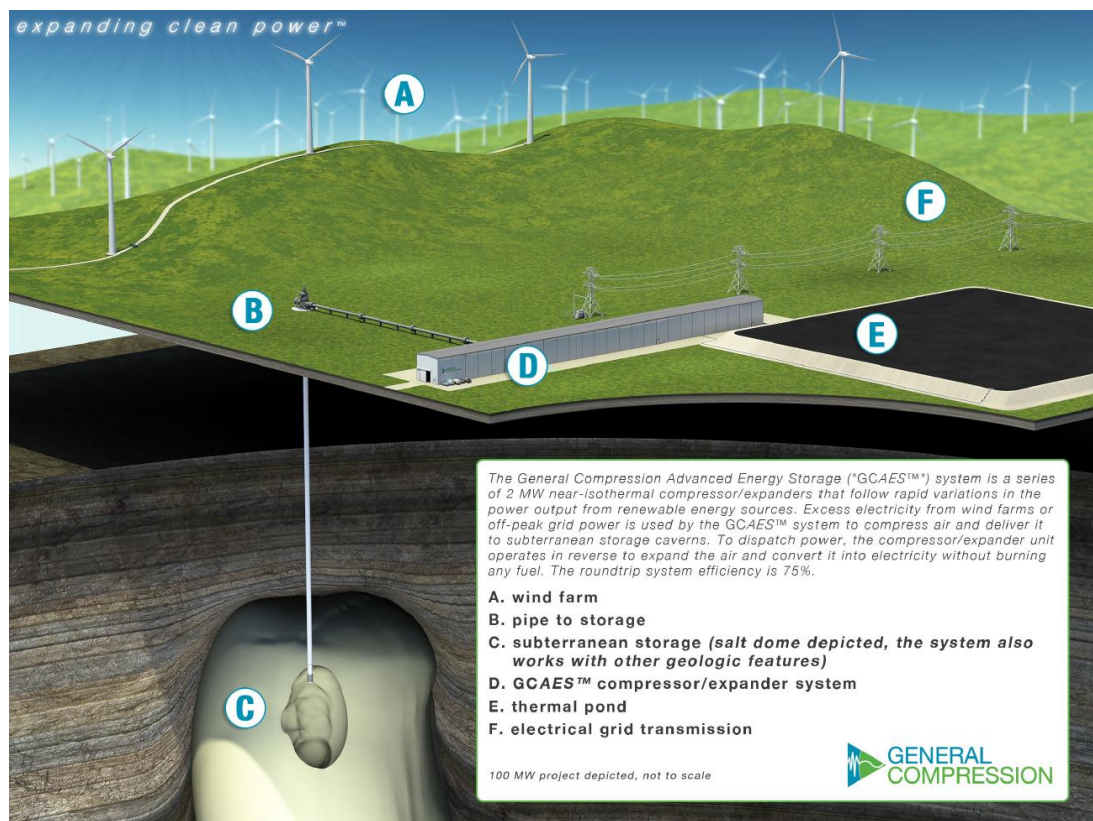
<sup>3</sup> <http://lightsailenergy.com/>

During a meeting with LightSail representatives at DONG Energy Headquarter, the market situation for CAES systems was discussed. It is evident that the LightSail system in its first version is not competitive in the Danish market, and in most of Europe, the infrastructure is so well developed that peak prices will not allow for the investment in CAES systems.

The first markets for LightSail systems would be remote locations where fuel is very expensive due to long transports, or locations where wind- and solar power is used, but reserves are needed for night or windstill hours. Actual examples were presented, such as an island in Newfoundland, where a large fraction of the electricity is produced by windmills, and the only alternative was a diesel genset, or a mining location in the mountains of Chile, where solar power is abundant, but reserves for the night are needed.

## General Compression

General Compression<sup>4</sup> is another American company claiming to be close to commercialization of an innovative CAES-technology. The company holds several patents that describe how to operate a CAES system based on wind farms. The main idea is to use windmills for compressing air into a tank/vessel/cavern and withdrawing the compressed air for electricity production as needed.



Some of the patents describe air compressors driven directly by windmills with compressors fitted in the windmill top, where electric generators are normally found.

Other patents describe hydraulic systems, where the hydraulic fluid is used to power the compression process. It is not quite clear, which system is intended for commercial applications, but the illustration might indicate that windmills driving hydraulic pumps feed high pressure hydraulic fluid to a central compressor station.

General Compression achieves near-isothermal compression by using multistage piston compressors with intercoolers that store the heat from the intercoolers in warm water ponds. Unlike LightSail, no water spray is used in the compressors.

<sup>4</sup> <http://www.generalcompression.com/>

## **SustainX**

SustainX<sup>5</sup> is yet another American company marketing a CAES system. In this case, near-isothermal compression of air is also attempted. The company holds several patents for compression technologies; some include a process where water is mixed into the air being compressed.

According to the company website, the technology is centered on mature industrial components (according to an anonymous source, SustainX has purchased the basic components of a large marine diesel engine with the purpose of converting them into a compressor/expander). Air storage can be caverns, but also ground level tanks.

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<sup>5</sup> <http://www.sustainx.com>