Synthesis

Electricity storage via adiabatic air compression

Electricity storage via adiabatic air compression

Joint synthesis

1. Electricity storage via adiabatic air compression

Synthesis of the NRP 70 joint project “Electricity storage via adiabatic air compression”

1.1. Summary

1.1.1. Summary

The phasing out of nuclear power plants and the expansion of solar and wind energy mean that electricity production is becoming more volatile. New storage systems are needed to ensure that electricity is available as and when it is required.

A promising technology for this purpose is adiabatic compressed air storage. It uses excess electricity from solar and wind energy systems to compress ambient air and store it in an underground cavity. When it is required, the compressed air is expanded again, driving a turbine and generating electricity once more. As the heat which was generated during compression is used for this process, the efficiency level stands at 65 % to 75 %, which is similar to that achieved by pumped-storage systems. The environmental compatibility of compressed air energy storage (CAES), in terms of the potential for emitting greenhouse gases and the damage inflicted on ecosystems, is also comparable to that of pumped-storage systems.

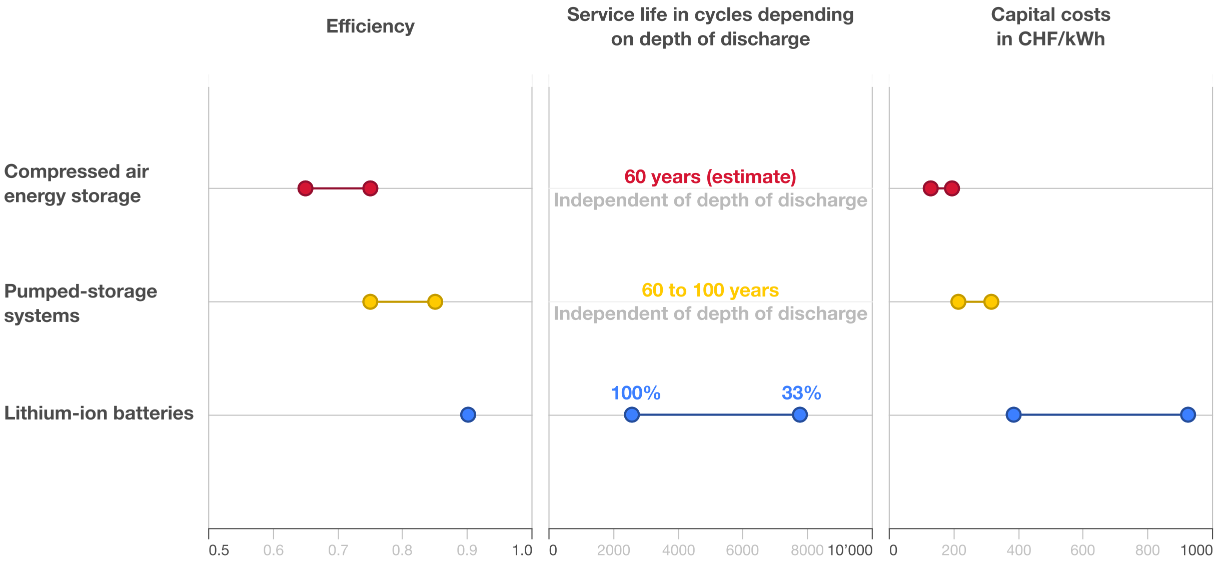
CAES systems are technically feasible. Important components such as turbomachinery and heat accumulators are either already available on the market or have been tested in a pilot plant. The process for constructing cavities is also well-developed due to the experience gained in tunnel and cavern construction.

Adiabatic CAES therefore represents an efficient, environmentally friendly and technically feasible storage solution. Due to the high capital costs and the unclear economic and legal framework conditions, however, it is uncertain whether they can be economically viable. This also complicates the financing of a demonstration plant.

1.2. Core messages

Sustainability

1.2.1. Compressed air energy storage (CAES) is efficient, technically feasible and environmentally friendly



Graphical overview of comparative data on compressed air energy storage (CAES), pumped-storage systems and lithium-ion batteries. *Source: Sources for the service life: C. J. Rydh and B. A. Sandén, Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies, Energy Conversion and Management, 46(11–12):1980–2000, 2005 (for lithium-ion batteries), and J. Giesecke, S. Heimerl and E. Mosonyi, "Wasserkraftanlagen: Planung, Bau und Betrieb", 6th edition, Springer-Verlag, 2014 (for pumped-storage systems). Source for the capital costs: "Lazard's Levelized Cost of Energy Storage", Version 2.0, December 2016 (conversion rate: USD 1 = CHF 1).)*

In the context of Energy Strategy 2050, energy storage is a much-discussed issue. More attention should be paid to CAES as it represents an efficient, technically feasible and environmentally friendly technology.

The efficiency of CAES plants with heat recovery stands at around 65 % to 75 %[1]. These figures are close to the values of between 75 % and 85 % which have been achieved in practice by pumped-storage systems. CAES systems and pumped-storage systems are less efficient than lithium-ion batteries, which have a stated efficiency of around 90 %. In this comparison, however, it must be taken into account that CAES systems and pumped-storage systems have significantly longer service lives and – unlike lithium-ion batteries – do not depend on the depth of discharge.

No major technical hurdles stand in the way of the construction CAES plants: important components such as turbomachinery, heat accumulators, motors and generators are either already available on the market or have been demonstrated in a pilot plant – and the technology for constructing storage cavities is at a mature stage thanks to many years of experience with tunnels and caverns. The greatest challenge – in view of the high investment costs and the unclear legal and economic framework conditions – is the financing of a demonstration plant.

Measured against various indicators, such as greenhouse gas emissions, CAES is as environmentally friendly as pumped-storage systems. Relative to pumped-storage systems, CAES systems have the important advantage that they can be built completely underground and do not necessitate the flooding of mountain valleys. It can therefore be assumed that the construction of CAES plants will trigger less resistance than the construction or expansion of pumped-storage systems.

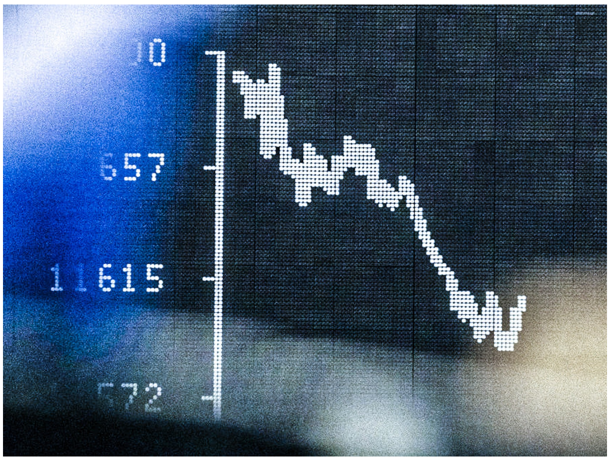
For these reasons, CAES represents an attractive storage technology. In Switzerland, it could be interesting for storing large amounts of electrical energy and as an alternative to pumped storage. CAES plants also represent an opportunity for the economy, as local companies could become active during the construction phase and as suppliers.

Notes and References

1 An efficiency of 75 % means that 1 kWh is lost from 4 kWh of electricity to be stored. The losses influence both economic viability and environmental compatibility. High efficiency is particularly important when there is little potential for electricity from wind and solar energy.

Costs / benefits # Investment # Incentives

1.2.2. The cost-effectiveness of compressed air energy storage (CAES) is still unclear



According to calculations, a CAES plant could be profitable in the Swiss secondary[1] control market under ideal conditions. Whether it could also be cost-effective under realistic conditions requires further investigation. However, even if profitability is confirmed, it still remains questionable whether an energy supplier would build a large CAES plant. The main reason is the high investment risk, which is based on two factors: on the one hand, the high investment costs must be written off over a long period; on the other, it is uncertain whether the legal and economic framework conditions for energy storage will change during this period.[2]

Not only CAES, but also other storage technologies, are struggling with profitability. This is partly due to the participation conditions in energy markets, which are not tailored to the technical characteristics of storage systems. Prerequisites for participation in the control power market include, for example, minimum durations and constant outputs. The minimum durations may result in storage capacities that adversely affect the profitability of battery storage solutions. The requirement to provide constant outputs can pose a challenge for CAES. This is currently being investigated in more detail.

The distribution of storage technologies is not only being impeded in Switzerland, but also in other countries. In Germany, for example, operators of wind and solar energy plants are compensated if the grid operator requests them to scale back production due to grid overload. This gives rise to false incentives – there is no reason for operators of wind and solar power plants to invest in energy storage in order to smooth out their production over time.

Notes and References

1 On the secondary control market, energy supply companies offer electrical power that is used to restore the balance between electricity production and consumption following a

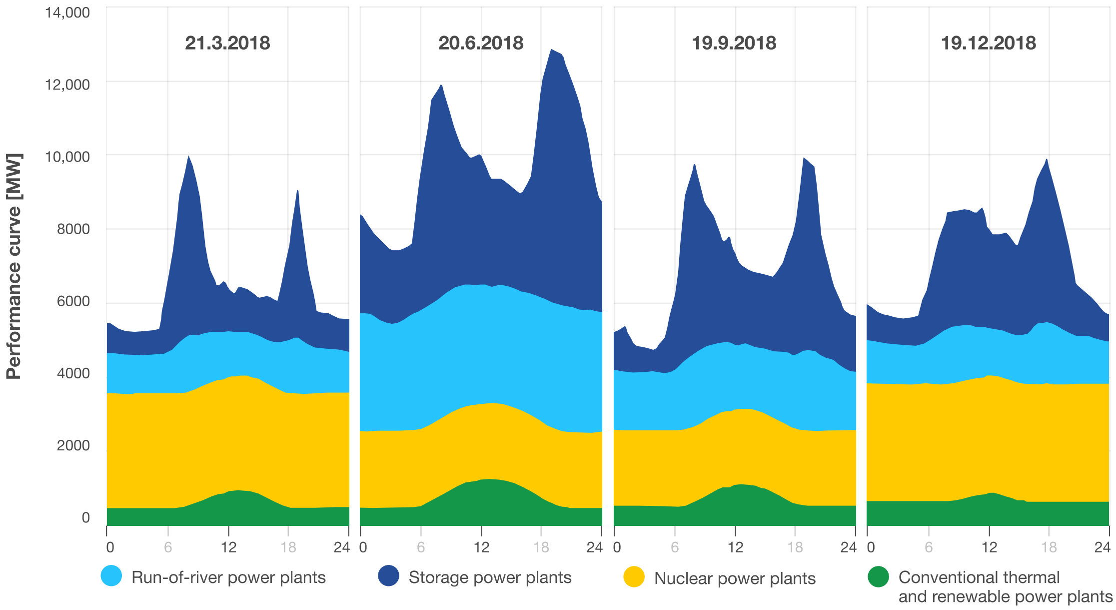
disruption. Such a disruption can be caused, for example, by the failure of a power plant.
2 The high investment risk is not limited to CAES, but also slows down the expansion of water reservoirs. See "Wo mit der Gletscherschmelze aus neuen Gletscherseen Stauseen werden könnten – und warum keiner sie bauen will", Neue Zürcher Zeitung, 20 September 2019.

1.3. Technology with great potential

In future, electricity production will become more volatile. This is because nuclear power plants are to be shut down while, at the same time, wind and solar energy plants are being expanded. To ensure that the electricity supply is guaranteed at all times – even in the event of irregular production – large electricity storage systems are required. Adiabatic compressed air energy storage (CAES) plants are ideal as they are efficient, technically feasible and environmentally friendly.

CO2 / greenhouse gases # Supply security

1.3.1. New energy and electricity storage systems are required



Performance on the third Wednesday of March, June, September and December 2018.
Source: "Swiss Electricity Statistics 2018", Swiss Federal Office of Energy, 201

The prosperity of our society is, in addition to other factors, based on the availability of affordable final energy, i.e. those forms of energy that are used by consumers. Switzerland's final energy consumption in 2018 was as follows: 49 % oil products, 25 % electricity and 14 % gas.[1] The consumption of oil products and gas must decrease if greenhouse gas emissions are to be reduced; the importance of electricity is therefore increasing.[2 3]

A special feature of electricity is that production must always be in balance with daily, weekly and monthly fluctuations in consumption. In Switzerland, fluctuations in production are currently primarily offset by the importing and exporting of electricity and by storage power plants. The stable share, the so-called base load, is chiefly covered by nuclear power plants and run-of-river power plants.

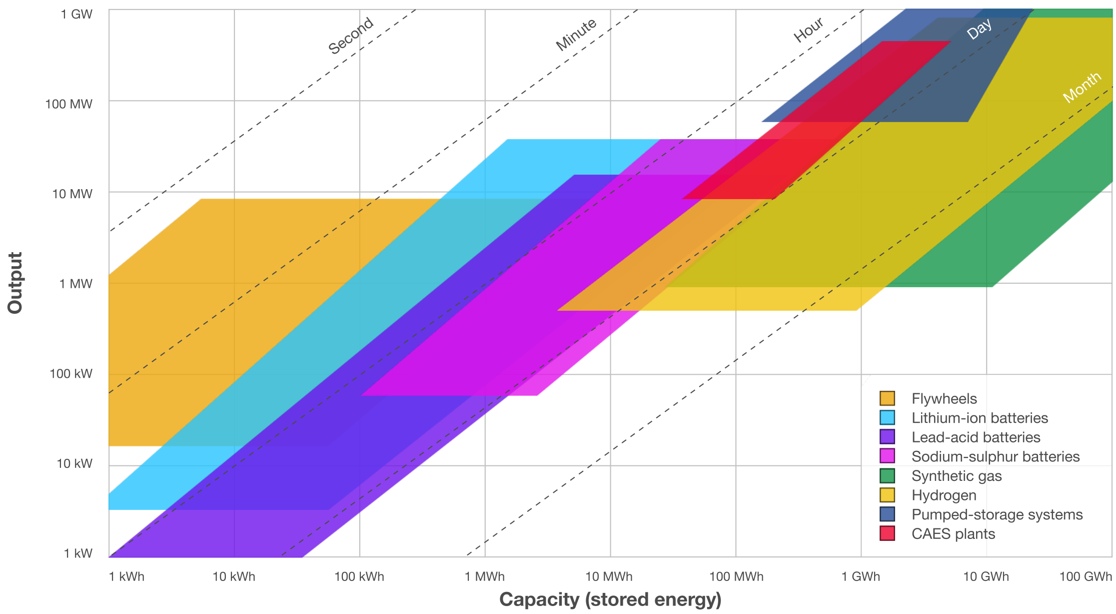
With the planned phasing out of nuclear power plants, Switzerland faces the challenge of having in future to secure its base load from volatile energy sources such as solar and wind energy if it does not want to become increasingly dependent on electricity imports. Overcoming this challenge will necessitate energy storage devices.

Notes and References

1 "Swiss Overall Energy Statistics 2018", Swiss Federal Office of Energy
2 G. Andersson, K. Boulouchos and L. Bretschger, "Energiezukunft Schweiz", ETH Zurich, 2011

3 “Zukunft Stromversorgung Schweiz”, Swiss Academies of Arts and Sciences, 2012

1.3.2. Methods of electricity storage



Capacity and output ranges as well as typical storage durations in which different storage technologies are considered appropriate due to their characteristics. *Source: "Technologie-Roadmap Stationäre Energiespeicher 2030", Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, 2015*

A special feature of electricity is that it can only be stored directly in relatively small amounts. If large quantities are to be stored, the electrical energy needs to be converted.

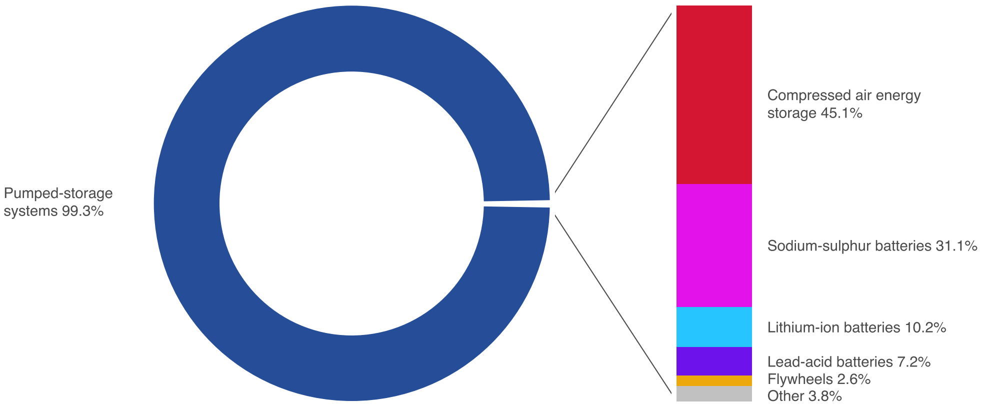
There is a wide range of storage technologies:

- Mechanical storage: pumped-storage systems, compressed air energy storage (CAES) systems, flywheels
- Chemical storage: hydrogen, synthetic natural gas
- Electrochemical storage: batteries
- Heat accumulators: sensible, latent, thermochemical

The efficiency, performance, capacity, land requirements and costs of each technology are determined by the physical processes that underpin the transformations and storage as well as the complexity of its practical implementation. From these parameters, an initial evaluation of the respective storage solutions can be carried out – and it can be deduced in which capacity and output ranges a certain storage technology is appropriate. CAES plants, for example, are considered appropriate for capacities of between around 10 MW and approximately 500 MW and for storage periods ranging from several hours to around one day.

Pumped-storage systems, CAES plants and batteries are already being used to store large quantities of electrical energy, with pumped-storage facilities clearly predominating.

Power shares of electricity storage systems that are already being used in electricity grids worldwide.



Source: “Technology Roadmap Energy Storage”, International Energy Agency, Paris, 2014 and “Electricity Energy Storage Technology Options”, Electric Power Research Institute, Palo Alto, 2010

1.3.3. The principle of adiabatic compressed air storage

Schematic diagram of an adiabatic compressed air storage system with a storage cavity in the rock. Blue and red indicate low (e.g. around 20°C) and high temperatures, with "high temperatures" ranging between 320°C and 580°C depending on the system design. The blue and red arrows show the flow direction of the air during the charging phase. During the discharge phase, the air flows in the opposite direction.

The basic principle of compressed air storage is simple to explain: Excess electrical energy – for example from solar or wind energy plants – drives a motor connected to a compressor. This compressor sucks in ambient air. Compression increases the pressure and temperature of the air. The compressed air is stored in a cavity. At a later stage, the compressed air is fed back into the surrounding environment through a turbine. The turbine powers a generator that in turn generates electrical energy.

To store as much energy as possible in a small space, a large pressure ratio is required, for example 100:1. This leads to high temperatures, which has two significant disadvantages. Firstly, the compressor and turbine must be made from expensive high-temperature materials. Secondly, high temperatures place a strain on the salt deposits or rock formations surrounding the storage cavity. It is therefore beneficial to cool the air after compression.

The simplest cooling option is to offload the heat to the surrounding environment. In order to prevent the turbine from icing up, however, heat must then be returned to the cooled air upstream of the turbine, for example by burning fossil energy sources. This is referred to as diabatic compressed air storage. This form of compressed air storage has the disadvantages that greenhouse gases are emitted and the efficiency rate stands at only around 40 % to 50 %. Diabatic compressed air storage power plants have existed in Huntorf, Germany, since 1978 and McIntosh, USA, since 1991.

A more attractive option is to extract heat from the air before the storage cavity, store it in a heat accumulator and then return it to the air in front of the turbine. This is referred to as adiabatic compressed air storage. It emits no greenhouse gases and achieves significantly higher efficiency rates of around 65 % to 75 %.[1] These values are similar to the efficiencies achieved in practice by pumped-storage systems.[2]

Notes and References

1 These efficiencies are net values after the deduction of losses in the motor, generator and power electronics.

2 Association for Electrical, Electronic & Information Technology (VDE), "Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger: Bedeutung, Stand der Technik, Handlungsbedarf", Frankfurt, 2009

1.3.4. Focus of synthesis

The focus of this synthesis is adiabatic compressed air storage in Switzerland. Compressed air energy storage (CAES) covers an output and capacity range similar to that of pumped-storage systems. Compared to pumped-storage systems, CAES systems, which have a similar level of efficiency and impact on the environment, offer a number of advantages:

- No mountain valleys need to be flooded;
- Capital and operating costs are estimated to be lower and less location-dependent;
- Compressed air reservoirs work with air instead of water; they are not affected by residual flow provisions and changes in the water cycle due to climate change.

This synthesis summarises the results of three projects[1]:

- Joint project “Power storage via adiabatic air compression”, Swiss National Science Foundation, National Research Programme “Energy Turnaround” (NRP 70) (January 2015 to December 2018);
- Innosuisse, Swiss Competence Centre for Energy Research for Heat and Electricity Storage (SCCER HaE), Phase 2 (January 2017 to December 2020);
- Grid-to-grid project, Swiss Federal Office of Energy (October 2017 to June 2019).

The projects examined two system configurations in which compression and expansion are divided into low and high pressure stages. After each compressor there is a storage cavity with a thermal storage tank. In both configurations, the maximum pressure in the second storage cavity is approximately 100 bar.

- In the first configuration, the air is compressed to 33 bar and 580°C in the low-pressure compressor. In the high-pressure compressor, the air is compressed from 33 bar to 100 bar.
- In the second configuration, the air in the low-pressure compressor is only compressed to 10 bar and 320°C. In the high-pressure compressor, the air is then compressed from 10 bar to 100 bar.

The advantage of the second configuration: the lower temperatures make it possible to use existing industrial compressors and turbines.

Both system configurations have a nominal discharge capacity of 100 MW and a capacity of 500 MWh. This means that the second storage cavity must have a volume of around 177,000 m^3. This corresponds to a cube where each side has a length of about 56 metres.

Notes and References

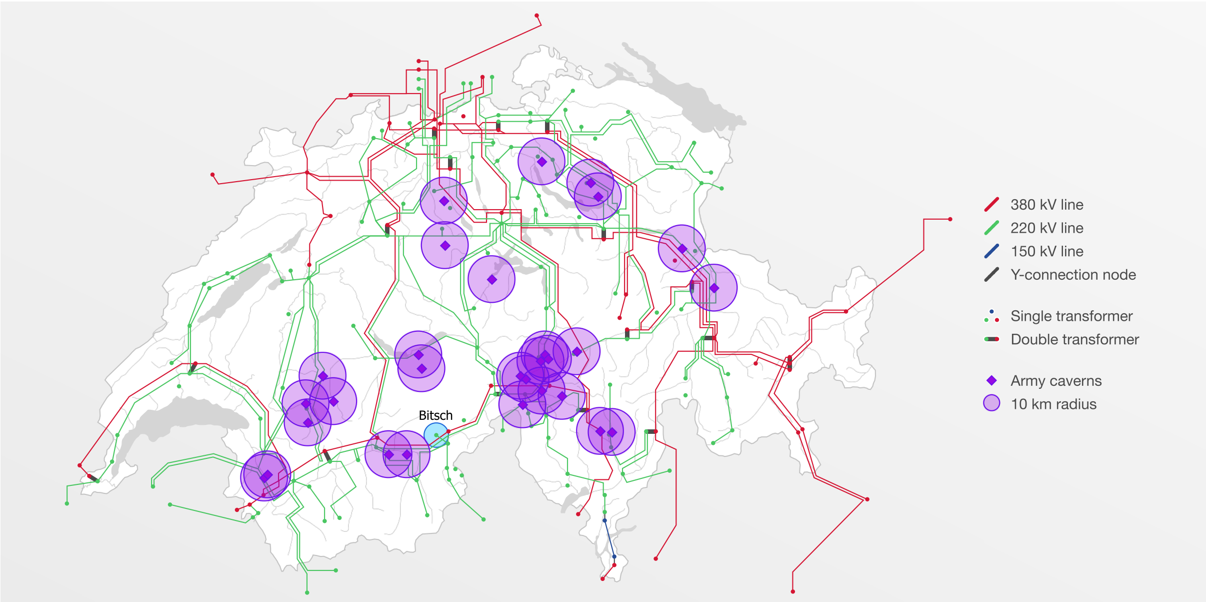
1 These projects are closely linked to a pilot and demonstration project supported by the Swiss Federal Office of Energy in which an adiabatic compressed air storage pilot plant (without turbine) was built and tested in Biasca – see G. Zanganeh, “Demonstration of the ability of caverns for compressed air storage with thermal energy recuperation”, Final Report, Swiss Federal Office of Energy, November 2016.

1.4. Technical, structural and environmental challenges

Where could compressed air energy storage (CAES) facilities be built? Which machinery could be used? And how does the compressed air energy storage plant compare from an environmental perspective with other technologies?

Planning

1.4.1. Possible locations for compressed air energy storage (CAES) facilities



Swiss electricity grid (as at 2025) and locations of selected disused army caverns.
Source: Swissgrid and Armasuisse

The search for possible locations for compressed air reservoirs initially focussed on disused army caverns. Their use could reduce or even eliminate the cost of excavating the storage cavity, depending on the volume of the caverns. One advantage would be a location close to a grid node – this would reduce the cost of connecting the CAES plant to the grid.

A closer look at the disused caverns revealed, however, that they are much smaller than the required volume of 177,000 m^3. Most of them are so small that the savings in construction costs are negligible.

Further investigations also showed that the reuse of the disused army caverns is also associated with several disadvantages:

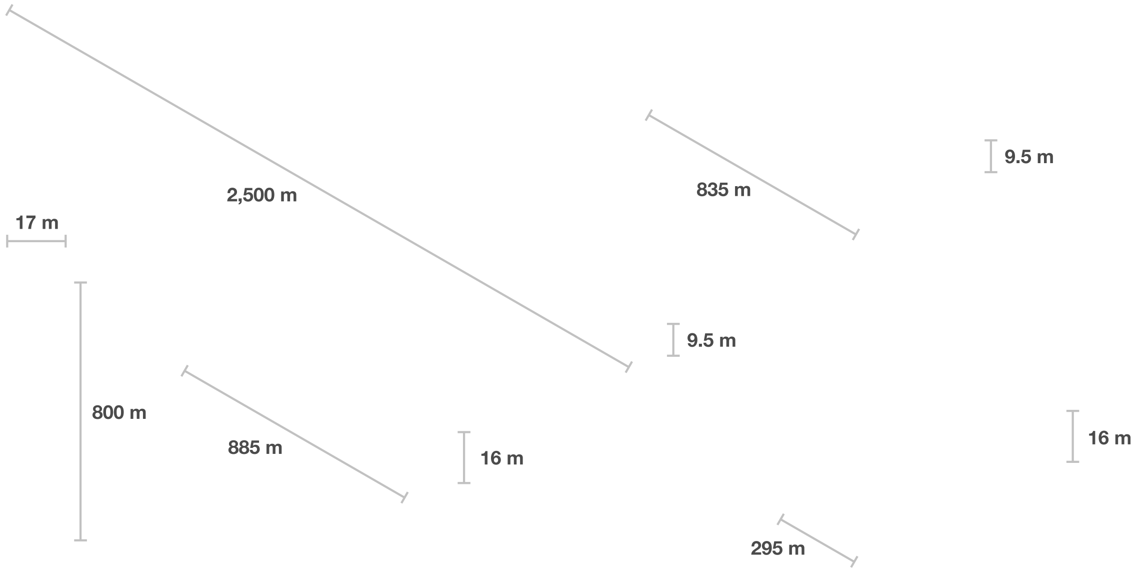
- The caverns are too close to the surface; the distance between the cavern roof and the overlying ground surface is less than the 1,000 metres necessary to withstand the maximum pressure of around 100 bar. Where this is the case, costly reinforcing linings of the caverns are necessary;
- The caverns normally have several entrance and exit points, which represent possible paths for pressure losses;
- The caverns are normally significantly branched, resulting in large surface-to-volume ratios. This promotes heat losses from the air to the rock;

- The cross-section of most caverns is horseshoe-shaped. This can lead to stress concentrations and cracks and thus to pressure losses;
- Only a few caverns are located in areas of high quality rock, such as the Aare Massif. They would therefore probably have to be sealed with a lining.

For these reasons, the reuse of disused army caverns is not being pursued. Instead, it has been decided to excavate completely new storage cavities. What this means in terms of investment costs is being examined more closely within the project of the Swiss Competence Centre for Energy Research (SCCER) and a new project of the Swiss Federal Office of Energy.

Planning

1.4.2. Construction of storage cavities



Five possibilities for realising the storage volume of 177,000 m³ with tunnels and shafts. For the sake of clarity, the ratio of diameter to length is not true to scale. *Source: Philipp Roos / Andreas Haselbacher*

The storage volume of 177,000 m^3 can be achieved in different ways. For example with

- a tunnel with a diameter of 9.5 metres and a length of 2.5 kilometres – roughly equivalent to the new SBB tunnel through the Bözberg;
- three parallel tunnels with a diameter of 9.5 metres and lengths of 835 metres;
- a tunnel with a diameter of around 16 metres, as is quite common for caverns, and a length of 885 metres;
- three parallel tunnels with a diameter of 16 metres and lengths of 295 metres.

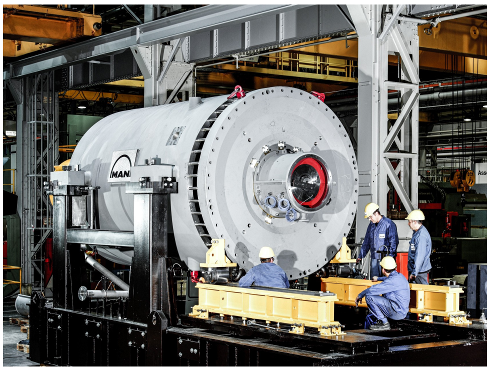
In addition to horizontal alignment, vertical arrangement in the form of shafts is also possible. The storage volume would require a good four Sedrun shafts.

The construction of a tunnel with a length of 900 metres and a diameter of 9.5 metres does not pose a major structural challenge. It can be assumed that the cavities will primarily be built in undisturbed hard rock formations. As no extensive experiments with compressed air energy storage (CAES) plants in such formations have been carried out yet, there is little experience regarding how they respond to cyclic pressure loads.

Tunnel carcass in the Ceneri Base Tunnel. The excavation of the storage cavity for a possible compressed air reservoir in Switzerland would benefit from the extensive experience of Swiss companies in the construction of caverns, tunnels and shafts.

Source: Amberg Engineering AG

1.4.3. Turbomachinery for compressed air energy storage (CAES)



The radial compressor has a length of approximately 4 and a diameter of approximately 3 metres. *Source: MAN Energy Solutions AG*

A compressed air energy storage (CAES) plant requires one or more compressors driven by electric motors for the charging process as well as one or more turbines linked to generators for the discharging process. Decisive factors for the design of the turbomachinery include the desired performance during the charging and discharging processes, the maximum and minimum pressures in the cavern and the temperature levels of the thermal storage tanks. The turbomachinery, in turn, has a significant influence on the efficiency and investment costs of the CAES plant.

To keep the investment costs low, turbomachinery that is already available should be used. However, these are not designed for the very high temperatures that occur at high pressures. When ambient air is compressed to 100 bar, for example, a temperature of around 950°C is reached. It is therefore necessary to perform the compression in two stages and to cool the air in between with a thermal storage tank.

In order to achieve the lowest possible temperatures for the turbomachinery as well as all other components such as pipes and valves, similar pressure ratios are required for the two compression stages. Low temperatures mean that shorter start-up times are possible for the CAES plant, which is advantageous in terms of both operation and profitability. Compression is carried out with one axial and one radial compressor, while two axial turbines ensure expansion.

Turbomachinery is important for the operation and profitability of CAES plants for several reasons. On the one hand, their efficiencies at the optimum design point determine the efficiency of the CAES plant. On the other, their partial-load behaviour at reduced power and their transient behaviour during the starting up and shutting down of the machines between the charging and discharging procedures must also be taken into account. Therefore, the time and energy required to start up the turbomachinery, for example, influence the markets in which the CAES plant can be used.

1.4.4. Thermal storage for compressed air energy storage (CAES) plants

A look into the sensible thermal storage system at the pilot plant in Biasca. The storage solution is filled with pebbles with a diameter of around 2 centimetres. *Source: Andreas Haselbacher*

The thermal storage solution is the key component of an adiabatic compressed air energy storage (CAES) plant: it increases the efficiency of the CAES plant from between 40 % and 50 % to between 65 % and 75 %. The greater efficiency has a positive effect on the cost-effectiveness and environmental compatibility of the CAES plant.

Thermal storage solutions should meet a range of requirements for use in a CAES plant:

- High efficiency, i.e. low heat loss;
- High volumetric energy density to keep the volume of the storage tank as low as possible;
- The outlet temperature during discharging should be as constant as possible so that the turbines can operate efficiently;
- Lowest possible costs.

With regard to these requirements, two types of thermal storage were investigated in the projects. The first type, a so-called sensible heat storage system[1], uses pebbles with a diameter of about 2 centimetres from river deposits near Zurich as a storage material.[2] The second type, a so-called sensible-latent heat storage system[3], uses, in addition, a metal alloy filled in steel pipes as a storage material and supplements the sensible heat storage. By melting and solidifying the metal alloy, energy can be stored and released as latent heat at a constant temperature.

Sensible-latent heat storage system at the pilot plant in Biasca. On the left is the sensible heat storage system filled with pebbles, on the right the is the latent heat storage system. The sensible heat storage system is 3.1 metres high, 9.9 metres long and 4 metres wide. The latent heat storage system is about 1.5 metres high, long and wide.

Source: Viola Becattini

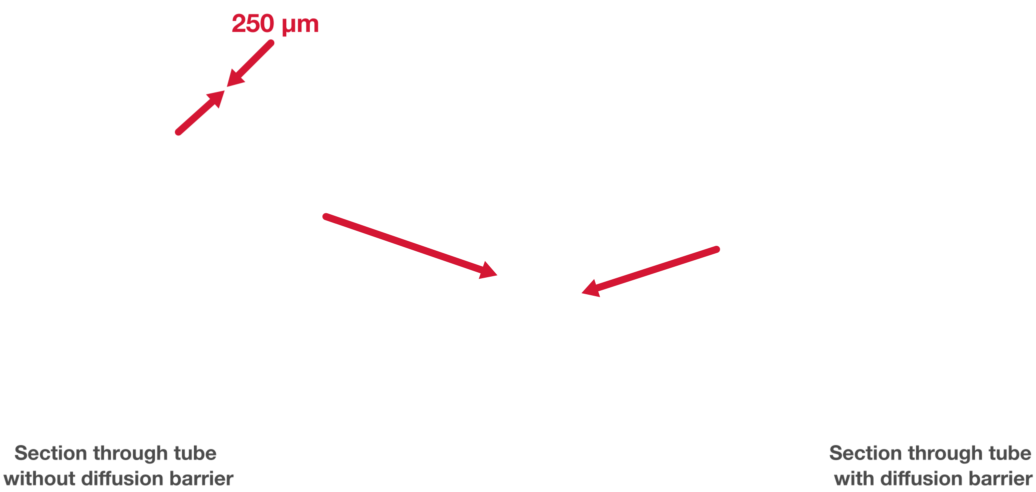
Notes and References

1 L. Geissbühler, V. Becattini, G. Zanganeh, S. Zavattoni, M. Barbato, A. Haselbacher, A. Steinfeld, “Pilot-scale demonstration of advanced adiabatic compressed air energy storage, Part 1: Plant description and tests with sensible thermal-energy storage”, Journal of Energy Storage 17:129-139, 2018

2 V. Becattini, T. Motmans, A. Zappone, C. Madonna, A. Haselbacher, A. Steinfeld, “Experimental investigation of the thermal and mechanical stability of rocks for high-temperature thermal-energy storage”, Applied Energy 203:373-389, 2017

3 V. Becattini, L. Geissbühler, G. Zanganeh, A. Haselbacher, A. Steinfeld, “Pilot-scale demonstration of advanced adiabatic compressed air energy storage, Part 2: Tests with combined sensible/latent thermal-energy storage”, Journal of Energy Storage 17:140–152, 2018

1.4.5. Phase change materials for thermal storage



The picture in the middle shows the latent thermal storage system partially filled with the steel pipes. When fully filled, there are 296 steel pipes filled with an aluminium-copper-silicon alloy in the storage tank. On the left, you can see a section through a pipe without a diffusion barrier. After about 100 hours at high temperatures, a 250 µm thick intermetallic intermediate layer has formed. On the right, a section through a pipe with a diffusion barrier can be seen; despite high temperatures, no intermetallic intermediate layer has formed. *Source: Sophia Haussener (left and right), Viola Becattini (centre)*

A latent heat storage system uses an encapsulated phase change material as a storage material. The phase change material absorbs heat during charging through the melting process and releases it again during discharging through the solidification process. A peculiarity of the phase change is that the temperature corresponds to the melting temperature of the material until the entire material has melted or solidified. This makes it possible to stabilise the outflow temperature close to the melting temperature of the phase change material.

If the thermal storage system comprises both a sensible and a latent part, the heat is first stored in the latent part and then in the sensible part during charging. During discharging, heat is first released in the sensible part and then in the latent part.

For the tests with the pilot plant in Biasca, the phase change material had to have a melting temperature of about 500°C to 550°C. Metallic materials are particularly interesting because they have high thermal conductivity and therefore enable faster charging and discharging of the storage system. For the tests, an alloy of aluminium, copper and silicon with a melting temperature of 525°C was selected.

As the phase change material melts, it must be stored in an enclosure, for example in a steel pipe. The latent heat system can then be filled with several steel pipes. At high temperatures, the encapsulation and the phase change material are particularly reactive, resulting in the formation of an intermetallic layer between the encapsulation and the phase change material. The slow growth of this layer reduces the storage capacity. In addition, the encapsulation is attacked, which can endanger the mechanical stability of the encapsulation and the latent storage system.

The formation of the intermetallic intermediate layer can be prevented using a thin ceramic protective layer – the so-called diffusion barrier.[1] This extends the service life of the steel pipes and the thermal storage system.

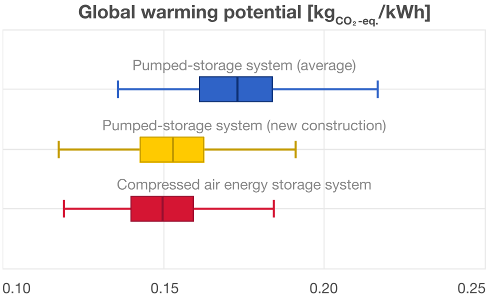
Notes and References

1 S. R. Binder and S. Haussener, "Design guidelines for Al-12 %Si latent heat storage encapsulations to optimize performance and mitigate degradation", Applied Surface Science, 143684, 2019

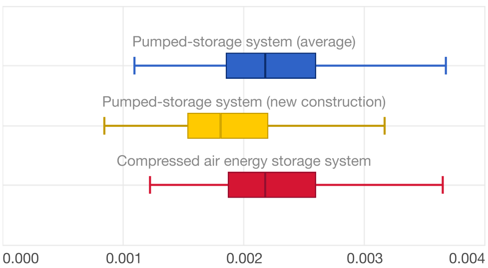
Sustainability

1.4.6. Environmental compatibility of compressed air energy storage (CAES)

Global warming potential [$kg_{CO_2\text{-eq.}}$/kWh]



Damage to ecosystems [thousandths of a point]



Greenhouse gas potential and damage to ecosystems from stored and re-fed electricity (Swiss supply mix) for CAES systems and pumped-storage systems (new construction or Swiss average). Damage to ecosystems is estimated on the basis of the impact of land use on biodiversity and the emission of pollutants. The ranges shown represent uncertainties and potential location-specific differences and show the median, the lower quartile and the upper quartile.

A complete life cycle assessment shows that CAES systems and pumped-storage systems perform similarly in terms of ecology. A more accurate comparison depends on assumptions and the comparative criteria, meaning no clear statements can be made. An example: while the investigated compressed air storage configurations have a lower material intensity than pumped-storage systems, they have a higher metal intensity. A clear advantage of CAES systems is that, in contrast to pumped-storage systems, they entail virtually no direct land use.

The environmental impact of CAES is primarily determined by energy loss. At efficiencies of 65 % to 75 %, some 25 % to 35 % of the electrical energy that is fed in is lost, and this loss has an impact on the environment. For example, the Swiss electricity consumption mix has a global warming potential of around 100 g CO_2/kWh.[1] If this is stored in a CAES plant with an efficiency of 75 %, the recovered electricity is around 135 g CO_2/kWh. Only 2 grams of the increased global warming potential comes from the storage system – the remaining 33 grams comes from the lost energy. Therefore, it can make sense from an environmental perspective to use advanced materials such as phase change materials if they increase the efficiency of the CAES plant – even if the materials themselves have a greater impact on the environment. CAES plants offer the greatest benefit when they are used to store surplus electricity, for example from wind and solar power plants, and thus replace electricity produced from fossil energy sources.

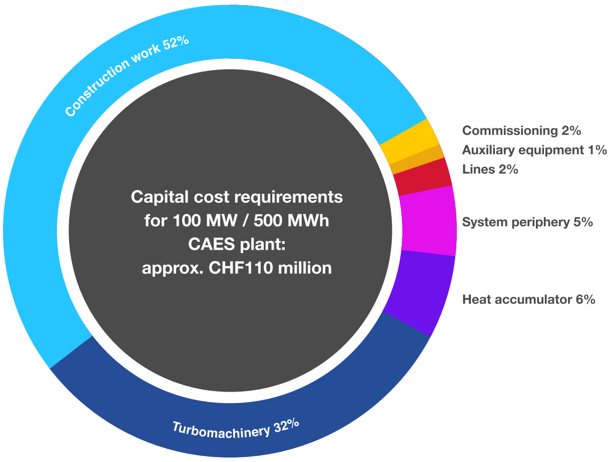
The greatest impact on the environment related to a CAES plant is caused by metals. These are primarily found in the infrastructure, for example in the turbomachinery, generators and substations.[2] The impact of the metals could be reduced through recycling. In contrast, the impact of the excavation of the storage cavity and the removal of the excavated material, is negligible.

Notes and References

1 G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology", The International Journal of Life Cycle Assessment, 21(9):1218–1230, 2016
2 The following service lives were assumed: storage cavity 60 years, heat accumulator 40 years, turbomachinery 25 years.

Costs / benefits

1.4.7. Capital and operating costs of compressed air energy storage (CAES)



Relative shares of various components in the capital costs of a CAES plant with an output of 100 MW and a capacity of 500 MWh. Costs for electrical components such as motors and generators are included under "System periphery".

The capital and operating costs of compressed air reservoirs are similar to those of pumped-storage systems; both types of storage system consist of similar primary components such as turbomachinery, cavities and high-voltage electronics. However, as CAES plants do not require dams, the costs are less location-specific and are estimated to be about 20 % to 30 % lower than pumped-storage systems. For a CAES plant with an output of 100 MW and a capacity of 500 MWh, a capital cost requirement of approximately CHF110 million can be assumed, which corresponds to CHF200 to CHF300 per kWh of installed capacity. The annual operating costs amount to approximately 2.5 % of the capital costs.

The construction work accounts for more than half of the capital costs. They include the construction of the access tunnel, the storage cavities, the closure plug and the sealing mechanism. The turbomachinery accounts for 32 % of capital costs and heat accumulators, which form the heart of an adiabatic compressed air storage system, are responsible for 6 %.

The capital costs of compressed air reservoirs are about half the capital costs of battery storage systems, although the cost of batteries will continue to fall. It should be noted, however, that the service life of compressed air reservoirs is at least 60 years, similar to that of pumped-storage systems, while that of batteries is only 10 to 15 years. Compressed air reservoirs are therefore considerably cheaper than battery storage tanks over their entire life cycle.

1.5. Economic challenges

Questions still remain about the financing of compressed air energy storage. While it is estimated that the cost of capital per kWh is lower than that of pumped-storage systems, it is not yet clear whether compressed air energy storage plants can be profitable.

Market

1.5.1. Which usage makes sense?

To assess the cost-effectiveness of a compressed air energy storage plant, it is necessary to analyse how different storage configurations can be used in existing markets. To date, two applications have been investigated:

- Electricity price arbitrage
- Secondary control power

In future, the questions of how forecasting uncertainties and assumptions, as well as how other applications and combinations, affect cost-effectiveness will be investigated.

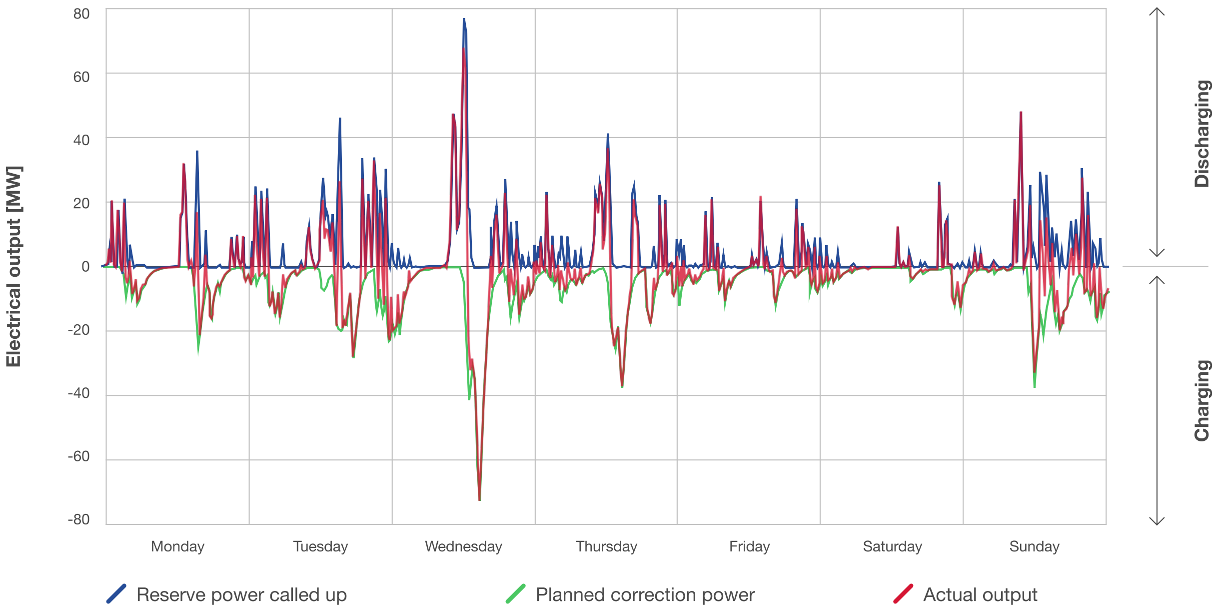
Market # Price # Costs / benefits

1.5.2. “Electricity price arbitrage” usage model

Electricity price arbitrage is based on the fact that electricity is stored when the electricity price is low and fed back into the grid when the price – usually a few hours later – is high. To investigate the cost-effectiveness of arbitrage, the electricity grid of Switzerland and its neighbouring countries in 2025, with and without compressed air storage, was simulated. The costs of covering electricity requirements were then compared. Ten plant sites were investigated to determine which location would provide the lowest coverage costs. The results show that compressed air energy storage (CAES) plants can reduce coverage costs and that a storage solution in Bitsch in the canton of Valais has the lowest costs. They also show, however, that arbitrage for compressed air reservoirs is not currently profitable due to the small price differences and losses of around 30 %.

Market   # Price   # Costs / benefits

1.5.3. “Secondary control power” usage model



Use of a compressed air reservoir for secondary control power. The reserve power called up (blue) corresponds to a signal from Swissgrid. To balance the charge level, correction power (green) is procured on the intraday market on a delayed basis. The actual system output (red) is provided either by the turbine or the compressor.

The secondary control market is used to balance out forecast errors and interruptions or generation unit outages. Various system configurations were simulated for the year 2018. The simulations are based on the assumption that the systems can generate partial load and achieve the average price for control power. The figure shows the power curves for a system with a capacity of 100 MW during a typical week in January. The effective system output is provided either by the turbine (positive output) or the compressor (negative output). To balance the charge level, correction power is procured on the intraday market with a delay. For many system configurations, an internal rate of return of 10 % to 15 % can be achieved. Based on the assumptions, these results provide an optimistic outlook for this application.

Market # Costs / benefits # Investment # Energy suppliers

1.5.4. Assessment of compressed air energy storage (CAES) from the perspective of an energy company

High efficiency, long service lives and environmental compatibility make CAES plants an attractive option for providing flexibility to the grid and electricity markets. Although flexibility has always been important, it will continue to gain in significance in future due to the expansion of wind and solar energy. Furthermore, the transmission capacity of some parts of the grid will not be able to keep pace with the expansion of wind and solar energy. The strategic placement of CAES plants could help to delay or even prevent expensive and time-consuming extensions to the transmission grid.

According to current market assessments and the expected expansion of renewable energy sources, the operation of large energy storage systems such as CAES could be attractive from 2030 onwards. To ensure that large storage facilities are then ready for use, investments and support are required from the industrial sector. Obstacles also need to be overcome, while open questions must be answered:

1. The legal framework conditions must be clearly defined in order to encourage the development and implementation of energy storage systems. At present, there is a lack of financial incentives – or they are insufficient for energy storage compared to incentives for the installation of new renewable energy sources.
2. Although there is broad agreement that energy storage is needed, it is still uncertain how large the storage capacity needs to be and how it should be optimally distributed. Without more certainty about future needs, finding investors to support a pilot or demonstration plant will be particularly challenging.

In view of current cost estimates and expected electricity price developments, it is difficult to formulate a reliable application case for the profitable operation of CAES plants. Although simulations have shown that profitability can be achieved thanks to high additional revenues from secondary services and intraday trading, forecasts are still extremely difficult and uncertain.

Regulation # Market # Financing

1.5.5. Need for action: clarify economic and legal framework conditions

The most important findings are as follows:

- The pilot plant at Biasca has shown that compressed air energy storage (CAES) plants are technically feasible and that an efficiency rate of 65 % to 75 % can be achieved;
- The estimated capital costs per kWh for CAES plants are lower than for pumped-storage systems;
- A CAES plant with an output of 100 MW and a capacity of 500 MWh would have been profitable as early as 2018 with ideal partial load behaviour in the secondary control market;
- The environmental compatibility of CAES plants compares well with with that of pumped-storage systems.

CAES plants are technically feasible, efficient and environmentally friendly, and they could also be economical. Further investigations will be completed by the end of 2020. Should the previous findings be confirmed, a complete plant should be built and tested in grid operation.

However, even for small systems there are few financing instruments. The Federal Office of Energy, for example, generally finances 40 % of the costs for pilot, demonstration and flagship projects up to an amount of CHF5 million. The industrial sector and investors therefore have to invest considerable sums – even in small plants. The investment risk is considered significant due to the uncertain development of the electricity market and the unclear economic and legal framework conditions. Perhaps the most important legal obstacle is that at present only pumped-storage systems are exempt from grid charges, meaning they are at an economic advantage.[1] In the case of large systems, the investment risk is even greater due to the long service life and the associated uncertainties about future markets.

The further development of appropriate storage technology is hampered by the unclear framework conditions. This may mean that this technology is not ready for the market when it could be useful due to the expansion of renewable energy sources. The economic and legal framework conditions therefore need to be clarified.

Notes and References

1 The favouring of pumped-storage systems is laid down in the Electricity Supply Act (SR 734.7, Article 4(1b)). An interpellation (18.4055 of 28 September 2018) calling for the technology-neutral treatment of electricity storage systems is currently pending in parliament. Legal framework conditions for energy storage systems and possible adjustments are investigated in further detail in S. Walther, “Regulierung von Energiespeichern in der Schweiz”, Dike Verlag AG: Zurich/St. Gallen, 2019.

Regulation # Financing

1.5.6. Need for action: clarify approach for constructing storage cavities

With regard to the construction of a compressed air energy storage (CAES) plant in Switzerland, two fundamental questions need to be clarified.

First: the legal situation regarding underground construction seems to be unclear. There is currently no corresponding law at federal level, which is why the cantons decide on the use of the land beneath public and non-arable areas.[1] The legal situations vary at cantonal level. However, due to the increasing use of underground areas, for example through geothermal energy or the storage of natural gas and CO_2, efforts are being made to clarify the legal situation.[2][3] Despite the uncertainties, it can be expected that the construction of CAES plants will benefit in part from the experience gained during the construction of underground structures such as machine centres for pumped-storage systems.

Secondly: it is not clear which laws and regulations could apply to the underground storage of air at high pressures. Since air is not flammable in itself, Federal Law 746.1, which regulates the storage of liquid and gaseous combustibles and fuels, does not appear to be relevant.

As there are no clearly defined legal requirements, it is to be expected that a comprehensive risk analysis will have to be conducted prior to the construction of the first large CAES plant in Switzerland. Until now, it appears that risk analyses for only diabatic compressed air reservoirs with storage cavities in salt deposits or empty gas reservoirs have been carried out.[4][5]

An obvious risk is posed by the rapid, explosive escape of the compressed air. At the existing facilities in Huntorf and McIntosh, there is no indication that any such event was imminent in the salt caverns. In the case of CAES plants with storage cavities in the rock, such events could be prevented by monitoring the deformation of the storage cavity and immediately reducing the pressure in the event of any unusual behaviour. Such measurements have already been carried out at the pilot plant in Ticino.[6]

Notes and References

1 G. Ruiz, “Niemandsland unter der Schweiz”, Horizonte No. 118, Swiss National Science Foundation, September 2018
2 A. Abegg and L. Dörig, “Rechtsgutachten: Untergrund im Recht”, Zurich University of Applied Sciences, School of Management and Law, Winterthur, October 2018
3 “Geologische Daten zum Untergrund”, report of the Federal Council in fulfilment of the Vogler postulate 16.4108 of 16 December 2016, December 2018
4 P. L. Hendrickson, “Legal and Regulatory Issues Affecting Compressed Air Energy Storage”, Report PNL 3862, Pacific Northwest Laboratory, Richland, Washington, USA, July 1981
5 M. C. Grubelich, S. J. Bauer and P. W. Cooper, “Potential Hazards in Compressed Air Energy Storage in Depleted Natural Gas Reservoirs”, Report SAND2011-5930, Sandia National Laboratories, Albuquerque, New Mexico, USA, September 2011
6 G. Zanganeh, “Demonstration of the ability of caverns for compressed air storage with thermal energy recuperation”, Final Report, Federal Office of Energy, November 2016.

1.6. Recommendations

With regard to adiabatic compressed air storage, the facts are known: the technology is environmentally friendly, efficient and safe. To help it to achieve a break through, however, further measures are needed, especially from politicians, energy suppliers and associations.

Politics (federal government, canton, municipality)

1.6.1. Create an energy storage strategy!

Politicians need to establish clear economic and legal framework conditions – and develop an "Energy Storage Strategy 2050".

It is now undisputed that energy storage is needed to integrate large amounts of fluctuating renewable electricity into our energy system.[1] [2] Which type of and how many energy storage systems are required is a matter of debate. Finding an answer is difficult because it depends on many factors which can only be partially influenced by Switzerland and which are all subject to major uncertainties.

Nevertheless – or precisely because of this – it is essential to take measures to advance the implementation of Energy Strategy 2050. This will require an "Energy Storage Strategy 2050" with the following focus areas:

1. Energy storage systems should be evaluated holistically and neutrally. In addition to efficiency and cost-effectiveness, greenhouse gas emissions during the life cycle of a storage system should also be considered;
2. The different types of energy storage systems that generate electricity again during the discharging process should be treated equally by law. At present, pumped-storage systems are preferred because they are the only electricity storage systems that are exempt from grid charges;
3. The testing of large energy storage systems that have been judged appropriate should be promoted in a targeted manner. To this end, new financing possibilities must be examined; the testing of storage systems is to be promoted by new promotion instruments such as the German regulatory sandboxes.[3]

Notes and References

1 G. Andersson, K. Boulouchos and L. Bretschger, “Energiezukunft Schweiz”, ETH Zurich, 2011 (p. 25 ff)
2 “Zukunft Stromversorgung Schweiz”, Swiss Academies of Arts and Sciences, 2012 (p. 103)
3 https://www.bmwi.de/Redaktion/EN/Dossier/regulatory-test-beds-testing-environments-for-innovation-and-regulation.html

Associations and NGOs

1.6.2. Associations must become more active!

Associations must take a more active and coordinated approach to informing politicians, businesses and the general public about energy storage systems. They should also demand clear economic and legal framework conditions for energy storage systems from politicians.

Associations such as AEE Suisse, energie-cluster.ch, SwissEnergy, swisscleantech and Swissolar can play an important role in the implementation of Energy Strategy 2050 because they are active at the interfaces between the population, business and politics.

In the area of energy storage, however, the activities of most associations are rather modest. On their websites, technologies such as heat accumulators, seasonal heat storage systems, power-to-gas and compressed air energy storage (CAES) are described either very superficially, one-sidedly or not at all.

A more active and coordinated approach would be appropriate in order to ensure the better provision of information about different storage technologies. Switzerland could learn from the German Energy Storage Association[1], which unites “companies and institutions involved in the manufacture, planning, sale, operation and development of energy storage solutions”. On its website, it offers an overview of the various storage technologies as well as fact sheets and application examples for a large number of the technologies. In Switzerland, only the Forum Energy Storage Switzerland of AEE Suisse has a similar role to the German Energy Storage Association.

Notes and References

1 https://www.bves.de

Energy suppliers # Politics (federal government, canton, municipality)

1.6.3. Involve energy suppliers more!

Energy suppliers should demand clear economic and legal framework conditions from politicians – and support the research and development of new storage technologies.

Energy suppliers can make two important contributions to the spread of energy storage solutions. On the one hand, they should make it clear to politicians that long-term investments will only be made once the economic and legal framework conditions for energy storage have been clarified.

On the other, energy suppliers should support the research and development of new storage technologies. As the current operators of energy storage systems, energy suppliers have valuable experience in the planning, construction and operation of storage facilities that so far has hardly been shared with the research and development community. The targeted involvement of energy suppliers in the management of research and development projects will ensure that the storage technologies investigated can be implemented and operated profitably.

Associations and NGOs # Energy suppliers # Politics (federal government, canton, municipality)

1.6.4. Better inform the population!

The population must be better informed about energy storage systems. Information campaigns should be implemented to increase the social acceptance of energy storage systems.

The population cannot make a direct contribution to the use of compressed air energy storage (CAES) – or other storage systems. However, it can contribute indirectly by supporting initiatives or referendums that lead to the promotion of storage in general or the construction of specific storage systems. To this end, the population needs to be better informed about energy storage. At present, the population primarily seems to understand “storage” to mean “electricity storage” and to think that it is only about pumped-storage systems and batteries.[1]

Better information will likely also increase the acceptance of energy storage systems. Social acceptance remains an underestimated component in the implementation of Energy Strategy 2050. It can play a decisive role especially for wind power plants,[2] [3] photovoltaic[4] plants, extra-high voltage lines[5] and smart meters.[6] There could also be acceptance problems with seasonal heat storage systems due to the intensive strain on underground areas.[7]

There are two reasons why CAES could enjoy a high level of social acceptance in Switzerland. First: they would be built completely underground in relatively remote areas. Secondly: due to the high involvement of Swiss companies, CAES represents a domestic energy storage solution.

Notes and References

1 The results of a survey conducted by Elektrizitätswerk Zürich (https://www.ewz.ch/de/ueber-

ewz/newsroom/medienmittteilungen/energiestrategie2050.html) show how poorly the population is informed about energy issues in general and Energy Strategy 2050, in particular. The survey shows, for example, that only 17 % of the population are aware of the objectives stipulated under Energy Strategy 2050.
2 R. Wüstenhagen, M. Wolsink and M. J. Bürer, "Social acceptance of renewable energy innovation: An introduction to the concept", Energy Policy 35:2683–2691, 2007
3 A. Fumagalli, "Trotz grösstem Potenzial der Schweiz: Neuerlicher Rückschlag für Waadtländer Windkraft", Neue Zürcher Zeitung, 18 October 2019, https://www.nzz.ch/schweiz/trotz-groesstem-potenzial-neuer-rueckschlag-fuer-waadts-windkraft-ld.1515944
4 A. H. Michel, M. Buchecker and N. Backhaus, "Renewable energy, authenticity, and tourism: social acceptance of photovoltaic installations in a Swiss Alpine region", Mountain Research and Development 35:161–170, 2015
5 I. Stadelmann-Steffen, "Bad news is bad news: Information effects and citizens' socio-political acceptance of new technologies of electricity transmission", Land Use Policy 81:531-545, 2019
6 D. J. Hess, "Smart meters and public acceptance: comparative analysis and governance implications", Health, Risks & Society 16:243–258, 2014
7 "Lösungsansätze für die Schweiz im Konfliktfeld erneuerbare Energien und Raumnutzung", Swiss Academies of Arts and Sciences, Zurich, 2012