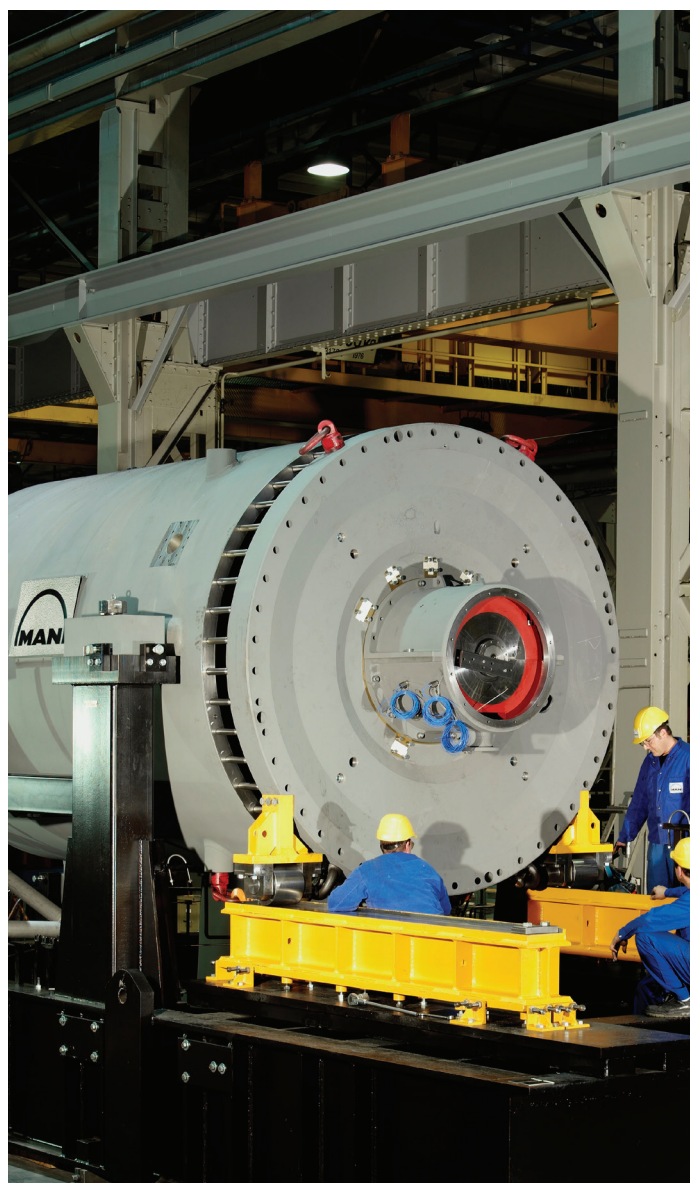


COMPRESSED AIR STABILIZES THE POWER GRID

For around five years, Swiss scientists have been working with industrial partners to investigate whether electricity can be stored in rock caverns in the form of compressed air. The interim results show: The technologies required for compressed air storage are available on the market, and such storage facilities could potentially be profitable in the future for the provision of secondary control power. At present, investors are being sought to further develop the technology, certain aspects of which have already been tested, to market maturity by building a comprehensive demonstration plant.

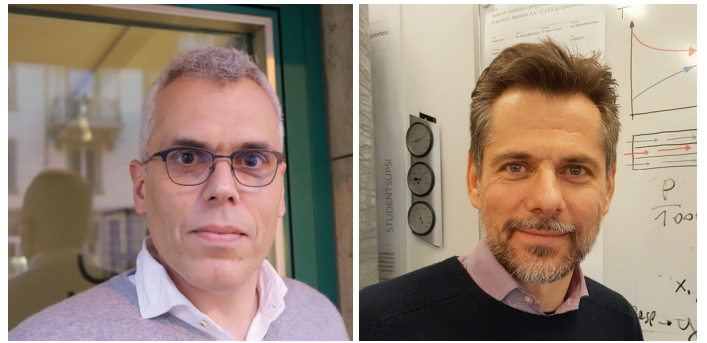
There was a time when the water reservoirs in the Alps were the pride of Switzerland. With them, the country produced its own environmentally friendly electricity. At the same time, they provided an efficient and lucrative means of storing electricity using pumped storage plants. Today, the construction of new dams is hardly possible, partly for reasons of landscape conservation. For some years now, a new, fascinating idea has been circulating about how the mountain world could be used for the electricity industry: By building rock reservoirs that store electricity not in the form of dammed water but as compressed air. While reservoirs store energy



Example of a radial compressor, as they could be used in an compressed air storage plant. Such compressors are widely used in the oil/gas business, in steel production or in the separation of air into nitrogen and oxygen. Source: MAN Energy Solutions Schweiz AG

seasonally, compressed air reservoirs are designed as short-term storage facilities: they could absorb temporary production surpluses of renewable electricity (e.g. solar power) in the Alps for hours or days until the electricity is needed by consumers, and this without impairing the landscape. Furthermore, they could provide so-called control power, i.e. control energy as required to stabilise the electricity grid.

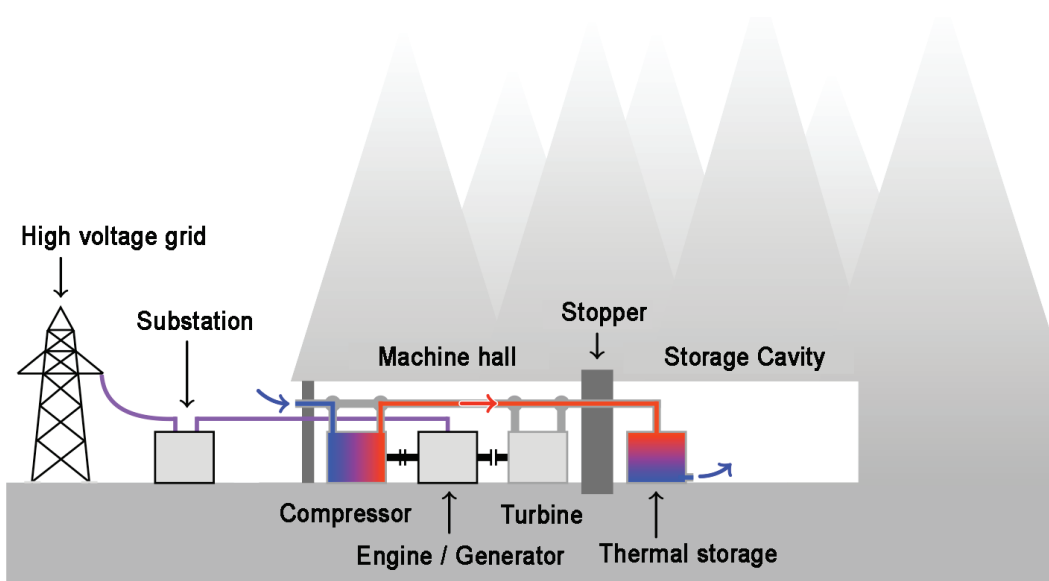
In Switzerland, scientists from various universities have been researching compressed air storage facilities over the past five years. They were supported by the Swiss Federal Office of Energy (SFOE), the Swiss National Science Foundation (SNSF) and Innosuisse within the framework of the Swiss Competence Center for Energy Research (SCCER). Together with industrial partners such as Airlight SA (solar power production/storage), MAN Energy Solutions Schweiz AG (compressors/turbines), Lombardi SA (construction) and Amberg Group AG (tunnelling, measurement technology), the researchers investigated whether rock storage facilities are technically feasible and could be operated economically. Dr. Andreas Haselbacher, who was involved in several research projects as a representative of ETH Zurich, draws a positive conclusion from the studies available to date: «A compressed air reservoir seems fundamentally feasible, as the necessary technologies are available on the market. Under optimal conditions, such a storage facility would also operate profitably if it provided secondary control power such as that needed to stabilise the Swiss electricity grid».



ETH researcher Dr Andreas Haselbacher (on the left) has coordinated various research projects on compressed air storage. Prof. Maurizio C. Barbato, Head of the Laboratory for Thermofluid Dynamics at the Mechanical Engineering and Materials Technology Institute (MENTI) of the University of Applied Sciences Southern Switzerland, has analyzed the process of loading/unloading. Photos: B. Vogel/SUPSI

Search for dense rock cavern in a suitable form

A compressed air energy storage plant essentially consists of three main components: During the charging process, compressors convert electrical energy into hot compressed air. This air is cooled by passing it through a heat accumulator and then stored in an airtight rock cavern. During the unloading process, the cold air from the cavern flows through the accumulator, absorbs heat and is then expanded in a turbine, which generates electricity via a generator. This is referred to as an adiabatic compressed air storage because not only the compressed air but also the heat generated by the compressor is stored. A pilot project led by Dr. Giw Zanganeh in a disused NEAT tunnel in Ticino gained initial experience with



Schematic representation of a compressed air storage facility: «Excess» electricity is compressed in a compressor. This produces hot compressed air, which is fed into a rock cavern equipped with a heat storage unit. In this way, the electrical energy can be stored in the form of compressed air (in the storage cavity) and heat (in the thermal storage). When discharging the compressed air storage plant, the process takes place in the opposite direction: The compressed air absorbs heat from the thermal storage and is then directed to a turbine, which produces electricity via the connected generator. Illustration: Andreas Haselbacher, ETH

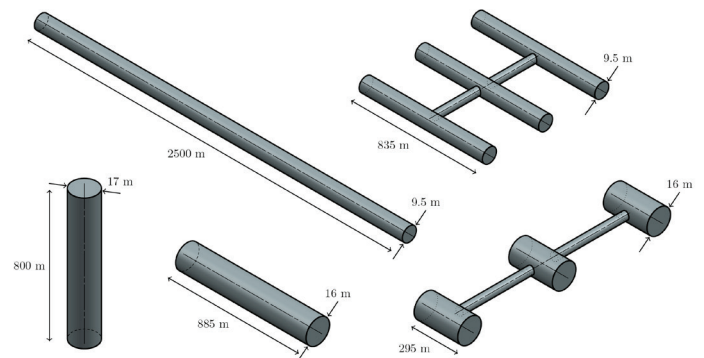
this concept between 2014 and 2016. The research project confirmed, among other things, that a heat storage system made of pebbles and an aluminium-copper-silicon alloy absorbs and releases the heat generated during compression as desired. The project also proved the tightness of the rock cavern at a pressure of 8 bar (while the target pressure of 33 bar was not achieved due to a technical problem with the sealing). Thus, to date, there is no experimental evidence that a rock cavern can withstand the 100 bar that is likely to prevail in a commercial compressed air reservoir sufficiently well, with a high degree of certainty and over thousands of operating cycles.

A SFOE follow-up project now aims to gain additional insights: Scientists at ETH Zurich want to clarify in what form (e.g. a sphere, a cylinder, several cylinders connected by a tunnel or a shaft) a rock cavern could be constructed in a practical and cost-effective manner. They also want to find out whether the tightness of a cavern could be ensured by lining it with a plastic film (as cheap as possible). Sika AG (specialty chemicals) and the Amberg Group AG are involved in the project. The results are expected to be available in the course of this year.

Application for the provision of control power

A further study, also supported by the SFOE, was completed in 2019. It investigated the behaviour of the turbomachines (compressors, turbines) with which the compressed air storage cavity is charged and discharged. Researchers from the University of Applied Sciences of Southern Switzerland (SUPSI), together with MAN Energy Solutions Schweiz AG and a team from ETH Zurich, carried out simulation calculations based on commercially available turbomachines. Of particular interest was the transient behaviour of the turbomachines during start-up and shut-down of the plant. It was shown that the energy consumption and the time required to start the turbomachines are of significance when the storage tank is operated with short charge/discharge cycles (< 30 minutes) or at low power (< 30%). The scientists concluded that from an energy point of view, it is most sensible to let the turbomachines rotate at a leisurely pace and keep them warm during breaks in operation (no charging or discharging) so that they do not come to a standstill and cool down. This helps to avoid long start-up times after cold starts.

«An air reservoir reaches the optimum operating point for taking up and discharging electricity within a few minutes. It



A commercial compressed air storage plant with a capacity of 500 MWh would require a rock cavern with a volume of 177,000 m³, which corresponds to a sphere with a diameter of 70 m. Apart from a sphere, other shapes are also conceivable, as shown in the diagram. Which shape is most suitable is being investigated in a SFOE project that is currently still ongoing. Illustration: Philipp Roos / Andreas Haselbacher

is therefore suitable for providing secondary control power,» says SUPSI Professor Maurizio Barbato. Provision of secondary control power means: Whenever the power grid is over- or under-supplied, compressed air reservoirs are charged or discharged for a short time to stabilize the power grid. The



The heat accumulator, as developed in the Ticino pilot project, consists of two parts: The 3 x 10 x 2 m concrete trough (centre) is filled with pebbles that absorb part of the heat generated when air is heated to around 600 °C during compression. The second part of the heat accumulator (right) consists of steel pipes stacked on top of each other and filled with an aluminium-copper-silicon alloy. The alloy stores latent heat during the solid/liquid phase transition (525 °C). The latent heat accumulator causes the two-part heat accumulator to emit an almost constant temperature during discharge, which is advantageous for the operation of the turbine. Photo: Viola Becattini

Comparison of different energy storage technologies

	Efficiency	Cycle Life at Depth of Discharge (DoD)			Capital Cost [€/kWh]
		100%	80%	33%	
Compressed Air Energy Storage	75%	> 25'000 DoD independent			200 - 300
Pumped Hydro Storage	85%	> 25'000 DoD independent			240**
Li-ion Battery	90%	4000*	6000*	8500*	590**
Vanadium Redox Flow Battery	75%	2900*	3500*	7500*	660**

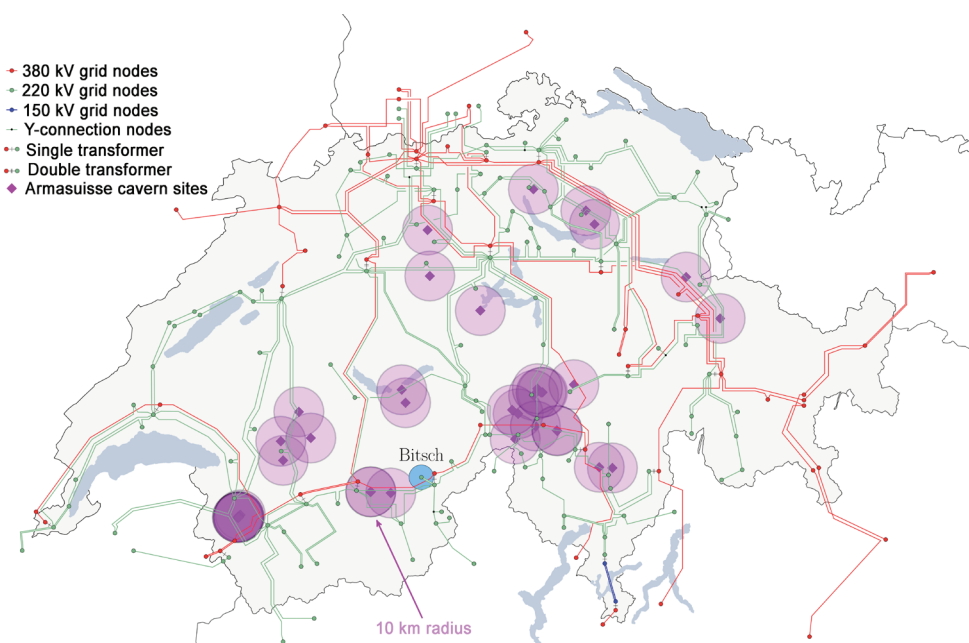
Compressed-air storage systems do not achieve the efficiency of pumped hydro storage plants or lithium-ion batteries, but according to the available calculations they have a long service life (60 years or over 25,000 charge/discharge cycles) and comparatively low investment costs. Table: Final report AA-CAES-G2G/edited B. Vogel

Swiss control power market has been open to all providers since 2009. The market volume for secondary control power alone is in the three-digit million franc range. Operators of compressed-air storage facilities could get a slice of the cake - provided they can subsequently procure the once delivered control power on the spot market at favourable conditions. The investment costs for a 500 MWh compressed air storage facility with up to 135 MW charging and 100 MW discharging capacity are between CHF 100 and 150 million. According to recent expert estimates, about half of the costs are attributable to the excavation of the caverns, about one third to the turbomachinery and about 5% to the two accumulators.

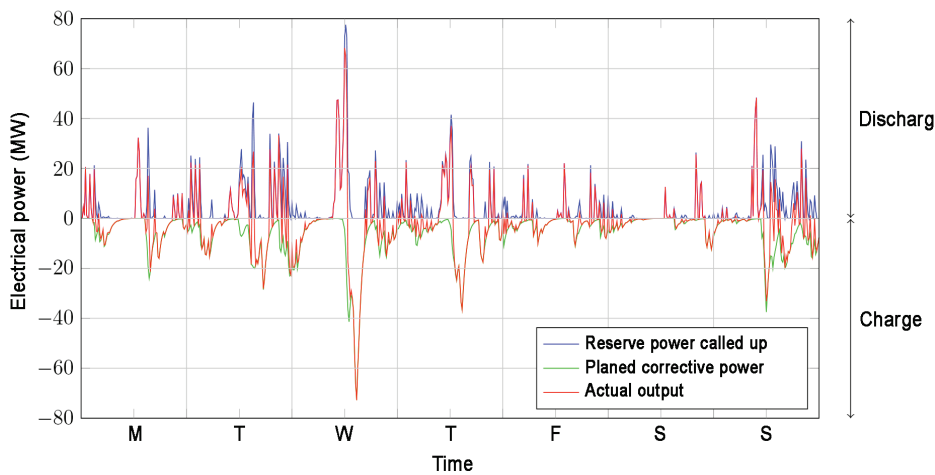
Excavating new caverns

In 2016, the Limmern pumped-storage power plant went into operation in the Glarus region. At an investment cost of CHF 2.1 billion, the plant can provide peak and control

power of up to 1000 MW and is thus around ten times larger than the compressed air reservoir described above. Under the conditions of the current electricity market, the pumped storage plant is operating at a loss. Despite this difficult environment, compressed air storage is a model for the future, says Prof. Barbato against the background of recent economic calculations: «Today, large electricity storage facilities are not operating profitably in our country, but this is likely to change in the medium term. We have to integrate more and more renewable energies from decentralized production into our energy system, and for this we need greater availability of storage systems, both in Switzerland and abroad». The scientists have compared different storage systems (see table above). According to this comparison, a compressed air storage system has a lower efficiency than pumped storage plants, but leads to a significantly lower impact on the Alpine ecosystem and the landscape. Moreover, compressed air reservoirs are significantly cheaper than battery reservoirs.



According to the calculations of the SCCER researchers, if a compressed air storage plant were to be built where it would relieve the Swiss electricity grid most, it would have to be located in Bitsch (Valais), where an important power line runs that brings French nuclear power to Italy. Selected disused army caverns are shown in violet. According to the researchers' findings, these are not suitable for conversion into a compressed air storage facility. In general, the Gotthard region is recommended as a site because of its compact and therefore dense rock. Graphic: Jared Garrison, Energy Networks Research Centre, ETH



The figure shows the performance curves for a compressed air energy storage plant with a capacity of 100 MW, which provides secondary control power (also called 'reserve' or 'balancing' power) during an example week in January. The secondary control market serves to compensate for forecasting errors and failures of loads or generation units. The reserve power called up (blue) corresponds to a signal from Swissgrid. Corrective power (green) is procured on the spot market on a delayed basis to balance the charge level. The actual plant output (red) is provided either by the turbine (positive control power) or the compressor (negative control power). Graphic: Alexander Fuchs, Energy Networks Research Centre, ETH

The question remains as to where compressed air storage facilities could be built. Empty army caverns in the Alps are out of the question, as researchers have shown in a SCCER project running from 2017 to 2020. Existing caverns do not have the required volume and also have a large surface area in relation to their volume, which leads to relatively high heat losses to the rock. The numerous access points are also problematic, as this makes sealing them expensive. Furthermore, many caverns are not located in areas with good - i.e. dense - rock. Caverns for compressed-air storage facilities must be excavated as new. This is still cheaper than building a concrete pressure tank, as the EU project RICAS 2020, in which ETH Zurich was also involved, has shown.

Search for investors

If a compressed air storage plant is to become a reality in Switzerland, the next step would be to build a demonstration plant. It would not yet have the capacity of a commercial storage facility, but would contain all components in a marketable design and would be connected to the electricity grid. Who would be able to finance such a plant - the cost would be in the region of CHF 10 million - is not yet clear. Interest is certainly present in Swiss industry. «The provision of compressed air storage solutions to implement the new energy policy exactly fits our new strategic direction,» says Dr. Philipp Jenny of MAN Energy Solutions Schweiz AG (Zurich), which has its origins in the turbomachinery business of the Sulzer Corporation. Felix Amberg, Chairman of the Board of Directors of the Amberg Group (Regensdorf/ZH) is also expressing interest. «We are very interested in contributing our civil engineering know-how to the design and construction of such a plant». The construction of a demonstration plant remains a feat of strength.

- The **final report** of the project «AA-CAES-G2G - Advanced Adiabatic Compressed Air Energy Storage grid-to-grid performance modeling» can be found at: <https://www.aramis.admin.ch/Texte/?ProjectID=40602>
- Links to the **SNF project reports**:
<https://www.nfp-energie.ch/de/projects/umbrella/109/>
<https://www.nfp-energie.ch/de/projects/1010/>
<https://www.nfp-energie.ch/de/projects/1011/>
<https://www.nfp-energie.ch/de/projects/1012/>
- For **information** on compressed air storage, please contact Roland Brüniger (roland.brueeniger[at]brueniger.swiss), head of the SFOE's Electricity Technologies research programme.
- Further **technical papers** on research, pilot, demonstration and lighthouse projects in the field of electricity technologies can be found at: www.bfe.admin.ch/ec-strom.