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Abstract

The compressed air storage powerplant in Huntorf (Lower Saxony, Germany – A.K.A. “Neuenhuntorf”), consists of a gas turbine powerplant fed by two underground salt caverns for storing compressed air in order generate electricity on an industrial scale. The plant was commissioned in 1978 with the aim of peak-shaving (storing energy at off-peak times and producing electricity at peak times).

As a response to climate change and related politics, an energy transition has been happening in Germany over the past several years. The expansion of renewable energy systems and the reduction of nuclear and fossil energy capacities are leading to bottlenecks in the electrical transmission and distribution grids, which need to be balanced by flexible powerplants and storage facilities. A considerable capacity increase in energy storage is required to cover peak loads, assuming coal or gas-fired powerplants are no longer available as a reserve in the so-called “Dunkelflaute” (a period, mostly in winter when there is neither enough sunlight nor wind to power renewables) and if only renewables are to be used to generate electricity.

These conditions require the powerplant to adapt its use case from exclusively peak shaving with a short reserve capacity for a few operating hours per year to a commercially managed energy storage facility with significant operating times in residual load use. Residual load refers to the electrical load demand on the electricity grid that is to be provided by the remaining powerplants (gas, coal and nuclear powerplants as well as storage powerplants) after deducting the share of volatile providers such as wind and solar energy. The flexibility of this type of powerplant will be fully utilized by customers, which leads to new challenges regarding plant operation. One such challenge comes in the form of more frequent usage of the plant, which entails a significantly higher number of start-up processes as well as longer runtimes per usage, summing up to increased yearly operation time.

This situation demands the existing system be updated. Initial considerations to retrofit the plant for increased compressed air cavern capacity and improved output and process efficiency of the existing plant have been tabled in favour of the expansion of the site by (at least one) new storage cavern and the construction of a new state-of-the-art powerplant. The possibility of hydrogen being introduced in the combustion process instead of natural gas is being considered as well.

The presentation will cover the development of the compressed air storage powerplant at Huntorf, including the current expansion plans.

Key words: compressed air, Huntorf, gas turbine, salt caverns, peak-shaving, energy transition, renewable energy, residual load, hydrogen

1. Introduction

The challenges of climate change and its surrounding politics have caused the German energy industry to undergo a massive transformation over the past several years. Renewable energy systems have been expanding rapidly, while nuclear plants and fossil fuel power generation is being phased out. Simultaneously, the country is facing significant electricity transmission and distribution grid bottlenecks, requiring extensive infrastructure upgrades. As it stands today, Germany has a stored energy reserve of less than half an hour at full load. To ensure energy security, the storage capacity must be increased multiple-hundred-fold in order to cover the "Dunkelflaute", if non-renewable power is to be phased out completely and replaced solely by renewables.

In this context, the operation of Europe's only compressed air energy storage facility must change considerably. Being designed for peak shaving with a reserve capacity of minutes for only a few operational hours per year, Huntorf must transition to handle significantly longer operating hours. This shift is driven by the increasing demand for flexible energy storage solutions, especially for residual load generation (the deficit currently covered by traditional non-renewable sources such as gas, coal, nuclear, etc.) to meet the grid's demand - after accounting for intermittent renewable energy sources like wind and solar.

Given these changes and the evolving energy landscape, further technical advancements at Huntorf are essential to meet the new demands of the energy market - now and in the years to come.

2. On Compressed Air Storage Powerplants

The concept of peak shaving in the context of compressed air refers to the use of electricity in low-price periods to compress air and store it. The storage medium for the compressed air can be either a tube or a cavern storage system. On a powerplant scale, storage in salt caverns is the most suitable option due to the large usable volume and the comparatively low construction costs per standard cubic meter of stored air. To ensure that the air can be stored at a temperature suitable for the salt cavern, the heat generated by the compressor is dissipated.

At peak load times, the air flows from the cavern into a turbine, providing electricity to the grid. Since the air cools down considerably during decompression, power generation and operating times would be significantly reduced without the reintroduction of heat. Based on the heat type of heat supply, compressed air storage plants are divided into two main groups: diabatic and adiabatic compressed air storage power plants.

Diabatic Compressed Air Storage Plants (D-CAES) utilize combustion turbines and therefore require a combustible gas – natural gas (Figure 1). Such powerplants are essentially gas-fired powerplants with enhanced efficiency due to lower fuel requirements. These plants can supply the grid during peak demand and also relieve it by drawing electricity if needed. Such plants can provide twice as much power compared to a comparable gas powered powerplant not utilizing compressed air. The natural gas can also be replaced by other combustible gases, such as hydrogen, if the turbines are designed accordingly. They can also be used as conventional gas turbines without the compressed air cavern, to supply the power grid with electrical energy for periods of time beyond the stored compressed air capacity – for instance during a "Dunkelflaute".

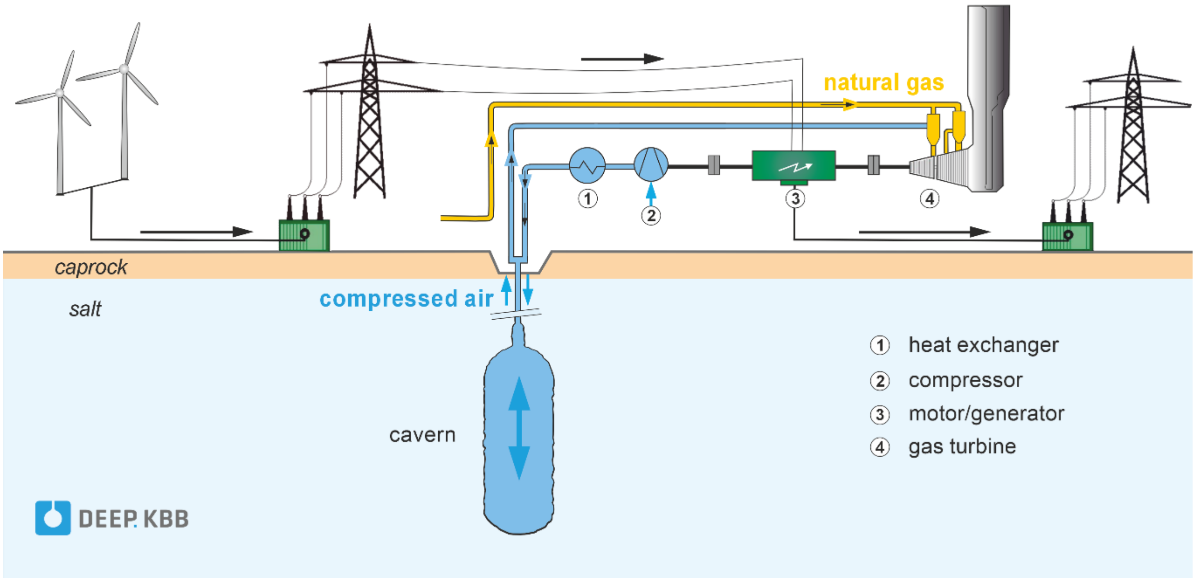

Figure 1: Diabatic compressed air storage powerplants (© DEEP.KBB GmbH)

Adiabatic Compressed Air Storage Systems (A-CAES) are pure electricity storage systems, analogous to pumped water or battery storage systems. An expansion turbine is used and the heat supply required is provided by a heat storage, which stores the heat from the compression before the air is stored in the cavern and releases it when the air is released before it enters the expansion turbine (Figure 2). There are various technical designs available for the heat storage, which are out of the scope of this paper.

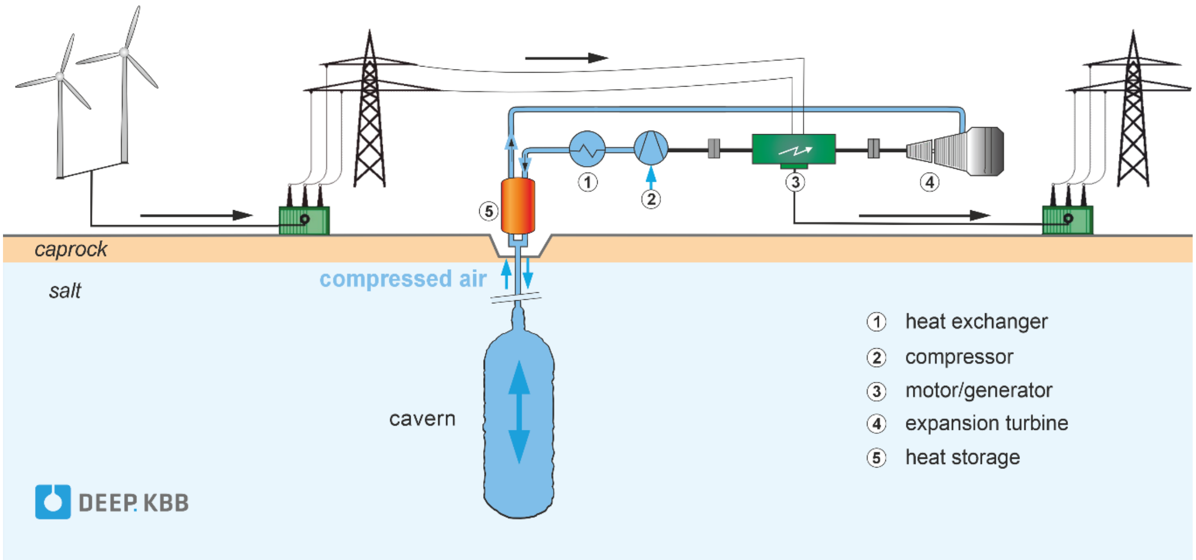

Figure 2: Adiabatic compressed air storage powerplants (© DEEP.KBB GmbH)

3. The Compressed Air Storage Powerplant at Huntorf

Huntorf is a diabatic compressed air storage plant located in Huntorf, near Bremen in northern Germany (lower Saxony) and is directly connected to the high voltage and natural gas grids (Figure 3). The plant runs fully automatically. Figure 3 depicts the turbine hall and switchgear building as well as the cooling building. The two compressed air caverns are visible to the left of the image. The pipelines connecting the caverns to the main building are clearly visible.

Figure 3: Aerial view of the powerplant and caverns (left,© DEEP.KBB) and location of the powerplant showing the high-voltage lines (purple and yellow) and the gas pipeline (orange) (right, source: https://energy-charts.info/map retrieved on 17.03.2025)

The decision to build a prototype plant for energy storage by combining a gas-fired power plant with an underground compressed air storage facility was taken in 1973 by Nordwestdeutsche Kraftwerk AG (NWK) and implemented in the following years by NWK, Brown, Boveri & Cie (BBC) and Kavernen Bau- und Betriebs-GmbH (KBB). The plant was designed to store energy during off-peak periods and to produce electricity during peak periods, being able to demonstrate rapid start-up times and high load change gradients. The following aspects also played an important role in the design: use of low-cost base load electricity, short-term generation of peak load electricity, control of the grid frequency, phase shifting and black start capability. In order to minimise the plant costs and the technical risk, the components of the above-ground plant should consist as far as possible of components available on the market and of simple designs.

The power plant was planned to be used for 600 to 700 operating hours per year, with up to 2 hours of electricity being generated during the midday peak and up to 8 hours of electricity being stored at night. The plant was commissioned in 1978. Today, the Huntorf compressed air storage power plant is operated by Uniper Kraftwerke GmbH.

With the influx requirements of the turbine in mind, the compressed air caverns were designed with the target gas turbine output of 290 MW (grid feed-in), which translated to an air mass influx flow of 417 kg/s (919.3 lbm/s), a compressor maximum output pressure of 72 bar (1044.2 psi), and an extraction time of at least 2 hours.

The resulting required cavern volume of approx. 300,000 m³ (1.059×10^7 ft³) could have been met with just one cavern, but the following reasons led to two caverns being mined:

- Providing redundancy during maintenance and in the event of a wellbore failure.
- Re-pressurizing one cavern using the other, following depressurization due to maintenance.
- The compressor needs at least one of the caverns to have a pressure of 13 bar (188.5 psi), in order to operate.

The caverns' depth was determined by the pressure requirements. On the one hand, cavern stability at atmospheric pressure during an extended service period needed to be guaranteed and, on the other hand, a maximum pressure of up to 100 bar (1450 psi) was to remain possible. Therefore, a depth of at least 600 m (1968 ft) was deemed necessary for the cavern roof.

Wellbore design posed a challenge, as the high air mass influx and the low maximum allowed friction loss meant that large diameters wells were required, if only two wells were to be implemented. After technology and cost optimization, the wellbore design was implemented as shown in Figure 4.

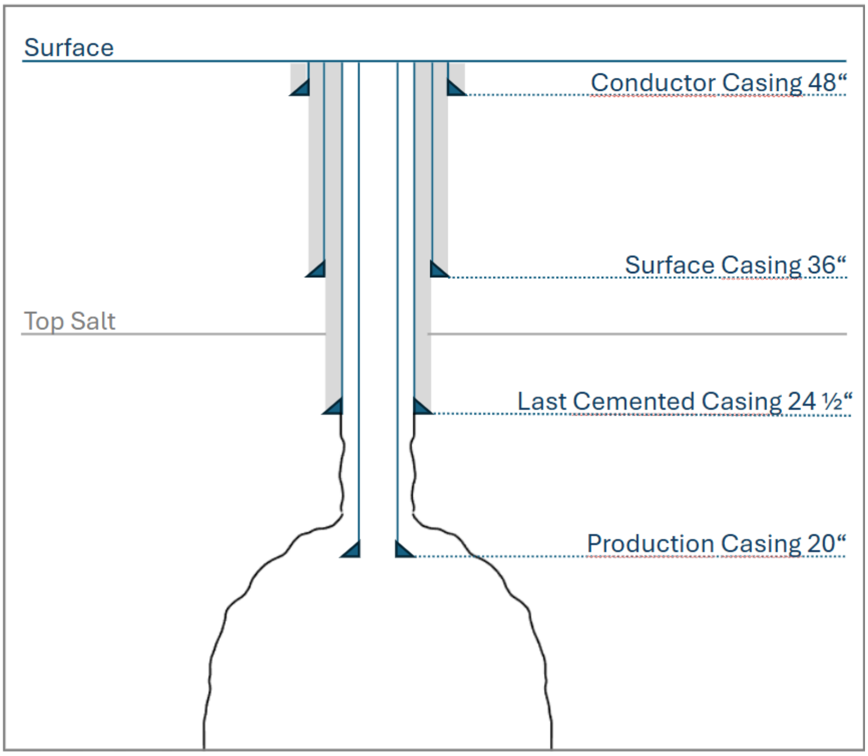

Figure 4: Borehole and completion diagram of the Huntorf compressed air caverns (© Uniper Energy Storage GmbH)

4. Increasing the Capacity of the Compressed Air Storage Powerplant

The powerplant was operated as designed until the 1990s. The number of start-ups was subject to significant fluctuation. From 1985 onwards, a general reduction in the number of necessary starts was observed, as the local power grid was connected to a larger one and had also integrated pumped storage powerplants.

Changes in the electricity price and supply caused the demand characteristics to shift. System starts were required more frequently but with significantly shorter operating times per system start, regardless of the time of day. Figure 5 shows an example of the number of starts and hours of operating time for the original operation design in 1980 compared to 1988 and 2018. Overall, the operating time increased significantly when the system was available.

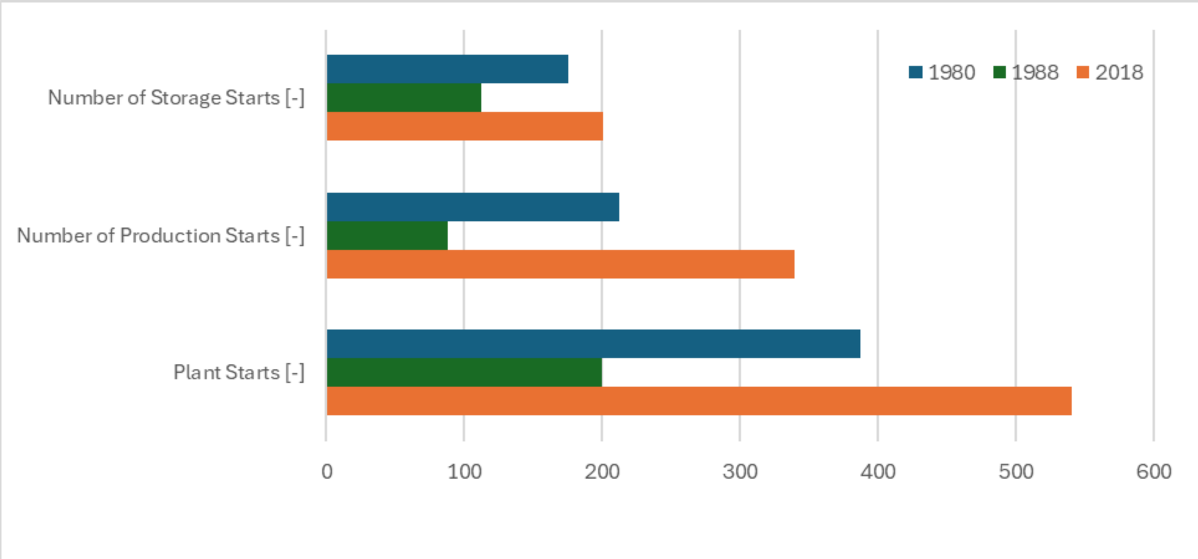

Figure 5: Number of start-ups and operating times for the years 1980, 1988 and 2018 (© Uniper Energy Storage GmbH)

In 2006, the turbine output was increased from 290 MW to 320 MW. An increase in the operating pressure range was examined and approved in 2016, in order to increase the storage capacity. As part of a research project in Huntorf 2020 carried out by Uniper and the Clausthal-Zellerfeld University of Technology, a withdrawal operation was carried out and measured starting at 66 bar (957 psi) down to the new minimum operating pressure of 30 bar (435 psi) (see Figure 6). This was part of the 6th Energy Research Program of the Federal Ministry of Economics and Technology. A portable measuring device was installed in a cavern to measure and evaluate the pressure and temperature. This device was provided by SOCON (Sonar Control Kavernenvermessung GmbH). The measurement results proved the suitability of the salt caverns for this new extended pressure range.

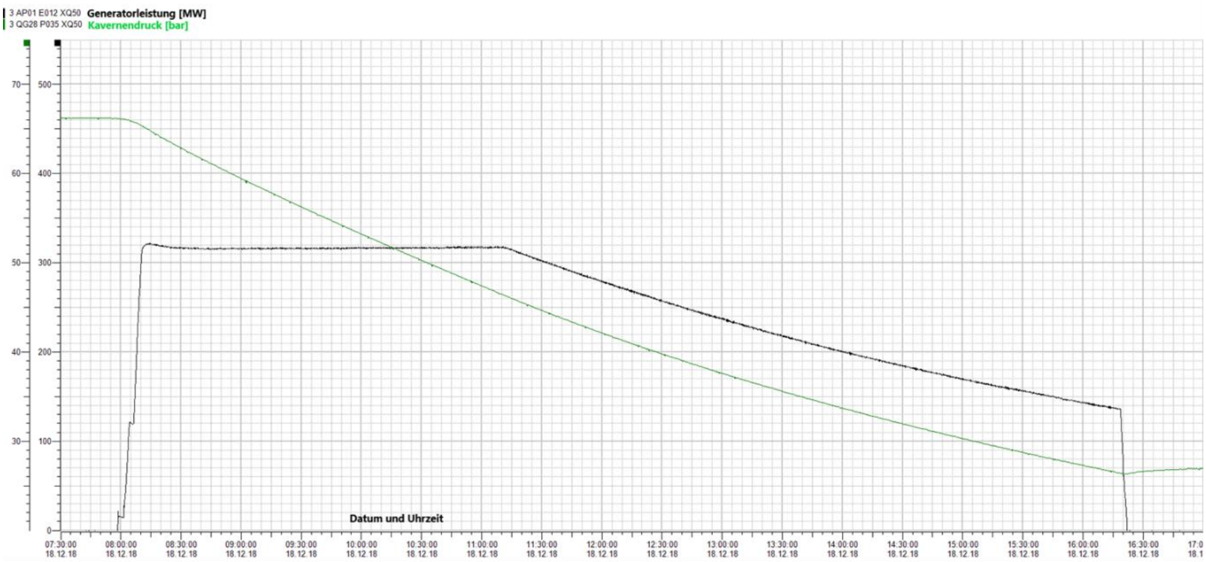

Figure 6: Generator output vs cavern pressure in withdrawal mode from 66 to 30 bar (957 to 435 psi) (© UNIPER Kraftwerke GmbH)

Other ideas, such as further expansion of the operating pressure range beyond the current operating pressure, improving process efficiency and enhancing nominal output (retrofitting the plant), require a further upgrade of the existing powerplant and have not yet been considered. Customers can currently be supplied with power generation capacity of between 100 MW and 320 MW over a period of up to ten hours, depending on their requirements.

5. Investigating the Added Value of CAES in the Energy System

The depiction of system start-ups and operating times in Figure 5 shows that an expansion of the site may still be of economic interest. This is why Uniper Energy Storage has commissioned a study titled "Economic added value of compressed air energy storage (CAES) in the energy system", which was carried out by the Büro für Energiewirtschaft und technische Planung GmbH (BET) with the support of ef.Ruhr GmbH. The study was intended to shed light on the added value of compressed air storage systems for the electricity grid in order to enable a technologically neutral selection of the best options.

Against the backdrop of the powerplant strategy put forward by the Federal Ministry for Economic Affairs and Climate Protection (BMWK) in July 2024, which envisages 500 MW of long-term storage to support gas-fired powerplants, the detailed classification of the added value from other storage technologies gained additional urgency. While pumped water storage is not seen as an option to satisfy the future demand for storage solutions due to limited expansion capacity in Germany, the question arose, to what extent can CAES add value to the future climate-neutral energy system, working alongside batteries and hydrogen.

In this context, residual load shift demand in the electricity system was analysed and assigned to different time slices. Figure 7 shows the result for the year 2037.

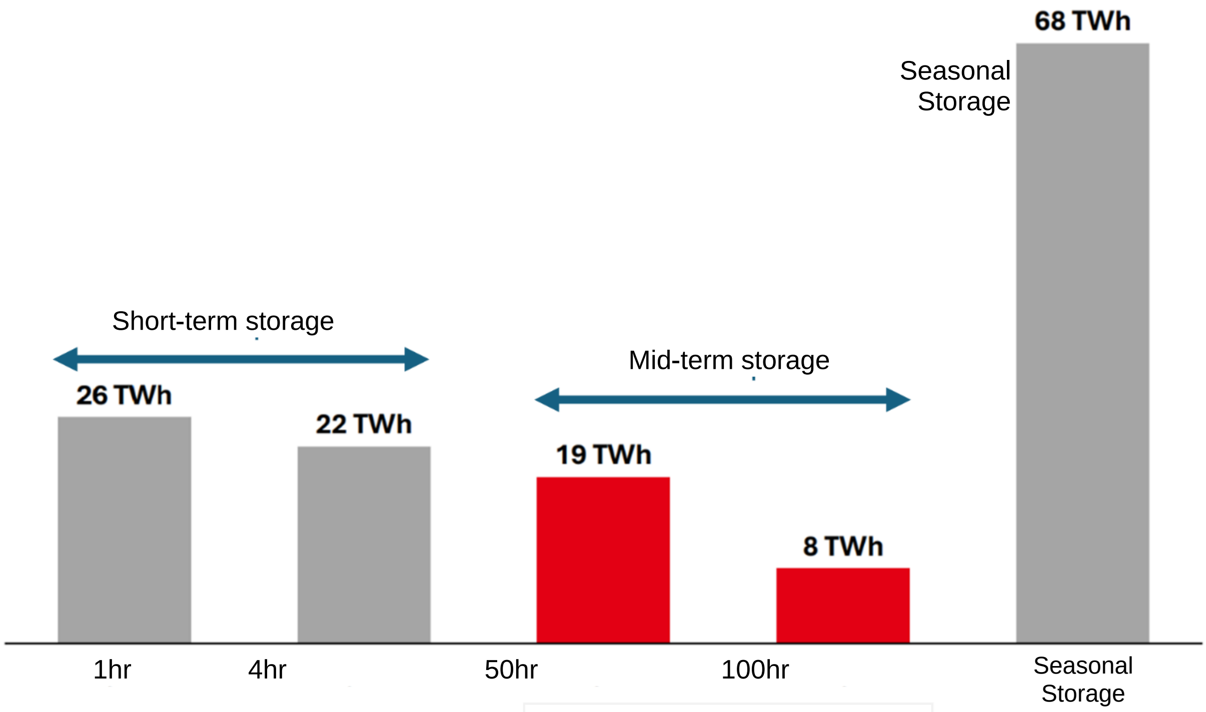

Figure 7: Estimation of the maximum residual load shift demand in 2037 (© Uniper Energy Storage GmbH)

The figure clearly shows, that although the demand for mid-term storage (50 to 100 hours) is lower than that of seasonal and short-term storage, there is still a considerable demand in the TWh range for these storage solutions. A storage cost comparison (Figure 8) demonstrates that this is the area in which diabatic compressed air storage and pump storage powerplants find their place. LCOS stands for Levelized Costs of Storage and was calculated as a function of the withdrawal duration. Battery storage powerplants and H2 hybrid storage powerplants are the most cost-effective options, in the 1 to 8 hour and 100 to 1000 hour ranges.

This supports the further considerations of Uniper Kraftwerke GmbH to examine an expansion of the Huntorf site.

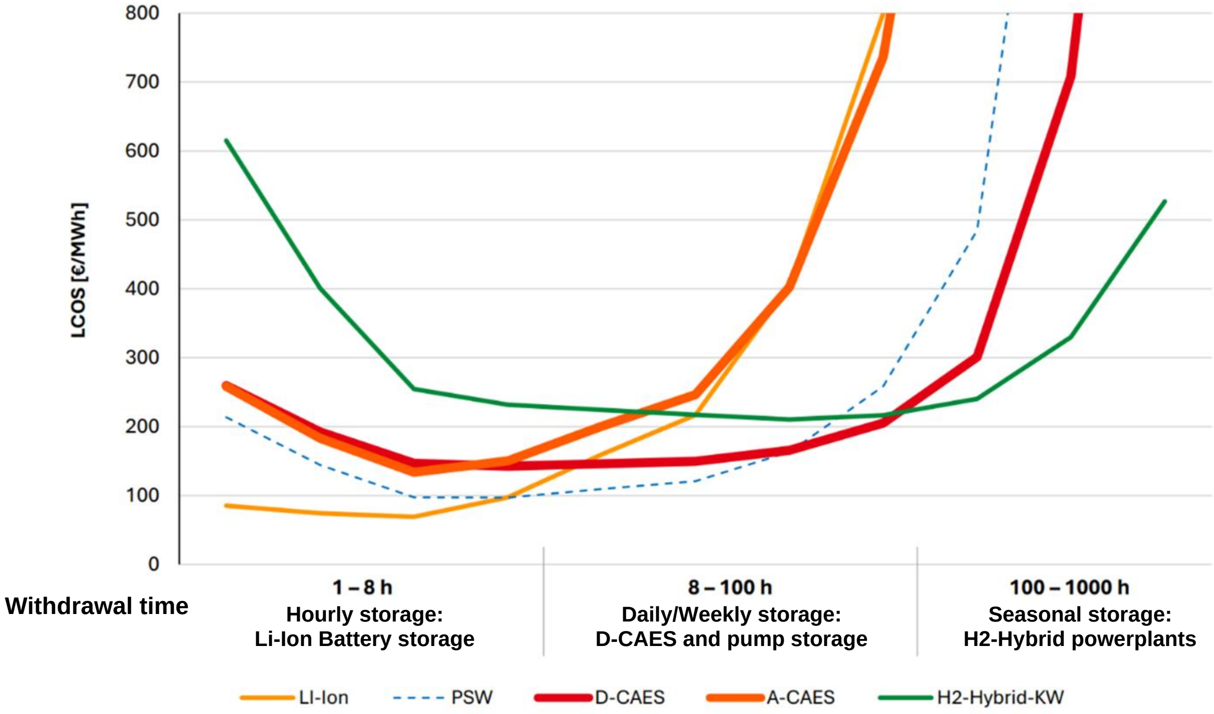

Figure 8: Storage costs for different discharge durations (© Uniper Energy Storage GmbH)

6. Current plans

As investment in the site will happen over the course of many years, it is considered a basic requirement that the new components and/or new plant be hydrogen compatible. However, as the exact timeline of the transition to hydrogen is not clear as of today, the powerplant is to be provided with natural gas. Retrofitting the existing plant to meet the new requirements while remaining within confines of the existing building poses a major challenge and would also mean temporarily disconnecting it from the power grid. This is an additional justification for the consideration of a new plant at this location. The new powerplant will be the first of its kind and is being planned by Siemens Energy Global GmbH & Co KG. One possible configuration of the plant is shown in Figure 9; the final design would be enclosed for noise protection.

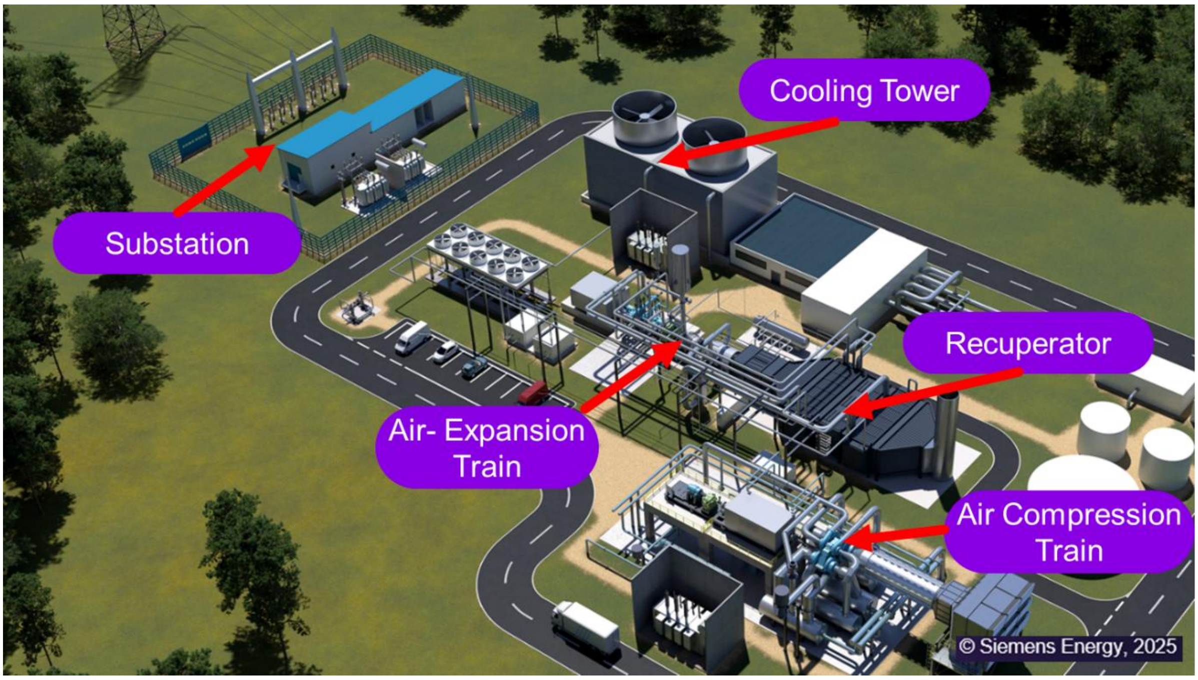

Figure 9: Possible configuration of the new plant at Huntorf (© Siemens Energy Global GmbH & Co. KG)

In addition, a storage volume expansion via construction of further caverns is being considered. Geological feasibility and state-of-the-art drilling and completion designs are being reviewed.

An economic assessment of the project is carried out parallel to the technical feasibility assessment. The scenarios include multiple markets and revenue opportunities, the frequency of use as a function of volatile electricity generation (renewables), different maximum possible production periods and various transitions from natural gas to hydrogen. Depending on the scenario, this results in over 2000 system start-ups per year. If the business case is positive at the end of the study, the new powerplant will be commissioned in the first half of the 2030s.

7. Conclusion

The CAES powerplant at Huntorf has been in operation since 1978. Due to the increased share of volatile energy production via renewables into the power grid, the number of plants starts-ups and its operating hours have increased sharply compared to the intended design of the plant, requiring upgrades be made to increase output and prolong the possible withdrawal period. Further upgrades for futureproofing are currently being considered. Based on the economic analysis, the plant will continue to be run as a diabatic system, with the design considering both natural gas and hydrogen as fuel gases. The considerations include the construction of a new powerplant, the expansion of the cavern storages and the influence of various deployment scenarios on the business case.

References

P. Quast, H. Lorenzen: The Huntorf 290-MW CAES Power Plant - Design, Construction and Commissioning of Underground Facilities, Erdöl-Erdgas-Zeitschrift, 95. Jg., Heft 3, S. 90, March 1979

P. Quast, F. Crotogino: Initial Experience with Compresse-Air Energy Storage (CAES)
Project of Nordwestdeutsche Kraftwerke AG (NWK) at Huntorf/West Germany, Erdöl-Erdgas-Zeitschrift, 95. Jg., Heft 9, S. 310, September 1979

F. Crotogino, K.-U. Mohmeyer, R. Scharf: Huntorf CAES: More than 20 Years of Successful Operation, SMRI, Orlando, Florida, USA, April 2001

P. Radgen: 30 Years Compressed Air Energy Storage Plant Huntorf - Experiences and Outlook, 3rd International Renewable Energy Storage Conference, Berlin/Germany, November 2008

U. Krüger, H. Zindler, R. Leithner: Erfahrungen mit dem Druckluftspeicherkraftwerk Huntorf im Residuallasteinsatz 2018 und das Retrofit für die nächsten Jahre, 51. Kraftwerkstechnische Kolloquium Dresden, October 2019

R. Weber, H.-P. Beck, A.-K. Klaas, M. Mancini, U. Krüger, A. Schwabauer, E.-A. Wehrmann: Huntorf 2020 – Schlussbericht, September 2021

Ef.Ruhr, BET: Volkswirtschaftlicher Mehrwert von Druckluftspeichern (CAES) im Energiesystem, Studie im Auftrag der Uniper Energy Storage GmbH, October 2024