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# Innovative Approaches of Pumped Hydro in Mining Areas as Key Technology in solving the Energy Storage Problem in the Energy Transition

**Henry Risse[1*], Horst Schmidt-Böcking[2], Joachim Schwister[3] and Michael Hollerbach[4]**

*[1]Research Institut for water management end climate future at the RWTH Aachen university, Germany.*

*[2]University of Frankfurt/M, Germany.*

*[3]Former technical Director Municipality Kerpen (Rheinland)*

*[4]Renewable energy initiative Hessen.*

***Corresponding author**

**Henry Risse,**
Research Institut for water management end climate future at the RWTH Aachen university, Germany.

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**Abstract**

*The success of the energy transition from fossil fuels to renewable energies depends significantly on storage capacities for electric energy. The decommissioning of coal-fired power plants in Germany over the next ten years will lead to a supply deficit of approx. 35 GW at night without wind power. On sunny days, however, a surplus of photovoltaic electricity of over 100 GW is expected in the near future. At some days currently (1. May 2026) already exist a surplus of 40 GW with strong negative prices at the exchange. The traditional technology for storing large amounts of electricity is pumped storage. This robust technology has a service life of approximately 100 years, compared to batteries with approximately 20 years. However, there are very few sites for new pumped storage power plants available and approved in Germany. Therefore, alternative locations must be found.*

*This article describes new approaches that proposes using existing, old open-cast lignite mines as sites for new pumped storage power plants in two different areas in Germany with different geological conditions. In the Renish mining district – a region between Cologne, Erkelenz, and Aachen – three large open-cast lignite mines are currently in operation, but these will be decommissioned in the coming years. The open-cast lignite mines reach depths of between 200 and 400 meters, thus offering ideal conditions for pumped-storage power plants. The Hambach mine, in particular, with its 400-meter depth, is exceptionally well-suited for such an unconventional pumped-storage power plant.*

*The locations Hambach, Garzweiler and Inden provide the advantage that a high voltage grid system (generating station Neurath and Weisweiler) already exists. Pumped-storage hydro-electric systems are well suited to this current power grid better than batteries. Consequently, pumped-storage systems would also reduce the costs associated with grid expansion, as they can be seamlessly integrated into the prevailing energy distribution system.*

*In the Lausitzer Revier exist coal mines with lower depth (approx. 100 m) but they got a vertical an deep sealing against groundwater inflow so that the can operate with low water levels independent from the environment.*

*A key feature of the here presented hydro power plant in the Rhenish revier is the separation of the water volume between the upper and lower storage basins from the residual water in the retention basins. The lower storage basin can be constructed in large, reinforced tube concrete caverns with a diameter of over 20 meters. The upper storage basin is located near the former ground level. The Hambach site allows for the installation of a capacity exceeding 6 GW and a storage capacity of more than 50 GWh, which would surpass the maximum output of the largest pumped-storage power plant in Germany by at least five times. This Hambach pumped-storage power plant could cover a large portion of Germany's total storage demand during the day-night cycle.*

*Furthermore such a huge storage capacity would improve the profitability of the green hydrogen production in Germany, since the electrolysis stations can obtain also during night time the needed electric power from these hydro power plants. Electrolysis stations must not switched –off after sun set and must not be heated up next morning. Thus electrolysis operation time increases from about 1400 hours per year up to 5000 hours.*

## Introduction

Photovoltaics and wind energy play a central role in Germany's energy transition. However, their growing share of electricity generation is causing increasingly pronounced grid fluctuations. Therefore, the short-term storage of renewable electrical energy for periods ranging from hours to a few days is crucial for the success of the energy transition. Currently, however, this remains an unresolved problem.

While wind power depends on position of low-pressure atmospheric systems and the course of the jet stream, the further expansion of photovoltaics in electricity generation is expected to lead to enormous fluctuations between day and night. As Figure 1 clearly shows, daytime surpluses currently exceed 30 GW and some 100 million kWh on many days, while at night there will be a deficit of several hundred million kWh. Photovoltaics, in particular, will be responsible for these large surpluses.

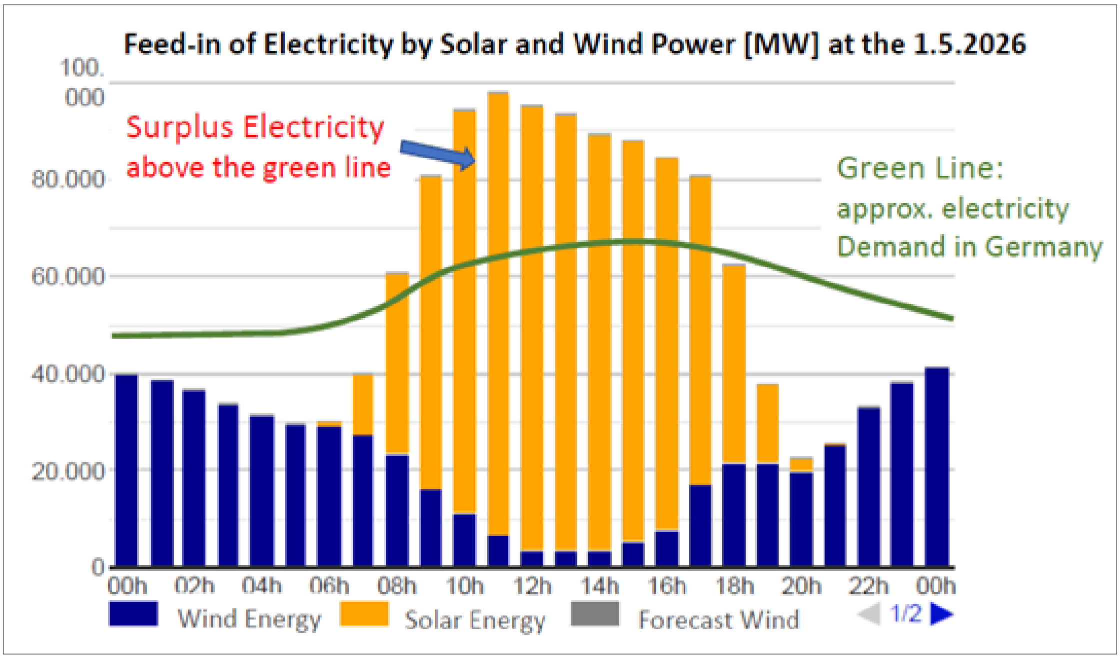


**Figure 1:** Electricity generation by wind and solar power and demand in Germany currently as an example of the 1.5.2026 (Wind journal, 2026).
https://www.windjournal.de/erneuerbare-energie/aktuelle_einspeiseleistung_wind_und_solar_energie

The green curve in Figure 1 describes the approx. total electricity consumption of industry and households in MW (Wind journal, 2026). while the blue columns represent the hourly electricity generation by wind power and the yellow columns represents the solar power generation. In this graph the power generation of biomass (approx. 5.000 MW) and hydro power (similar range) are not included. This graph illustrates the currently big necessity for power storage and the strong increasing demand in the future!

In addition, the large fluctuations in electricity generation (surplus and deficit) cause significant problems in the high-voltage grid. The following diagram shows the forecasts for power curtailments over the course of the year depending on different photovoltaic production expansion scenarios with timeline until 2045.

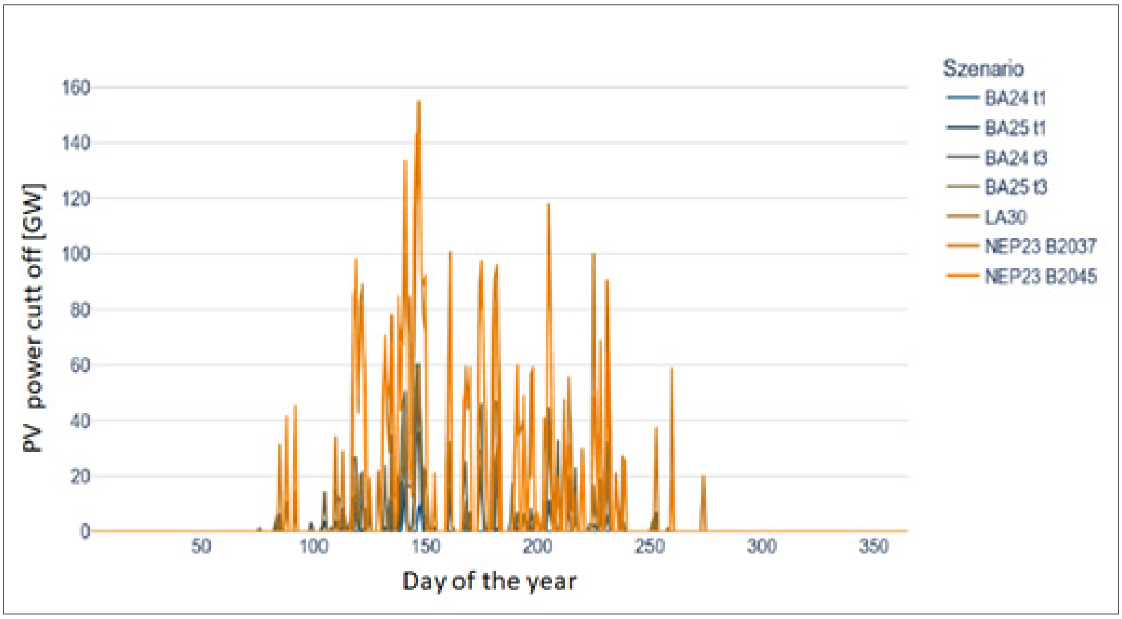


**Figure 2:** Scenarios of PV curtailments over the course of a year with insufficient storage capacity (Bundesnetzagentur, 2025).

## Available Storage Systems

When it comes to storing electrical energy on a large scale, the fundamental question arises as to which storage concepts are best suited and what additional requirements they must meet. First, a distinction must be made between short-term and long-term storage. Large long-term storage systems for bridging extended periods of low wind and low solar irradiance can only store electricity by converting it into chemical energy, i.e., synthetic methane, methanol, biomethane, or hydrogen.

However, this article focuses primarily on storage for a few hours or days to compensate for fluctuations between day and night. Such short-term storage systems must be able to convert and store a total of several tens of gigawatts of electrical power within a typical 10-hour period. This corresponds to energy amounts of several hundred gigawatt-hours, and the conversion efficiency should ideally exceed 80%. Furthermore, the raw materials required for manufacturing the storage facilities should be environmentally friendly and, if possible, available in Germany. The necessary technology should be technically mature and have a very long lifespan. Last but not least, storage costs, and therefore costs for industry and the public, must be affordable.

Currently, the following three storage technologies are being discussed: conversion to green hydrogen, lithium/sodium-ion batteries, and pumped-storage hydroelectric plants. Electricity-to-hydrogen conversion is currently used in small and medium-sized plants and is a solution for long-term storage. However, the efficiency of reconversion to electricity is very low. Electrolysis systems using PEM require rare elements such as iridium and ruthenium, which are very expensive and are currently entirely used in other (chemical) processes.

Furthermore electrolysis stations in Germany can operate only during day time when a surplus in renewable energy exists. Electrolysis stations must switched–off after sun set and have to be started up again at the next morning. Thus electrolysis operation time per year does not exceed 1400 hours per year which is not economic. I.e. 80 % of the time these electrolysis stations are switched-off.

Electrochemical storage systems (lithium-ion batteries) are currently the preferred solution for storing surplus electricity. Their costs have fallen significantly, and they are now also being used on a large scale (100 - 300 MWh). However, battery production also requires highly limited raw materials (lithium, nickel, cobalt). With increasing global demand for batteries in cars, buses, and trains, these elements could represent a bottleneck in meeting the significantly increased demand. Many potential locations of battery storage systems have strong limitations by the capacity of high voltage grid.

The third storage technology – pumped-storage hydroelectric plants – is a proven system with very long lifecycles of up to 100 years (Wikipedia, n.d.). They deliver high power outputs from several hundred MW up to 1000 MW and have large capacities of over 8 GWh (Wikipedia, n.d.). The following diagram illustrates the operating principle of pumped-storage hydroelectric plants

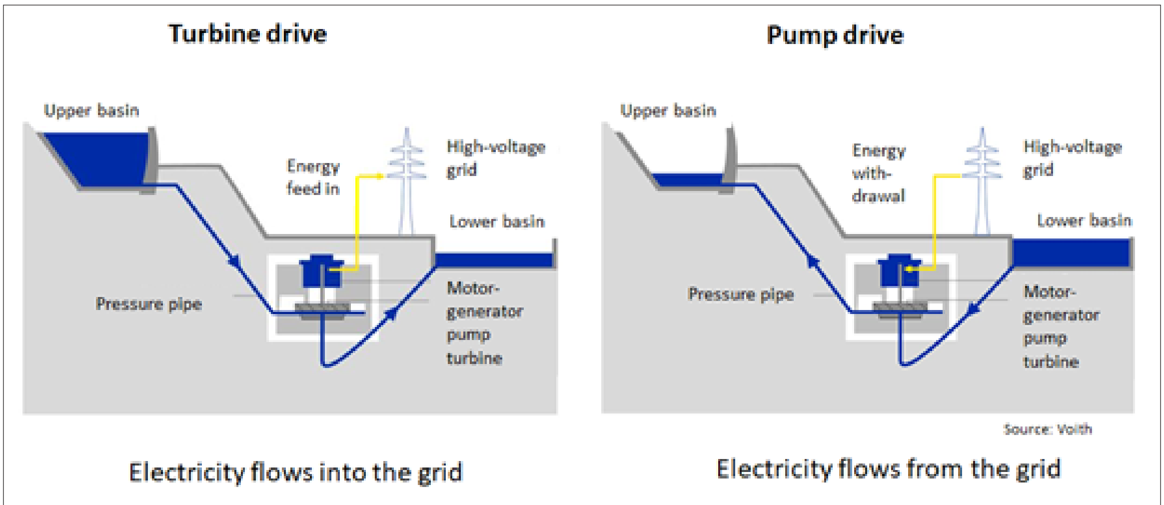


**Figure 3:** Operating principle of a pumped-storage power plant Source (Voith Hydro n.d.)

Their overall efficiency reaches 80%. Pumped-storage hydroelectric plants can start up very quickly – maximum power is available in the grid in less than 5 minutes. Due to their long lifecycle, the cost per stored kilowatt-hour (kWh) is very low – between 2 and 3 cents/kWh. Pumped-storage power plants can also be built using conventional materials such as sand, cement, steel, and copper – these materials are available in large quantities.

Overall, German pumped-storage power plants currently have a storage capacity of around 38 GWh with a maximum output of 6.6 GW (Wikipedia, n.d.). To achieve the targeted storage capacity of 400 GWh by 2045, pumped-storage power plants would theoretically need to be expanded tenfold. Is this feasible in Germany? There is a prevailing impression that the necessary topographical conditions are not present in this country. However, this is not the case, but it does require an innovative approach.

## New Approaches

The open-cast lignite mines in Germany offer a suited topography. While the open-cast mines in Lusatia (Lausitz) and the Leipzig mining area are only about 80 to 100 m deep, those in the Rhineland reach depths of between 200 and 450 m. Consequently, a pumped-storage power plant for such open-cast mines must be designed differently to optimally utilize the available depth and size. Additionally - some geological aspects have big impact to the possible technical solution.

Because of the huge daily ground water influx in the open pit mine in the Rhenish area (1 Million m³ per day) the hydrologic cycle between hydro power plant and flooded open pit mine must be completely separated. To achieve this the lower storage basins would be built in the form of large hollow structures, for example made of concrete, at the bottom of the open-cast mine (VOITH, n.d.); Schmidt-Böcking et al., 2013; Schmidt-Böcking et al., 2023). A small area separated from the open-cast lake, which would later be flooded, could serve as the upper storage basin of a pumped-storage power plant.

Figure 4 illustrates how the pipe / half pipe concrete caverns are constructed in the still-unflooded open-cast mine using sliding formwork, in which the formwork moves with the concrete structure. The arrangement of the caverns on the open-cast mine floor is flexible.

**Figure 4:** Pumped hydro storage power plant in open-cast mines – example Hambach open-cast mine (left image), example pipe caverns (right image) (Schmidt-Böcking et al., 2013), (Schmidt-Böcking et al., 2023).

Some pipe/half pipe caverns, each equipped with a pump turbine, form a unit with a total storage capacity of approximately 2.9 GWh at an average head difference of 360 m and an turn around efficiency of 80% per machine. A standard 350 MW pump turbine can store this amount of electricity in about eight hours and thus supply 300 MW to consumers for approximately eight hours. After flooding, the walls of the pipe-shaped caverns must be able to resist 400 m water column. To prevent the risk of floating the storage pipe caverns are to be covered with spoil (gravel, sand, clay)

## Hambach Open-Cast Mine - Case Study

Figure 5 shows a height realistic cross section through the mine and the whole pumped hydro power plant. Figure 5 shows also the situation in the Manheim Basin – a suitable area for the construction of the upper reservoir Basin – a reservoir with an area of over 6 km². The Manheim Basin has suitable geology – clay layers can serve as a natural seal for the upper reservoir. Figure 6 illustrates the current mining activities – only removing the approx. 35 m sand and gravel layers.

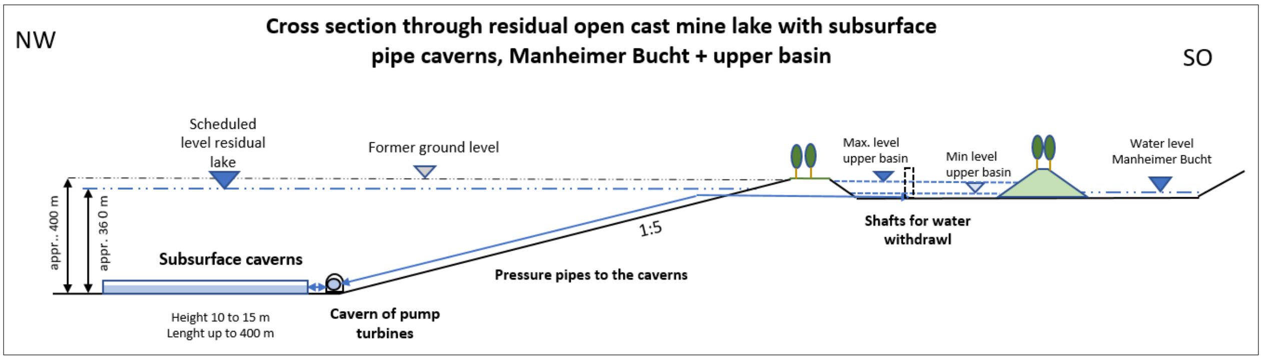


**Figure 5:** Cross-section of a possible pumped-storage power plant in the Hambach open-cast mine

**Figure 6:** View of the Manheim Basin (Manheimer Bucht) – in the current excavated area, potential location of the upper reservoir (own photo)

The energy storage potential of such a pumped-storage power plant in an open-pit mine depends on the difference in elevation between the lower and upper reservoirs, as well as the available volume of water pumped by the turbines. This fluctuating water volume corresponds to the sum of the cavern volumes. With a cavern volume of approximately 60 million m³ at the bottom of the open-pit mine, and a cycle length of 8 hours, a storage capacity of approximately 8 GW is possible in pumping mode and 6.6 GW in turbine mode. The available capacity in pumping mode is more than 50 GWh. This is significantly more than the total storage capacity of all other existing pumped-storage power plants in Germany of 38 GW in summary. This large amount can make a significant contribution to Germany's energy transition.

Another approach is possible in the Lausitzer Revier. The open cast mines are not so deep but they got in some cases very deep sealing walls to prevent that ground water pours in the open cast mines. The following figure 7 shows this schematically.

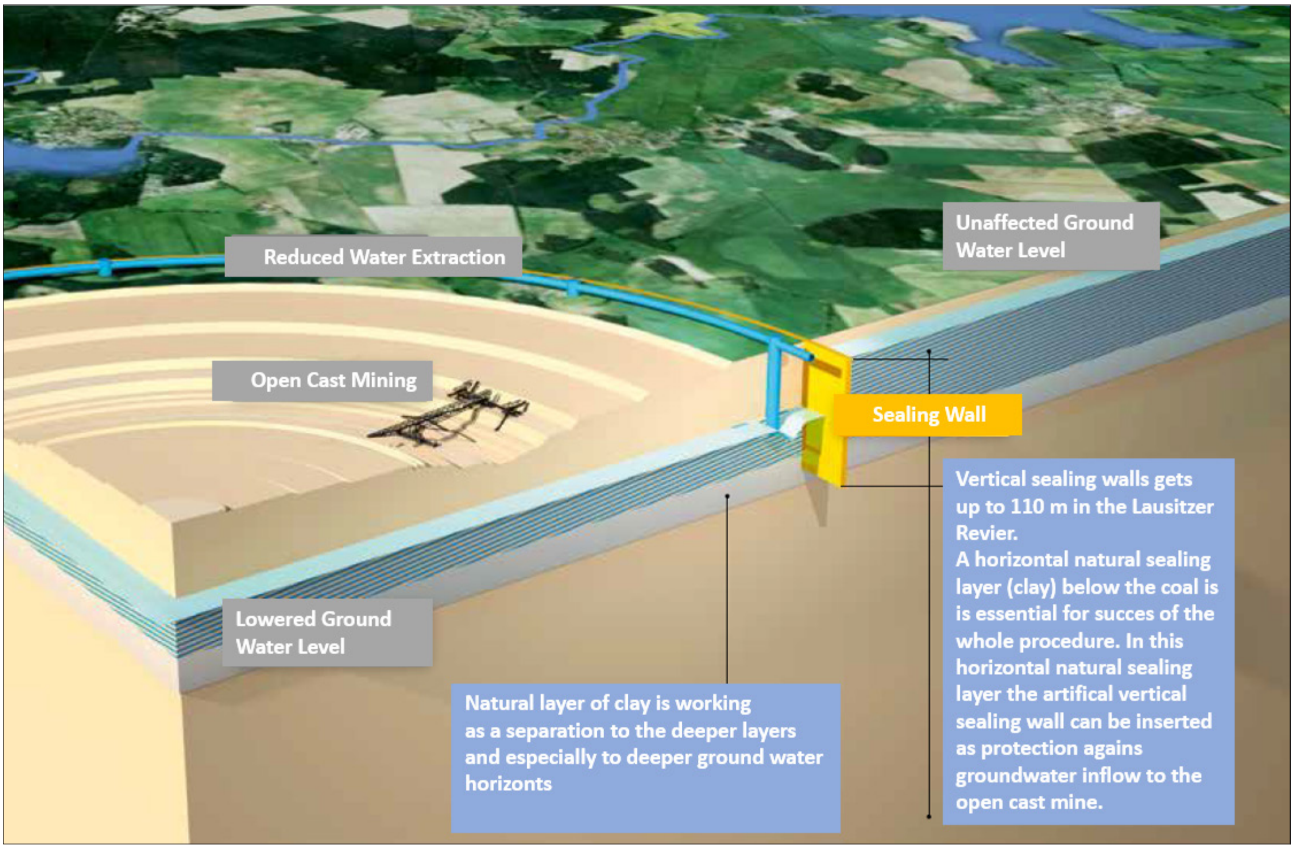


**Figure 7:** protection of open cast mining areas against big ground water inflows by implementation of vertical sealing walls using Bentonite around the open cast mining area in the Lausitz (Garg & Bender (n.d.). Vattenfall Info Broschüre Wasserbalance – Dichtwandtechnik im Lausitzer Braunkohlenrevier, (2014).

This vertical sealing wall prevents big ground water inflows over a long time (geological). This would be allowed the operation of the lake with very low water level compare to the former (natural) ground water level. This fact opens the chance, to create a simple and cheap lower basin for a pumped hydro power plant in the Lausitzer Revier. The upper basin can be installed at grown soil nearby the open cast mining with artificial sealing (Asphalt or special foils). To prevent slope damages at the lower basin the velocity of moving and the difference of water level should be low. Approx. 1 m per cycle (8 to 24 h) seems as a tolerable range in a first approach. But this has to be evaluated. Additional measures for stabilisation of the water change zone should be done as a precaution.

Design of open cast mining lakes using vertical sealing as lower basin of pumped hydro power plants in the Lausitzer Revier

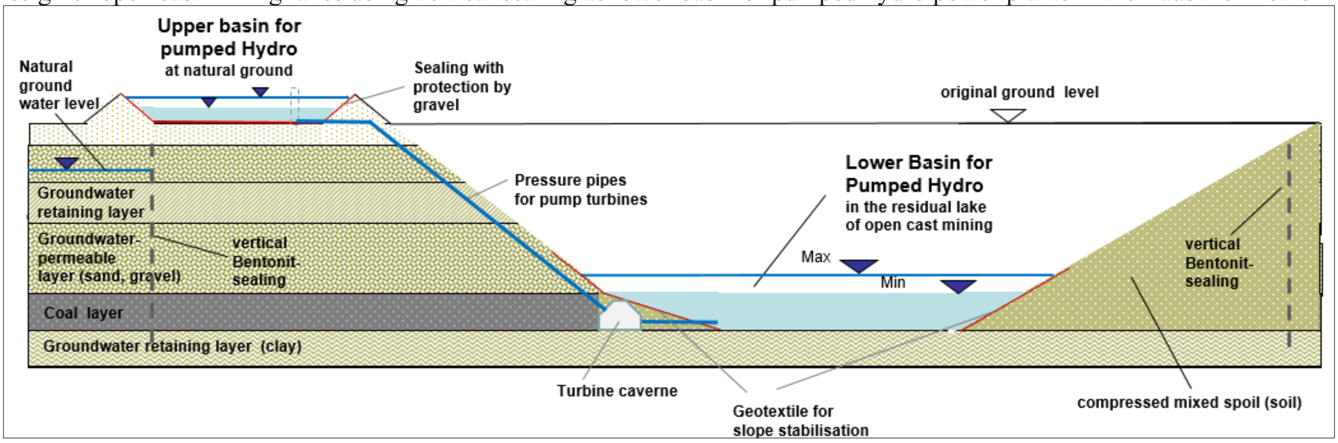


**Figure 8**: Implementation of lower basin and upper basin of a pumped hydro power plant in an open cast mining area in the Lausitzer Revier using vertical sealings using Bentonite

## Economic Considerations

The most important factors for economic viability are the investment costs, the operating cycles, the energy market framework, and the price difference between stored and drawn electricity (spread). Investment costs depend on construction costs, geology, logistics, grid connection, and the general economic situation. The number of operating cycles has increased significantly in recent years, from approximately 160 cycles per year to well over 200 cycles per year for pumped-storage power plants. This is due to the increased fluctuations between electricity generation from renewable energy sources and electricity demand. Current regulations favour battery storage systems, which are completely exempt from grid fees – pumped-storage power plants, however, are not! The price range is one of the most important factors – it has fluctuated considerably in recent years – but the average price has also increased. In summary, the economic conditions for pumped-storage power plants are improving.

The proposed technical solution for the Rhenish Revier creates a solution with very high power rates and storage capacities but high constructive efforts due to the pipe/half pipe caverns. This proposed plants would be located in a big hotspot of energy transport/generation and consumption in Europa (Ruhrgebiet, Chemical area around Cologne).

On the other hand the proposed design of pumped hydro in the Lausitzer Revier creates medium sized power rates an capacities (some 100 MW and 5 … 10 GWh) but the specific effort for construction would be probably significant lower compare to the solution of the Rhenish Revier.

Never the less – both approaches could serve a big part of required storage capacity in Germany and they are essential in their locations. Their big economic advantage results especially from the very long service life (100 years for turbines and 200 years for the concrete caverns compare to 20 years of batteries).

## Summary & Conclusions.

Pumped-storage power plants are a proven and durable technology that can be implemented on a very large scale. They use almost exclusively locally available and non-critical materials. Large pumped-storage power plants in open-pit mines are ideally suited for balancing electricity demand between day and night after the fossil fuel baseload power plants are decommissioned over the next 10 years. These massive pumped-storage plants could make a significant contribution to solving the energy storage problem for all of Germany and, in part, for the EU as well. The large rotating masses of the turbines and generators contribute to grid stability (frequency and voltage) without the need for power electronics, thus reducing complexity. The installation of pumped hydro plants in mining areas which are devastated areas avoids the use of other landscapes. Cavern pumped-storage power plants form the third (almost forgotten) pillar of the German electricity storage concept. Large cavern pumped-storage power plants could also act as an economic stimulus program for the construction and mechanical engineering industries and the planed huge KI computer centres and offer potential for storage solutions, including in cooperation with the Netherlands and Belgium.

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