# Challenges for the construction of an underground hydroelectric power plant with electricity storage (UPSHP) in terms of public acceptance and technical aspects

A Summary

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## Abstract

For the increasingly important storage of renewably generated electricity, this review explains the construction of a surface and underground pumped storage power plant. The problems for the construction of an underground pumped storage power plant are further listed. These are geological, environmental and economic problems as well as a low acceptance by the population. The geological problems are concerns about leaching of minerals and heavy metals as well as the statics of the cavities. Mining companies in Germany are obligated to renaturalize the landscape areas again, which could be realised by a lake. Furthermore, care must be taken to ensure that the mine water does not come into contact with the groundwater. According to a survey by RISP on the subsequent use of the mine areas for an underground pumped storage power plant, the acceptance of the population is over 70 percent. The economic consideration concludes that the arbitrage profit for a difference between off-peak and peak of 10 €/MWh is about 2.7 M€/a and for 100 €/MWh about 27.3 M€/a. With investment costs of about 630 M€, despite the assumption of 100 €/MWh, more than 20 years are needed for an underground pumped storage power plant to be amortized.

The acceptance could be increased by creating a lake as a recreation area as well as being used as an upper storage reservoir. Thus, the cost of renaturation decrease when combined with the creation of the storage basin. The problem of ground conditions can be solved by creating new cavities by means of tunnel boring at an inclination. For static safety as well as against leaching of minerals and heavy metals, the cavity walls can be sealed with reinforced concrete. The technology of underground pumped storage power plants can be used for better utilisation of renewable energies. This is especially in flat and densely populated regions a possibility to store energy, because the main part of the power plant is underground.

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## 1 Introduction

Considering the compliance with medium- and long-term climate protection goals to reach greenhouse gas emission neutrality in 2045 [1], even more renewable energy sources must be utilised, such as wind, solar and hydroelectric power. These are subject to large fluctuations throughout the day, resulting in an increasingly volatile power grid [2]. To be able to guarantee flexible power generation adapted to the load curve with a high proportion of renewable energy, it must be possible to store this energy. For energy storage, the "Büro für Technikfolgen-Abschätzungen beim Bundestag" (Office of Technology Assessment at the Bundestag) has published a list of possible technologies [3]. For this purpose, the list was subdivided into mechanical, thermal chemical and electrical storage systems. In this review, pumped storage hydropower plants are discussed in more detail. In the beginning, the structure of a pumped storage hydropower plant is described and extended to its underground use. In the main part of this review, an overview of the problems associated with the construction of underground pumped storage hydropower plants is given. At the end of this article, the problems are compared and possibilities are listed by which the problems could be played off against each other.

## 2 State of the art

### 2.1 Pumped storage hydroelectric energy

The storage of electrical energy in Germany is realised on a large scale via pumped storage hydropower plants (PSH). For this purpose, about 37.4 GWh per charge cycle can be stored in 31 PSH plants (PSHP) [2].

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Figure 1 shows the structure of a PSHP. The plant has an upper storage basin where the water is stored and a lower storage basin where the water is discharged. When electricity is available, the pump is started and the water is pumped from the lower to the upper reservoir. On the other hand, the water from the upper reservoir flows through a turbine on its way to the lower reservoir, which generates electric power. The turbine operation is used when electricity is needed to utilise the renewable generated electric power when few renewable energy sources are available. The turbine and the pump are installed in the powerhouse.

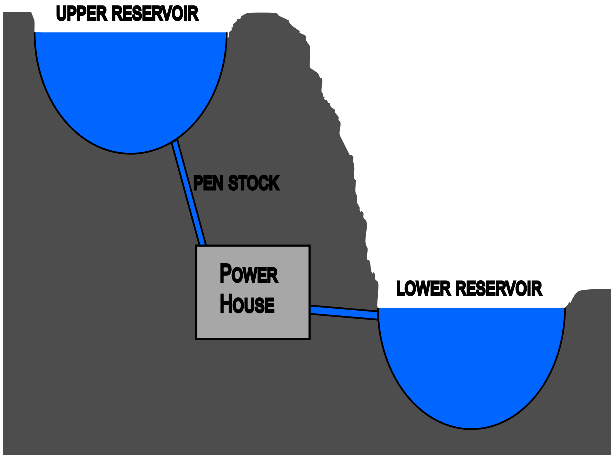


Fig. 1: Structure of a PSHP

For electricity storage, PSHP uses the potential energy of the different altitudes of the two storage basins. This depends on the earth's gravitational field, the mass of the body and the difference in altitude. [4]

$$E_{pot} = m \cdot g \cdot h \tag{1}$$

| | | |
|---|---|---|
| $E_{pot}$ | potential Energy | [kWh] |
| $m$ | mass | [kg] |
| $g$ | gravitation | $[\frac{m}{s^2}]$ |
| $h$ | height | [m] |

The gravitational force is almost independent of the location, so the potential energy of a PSHP depends mainly on the amount of water and the height difference between the upper and lower reservoir. The problem of reservoir development is to find new sites, which have both a certain height difference and a storage possibility for a quantity of water.

## 2.2 Underground PSH

The preconditions for PSH from chapter 2.1 are not given area-wide in Germany. Therefore, possibilities are being searched to develop PSH in regions that have had mining operations. This is the case, for example, in the Ruhr area in Germany. For the utilization of the potential energy, it is not relevant whether the facilities are built above or below ground, since only the difference in altitude is of importance.
The mining shafts in the Ruhr area are on average 500 - 1,000 meters deep. A larger height difference is reached above ground in Germany only in the Alps [4].
Figure 2 shows the structure of an underground PSHP (UPSHP). Here it has been assumed that the existing caverns can be used as a lower storage basin since they have a large volume of about 0.1 to 1 million $m^3$ [5]. Like PSHP, these UPSHP require an upper storage basin. Either an underground cavity located near the surface with a large difference in elevation from the lower storage basin or an aboveground lake can be used for this purpose. The turbine and pump are housed in the powerhouse, as in a conventional PSHP. [5]

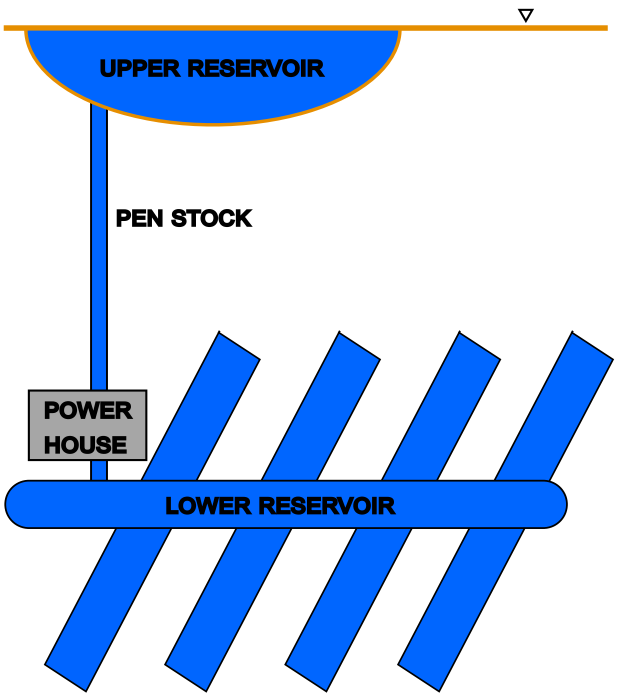


Fig. 2: Structure of an UPSHP

# 3 Problems of the UPSHP

## 3.1 Geological Problems

In an UPSHP, much depends on the nature of the lower storage basin. This should have a large volume. The implementation of this volume is a large cavity, which is created underground. For this, a check of the statics is relevant so that the cavity does not collapse. Homogeneous and stable rock layers are advantageous for good statics. These stable rock layers are only sporadically present in the area of the coal mines. [6]

In the Ruhr area, the longwall mining technique was predominantly used. Here, the surrounding rock is

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brought to collapse in a controlled manner after coal extraction. This causes the sediment in the region to sink further and further. As a result of the natural collapse of the mining network, it can be seen that the soft rock layers are not able to withstand the high mining pressure at depth. [cf. [5]]

Furthermore, it should be noted that in mining networks, water does not wash out minerals and water pollutants do not reach the surface. This is due to the fact that in mining operations the tunnel network is not fully flooded. Possible contaminants may include the following [7]:

- heavy metals
- uranium, radium, etc.
- potash and rock salt

## 3.2 Environment

In Germany, the operating companies of the former mining plants are obliged to restore and renaturalize the former mining areas. A lake used as an upper storage reservoir could serve this purpose. Thus, the costs of mining reclamation would be combined with the costs of creating an upper storage basin. [5]
Another environmental concern is the influx of water into the adit network. To prevent the contaminated mine water from coming into contact with the groundwater, the water level in the old mine shafts is kept at a constant level. For this purpose, a pump is operated to pump the water to the surface. The costs incurred as a result are referred to as perpetuity costs. [8]

## 3.3 Acceptance

A PSHP on a mountain range involves an intrusion into the natural environment. This encroachment often justifies the aesthetic and environmental concerns of local residents as well as conservationists. In the past, these concerns as well as the high technical requirements of PSHPs often led to project cancellations [5].
In a representative survey of the population in the Ruhr region in 2013, Grunow et al. [9] investigated the public opinion as well as the acceptance in the population for the after-use of the former mining area. Here it was determined that more than 80 percent of the respondents wanted a local recreation or cultural site. 63 percent of the respondents could imagine an industrial site. This subsequent use would in turn create jobs in an area where jobs are currently being lost because the decision has been made to phase out coal in Germany.
Furthermore, the population in the Ruhr region is in favor of the energy turnaround and the subsequent use of the mining site through the construction of a new UPSHP by around 72 percent. This is due to the security of energy supply in the region [9].

## 3.4 Economy

One of the biggest issues is the economics of a plant. For this purpose, Madlener and Specht [5] have set up an analysis in which the costs are derived in euros per kWh. Initially, the theoretical potential of a plant is determined. For this, a total efficiency for the feed-in and feed-out of 80 percent is assumed. The depths are 250 - 1,000 meters as well as a volume of the lower storage basin of 0,1 - 1 million $m^3$. If these values are inserted into the formula 1 and multiplied by the efficiency, a potential of 200 MWh to a maximum of 2,500 MWh capacity is achieved. This potential is in the upper middle range in the ranking for German hydropower.

For the height-dependent costs, it is assumed that the costs of the plant increase negligibly small since only the penstock become longer as well as somewhat thicker pipe wall thicknesses are used. These proportional costs are not significant when compared with the lower reservoir and the powerhouse. Thus, at 500 m depth the costs are 227 €/kWh and at 1,000 m depth 114 €/kWh. The cost difference is given by formula 1 since the same amount of energy at twice the depth requires only half the volume.

The costs for the powerhouse are the same as for a conventional PSHP. These are mainly costs for the turbines, the pumps, the excavation of the powerhouse, the tunnel boring works and the engineering works. These costs have been estimated by the design firm Black and Veatch in 2012 at 2,230 US$/kW for a conventional PSHP running 10 hours at 500 MW full load. Using an exchange rate of 0.8 € $\approx$ 1.0 $US$$, this results in 178 €/kWh. This cost is adjusted to a UPSHP because, unlike Black and Veatch, Madlener and Specht assume that a lake will be created for the renaturation of the mining areas. The brownfields used for this purpose are inexpensive and there is no need to build a dam to store water. Therefore, the cost of the upper storage reservoir in this calculation is set at 3 €/kWh instead of 33.6 €/kWh (Black and Veatch).

Combining the head-dependent costs including the lower storage basin and the costs for the powerhouse as well as the upper storage basin, an UPSHP at a depth of 1,000 m thus costs about 253 €/kWh.
Now assume that the UPSHP has 1,000 full load hours per year at a depth of 1,000 m and a lower storage

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basin volume of 1 million $m^3$. Madlener and Specht determined, under three different price scenarios, the profits that could be realized in an arbitrage transaction between off-peak and peak. This results in the profits per year given in the following table for an arbitrage profit of 10 €/MWh, 50 €/MWh and 100 €/MWh:

Tab. 1: Arbitrage and Revenues

| Profit arbitrage | Revenue per year |
|---|---|
| 10 €/MWh | 2.7 M€ |
| 50 €/MWh | 13.6 M€ |
| 100 €/MWh | 27.3 M€ |

However, it should be noted that even under very good conditions, such as a large altitude difference and a large reservoir, the estimated by Madlener and Specht 630 M€ are compared, resulting in a payback of more than 20 years. [5]

## 4 Discussion and Summary

Electricity generation in Germany is becoming more and more renewable based on section 3 climate protection act [1]. However, due to the use of wind and solar power plants, the volatility in the power grid is increasing [10]. For this problem, it is necessary that control energy is available quickly, cheaply and in large quantities. Currently, however, only PSH is available in capacity strength so quickly [11]. PSH has an overall efficiency per charging cycle of up to more than 80 percent, which makes this technology well suited for storage and the construction of the required facilities profitable [5]. However, siting is difficult because there is often a lack of public acceptance for PSH and a lack of regulatory approvals. According to the study mentioned in chapter 3.3, the acceptance for an UPSHP is higher compared to conventional PSHP. This comes from indirectly affects local residents. Furthermore, the construction of an UPSHP in the Ruhr area creates new jobs, which are reduced by the coal phase-out in other cases. The upper storage basin could additionally increase the acceptance by a local recreation area in the region and reduce the costs of renaturation of the former mine sites by a lake [cf. [5] [8]].
On a physical level, a storage technology for energy in the flat Ruhr area would be difficult to realize and thus associated with high costs. However, due to the existing underground mining networks, an UPSHP is well suited for densely populated cities in the flat countryside to store energy at low-cost [5].

That an UPSHP is more expensive than a conventional PSHP was explained in the chapter 3.4. This is mainly due to the higher costs for the lower storage tank and maintenance and repair. Another problem with using the old underground mine shafts is that the condition of the abandoned mine shafts is no longer known. On the one hand, this means uncertainty about the statics of the walls and, on the other hand, whether or how the shafts are laid with a gradient so that the water flows back to the feed point. Madlener and Specht [5] therefore suggest that the lower reservoir be re-excavated using a tunnel boring machine. This would make technical sense insofar as a sufficient slope is ensured and the tunnels are structurally correct. If the tunnel walls are subsequently sealed with, for example, reinforced concrete, this will prevent the leaching of minerals and heavy metals and the ingress of groundwater. In addition, the problem of soft rock in the Ruhr area is then not a reason to exclude the use of UPSH.

The ability to store energy will become increasingly important in the coming years. Many technologies are currently being researched to store renewable energy in the best possible way and on a large scale. Hydropower is a widely researched and therefore favorable technology. However, PSH often encounters problems. In flat regions, however, conventional hydropower utilization is difficult to implement. In Germany, mining has been carried out in many regions. The depths reached are up to 1,000 m with a large network of tunnels. Here the UPSH could be a technology for short- or medium-term energy storage. Because PSH is highly researched, an UPSHP can be used cost-effectively and efficiently in densely populated as well as flat regions.

## 5 Outlook

A slightly unconventional hydropower plant is under construction in Estonia in Maardu near the port of Muuga, initially scheduled for completion in 2020. The power plant is being built by the company OÜ Energiasalv and is to be operated by ÅF-Estivo. Here, the seawater will be used as an upper storage reservoir. The outcrops in the granite at a depth of about 550 m form the lower storage basin. The capacity of the lower storage basin is about 4.75 million $m^3$ for a 12-hour operation. Four pump-turbines of different power levels are to be installed in the plant. This means a total output of 500 MW:

Tab. 2: power levels of the turbines in Muuga

| Turbine quantity | Power per turbine |
|---|---|
| 1 | 50 MW |
| 1 | 100 MW |
| 2 | 175 MW |

In terms of design, care is taken to ensure protection against corrosion and penetration of organic as well as inorganic material in this plant. Cement will be placed in the lower storage basin for protection against stones made of less stable rock. For more information on this UPSH project, please refer to [12].

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