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An Exploratory Economic Analysis of Underground Pumped-Storage Hydro Power Plants in Abandoned Coal Mines

Reinhard Madlener1,2,* and Jan Martin Specht1

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Abstract

This study investigates the concept of underground pumped-storage hydro power plants in closed-down underground hard coal mines in Germany. After a review on how this could be realized technically and conceptually, an economic feasibility analysis is presented, with a particular focus on the costs for the underground storage reservoir. The analysis is performed for different lower (i.e. underground) reservoir sizes and temporal arbitrage potentials (peak/off-peak electricity price spreads). Cost uncertainty is dealt with by means of a Monte Carlo simulation for two distinct head heights and variation of the cost ranges for the major cost components. The findings regarding costs and acceptability of underground pumped storage hydro plants in flat, and densely populated areas are compared with those of a classic (on-surface) pumped-storage hydro power plant in a mountainous area. Based on the techno-economic evaluation we conclude that under favorable conditions the realization of such underground plants seems both technically feasible and economically reasonable. More specifically, an extension of a tubular system seems the most promising option. A plant in a mineshaft turns out to be only slightly more expensive than a conventional one, but this outcome depends strongly on the feasible head. However, the significant reduction of the adverse impacts on the landscape and local residents, as well as a potentially large number of feasible sites in flat terrain, could make UPSHPs an interesting option for the future energy transition, not just in Germany but worldwide – at numerous sites where underground mining is going to be abandoned.

Keywords: Hydro power, pumped storage, coal mining, reservoir engineering, massive energy storage

JEL Classification Nos.: D25; O25; P48; Q25; Q57; R32

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Abbreviations Used

CAES  Compressed Air Energy Storage
dena  Deutsche Energie-Agentur GmbH
EEG  Erneuerbare-Energien-Gesetz (German Act on Granting Priority to Renewable Energy Sources)
KELAG AG  Kärntner Elektrizitäts-Aktiengesellschaft
PSHP  Pumped-storage hydro power
RAG  RAG Aktiengesellschaft (est. 1968, formerly Ruhrkohle AG), Essen
UPSHP  Underground pumped-storage hydro power

1. Introduction

Since the 1980s, the political will to reducing the dependency of nuclear and fossil energy sources has risen in Germany [1]. Renewable energy sources, such as hydro, wind, biomass and solar have become the pillars of the sustainable energy transition. The promotion of renewables is thus in the political interest also in Germany and hence pushed by a dedicated regulatory framework [2,3]. Due to these favorable boundary conditions, renewable power production has increased tremendously over the last years. However, this development also raises problems in terms of safeguarding grid stability [4], as especially wind and solar power are intermittent and subject to strong seasonal and weather-dependent variations. Furthermore, daily and seasonal fluctuations in electricity demand are also characteristic for the final energy consumer side. Therefore, the future balancing of electricity supply and demand will probably require a mix of flexible power generating systems, enhanced flexibility on the demand side, and massive power storage capacities. Numerous technologies for electricity storage, flexible power supply and demand side management exist, and currently discussed and evaluated in research regarding their relative strengths and weaknesses. A considerable body of literature exists on these topics (e.g. [3-10]), the review of which does not need to be repeated here. Our research focus is on pumped storage hydro power plants (PSHPs), the most relevant electricity bulk storage technology available today and a well-established storage option for decades. In times of excess electricity, PSHPs pump water from the surface level to a level of higher altitude, typically a basin in mountainous terrain. In times when the supply of electricity is short, the hilltop water reservoir is drained and the potential energy converted back to electricity by means of a turbine. As in every conversion of energy, losses occur; for a conventional PSHP plant these amount to typically about 20% within one storage cycle [11,12].

A current problem with PSHPs is the limited number of potential sites remaining. This is caused by the technical need for sufficient vertical heights, continuously stiffened ecological
requirements as well as frequently observed public resistance due to ecological concerns or NIMBYism (“Not in My Backyard!” syndrome). The latter led to several project terminations in the past also in Germany (for example at the Runsee near Aachen). Especially the building of a storage reservoir on a hilltop or a mountain valley typically requires massive changes to the landscape, which often raises major aesthetic or ecological concerns articulated both by the local population and nature protection groups [11-12].

Due to these technological requirements on the one hand, in combination with significant public resistance against scenic or ecological interventions on the other hand, the number of potential locations, is rather limited in Germany. A possible future solution and way out of this dilemma might be the use of underground PSHP (UPSHP) plants, for example, in closed-down coal mines. Instead of pumping the water uphill in situations of electric surplus capacity, it is pumped from an underground storage located, for example, at the bottom of an abandoned mine, up to the surface. If additional electricity is needed, the water is allowed to flow back again through a turbine. The advantage is obvious: on the surface there is hardly any intrusion to the landscape. The only visible component would probably be the upper storage reservoir. If there is no suitable lake or river already available, a new lake would have to be constructed. The brownfields left over after the end of the coal production in the Ruhr Area are promising locations for that purpose, also in terms of providing new recreational areas on abandoned industrial sites (on the conversion of open pit mines to semi-underground PSHPs see [15]). The operating companies are obligated to reestablish the areas formerly used (and put in a degraded state) for coal processing. Also for them, a lake could be a low cost as well as high public acceptance option to meet their obligations. Grunow et al. [16] investigated the public opinion concerning the after-use of the mining districts in the Ruhr Area, finding that over 80% of the people interviewed favor recreation areas, while 63% could also well imagine some alternative industrial/commercial after-use. Furthermore, it was found that about 70% of the persons interviewed gave positive consideration to the after-use of abandoned mining sites as UPSHPs.

The achievable altitude differences from the surface to the deepest brines in Germany of up to 1000 meters can otherwise only be realized in the high mountains of the Alps or in Norway, i.e. typically in remote areas and above ground. The end of hard coal mining in the Ruhr area (since 2018), as well as the about 20,000 pits that exist in that region alone, offer promising framework conditions for realizing such projects there in the years to come. On the down side, however, there are high technical requirements, as well as a number of uncertainties and hard to estimate costs and revenues, rendering the investment decision-making quite challenging.
Research on UPSHP only started in the 1960s in the US, although a patent on a UPSHP concept was filed by Fessenden as early as in 1917 (see Table 1 and section 2.1 below), but has become a subject of growing media and research interest in recent years due to the rapidly increasing need for bulk storage which is coupled with the simultaneous phase-out of mining activities in many regions, especially in Europe but also in Australia and elsewhere. Table 1 provides a brief overview of some important seminal as well as more recent international studies on the topic of UPSHP.

**Table 1. Brief overview of the most relevant UPSHP literature**

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Contribution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitsikoudis et al.</td>
<td>2020</td>
<td>Belgium</td>
<td>UPSHP in an abandoned slate mine with focus on hydraulics and economic implications regarding volatile electricity prices</td>
<td>[17]</td>
</tr>
<tr>
<td>Menéndez et al.</td>
<td>2020</td>
<td>Spain</td>
<td>Impact of changes in air pressure in UPSHPs on the global efficiency</td>
<td>[18]</td>
</tr>
<tr>
<td>Pujades et al.</td>
<td>2020</td>
<td>Belgium</td>
<td>Interaction of a UPSHP in an abandoned slate mine with the ground water</td>
<td>[19]</td>
</tr>
<tr>
<td>Carneiro et al.</td>
<td>2019</td>
<td>Portugal</td>
<td>Screening of potential locations for different underground energy storage options in Portugal</td>
<td>[20]</td>
</tr>
<tr>
<td>Matos et al.</td>
<td>2019</td>
<td>Portugal</td>
<td>Development of geological screening criteria for various underground energy storage technologies, i.e. UPSHP</td>
<td>[21]</td>
</tr>
<tr>
<td>Menéndez et al.</td>
<td>2019</td>
<td>Spain</td>
<td>(I) Development of tunnel designs and (II) air pressure simulation</td>
<td>[22]</td>
</tr>
<tr>
<td>Schauer</td>
<td>2019</td>
<td>Germany</td>
<td>Techno-economic assessment for a UPSHP in the Ruhr area</td>
<td>[23]</td>
</tr>
<tr>
<td>Kaiser et al.</td>
<td>2018</td>
<td>Germany</td>
<td>Comparison of compressed air and UPSHP regarding technical and economic aspects</td>
<td>[25]</td>
</tr>
<tr>
<td>Alvarado et al.</td>
<td>2016</td>
<td>Germany</td>
<td>Comprehensive case study for a pilot UPSHP plant in the mine “Prosper-Haniel” in the Ruhr area</td>
<td>[26]</td>
</tr>
<tr>
<td>Olsen et al.</td>
<td>2015</td>
<td>Denmark</td>
<td>Concept study of a pumped hydro storage in a water pocket only a few meters below the surface</td>
<td>[27]</td>
</tr>
<tr>
<td>Perau et al.</td>
<td>2014</td>
<td>Germany</td>
<td>Geological and technical aspects regarding an UPSHP</td>
<td>[28]</td>
</tr>
<tr>
<td>Luick</td>
<td>2013</td>
<td>Germany</td>
<td>Holistic comparison of different UPSHP sites in the Ruhr area</td>
<td>[29]</td>
</tr>
<tr>
<td>Pickard</td>
<td>2012</td>
<td>USA</td>
<td>Summary of the research on UPSHP</td>
<td>[30]</td>
</tr>
<tr>
<td>Beck et al.</td>
<td>2011</td>
<td>Germany</td>
<td>Comprehensive analysis of UPSHP in German hard rock formations in closed iron ore mines</td>
<td>[31]</td>
</tr>
<tr>
<td>Min et al.</td>
<td>1984</td>
<td>Netherlands</td>
<td>Increasing turbine efficiency for UPSHP concepts</td>
<td>[32]</td>
</tr>
<tr>
<td>Coates</td>
<td>1983</td>
<td>USA</td>
<td>Suitability of rock formations in Illinois for an UPSHP</td>
<td>[33]</td>
</tr>
<tr>
<td>Willett et al.</td>
<td>1983</td>
<td>USA</td>
<td>Overview on the development of the UPSHP concept</td>
<td>[34]</td>
</tr>
<tr>
<td>Tam et al.</td>
<td>1979</td>
<td>USA</td>
<td>Explorational techno-economic study of the UPSHP concept in the US</td>
<td>[35]</td>
</tr>
<tr>
<td>Sorensen</td>
<td>1969</td>
<td>USA</td>
<td>One of the first general investigations of the UPSHP concept</td>
<td>[36]</td>
</tr>
<tr>
<td>Fessenden</td>
<td>1917</td>
<td>USA</td>
<td>Patent on the idea of underground pumped hydro storage</td>
<td>[37]</td>
</tr>
</tbody>
</table>

The aim of this paper, which is a revised and updated version of [38] published back in 2013, is to investigate and tackle some of the challenges of realizing UPSHP plants from an investor’s perspective. To this end, we undertake an assessment of the technical and economic feasibility of UPSHPs, and conduct a comparative economic analysis with existing PSHP plants. The main research question is whether, and under what conditions, UPSHPs in abandoned coal mines can actually be operated cost-effectively. To the best of our knowledge, this is the first detailed study of its kind, and thus of an exploratory character only. Due to its exploratory nature, the
data used and many assumptions made bear high uncertainties, which is why we made extensive sensitivity analysis regarding the costs and revenues determining profitability.

The remainder of this paper is organized as follows. In Section 2, we investigate for several real-world examples trends towards subsurface construction measures for existing PSHP. In Section 3, this trend is further developed into a PSHP concept that is totally realized underground as a UPSHP. Following the technical considerations, we then undertake an economic investigation in Section 4. Since the largest difference to existing PSHP is in the subsurface storage reservoir, we first calculate the possible cost range for its realization and assess the factors influencing these costs. To this end, we introduce especially the specific costs as an important and useful characteristic figure, based on which we make a trend projection of the other expected costs in comparison to surface construction. In doing so, we also briefly consider the expected annual revenues in Section 5. Finally, all insights gained from our study are summarized, evaluated and discussed in Section 6, leading to some preliminary conclusions as to whether the realization of the developed concept seems feasible.

2. Underground pumped-storage plants

2.1 Rediscovery of an old idea

The idea of using underground reservoirs for energy storage is not new, cf. [32-37]. Already back in 1917, the famous radio pioneer Reginald A. Fessenden patented a “system of storing power” in the underground (U.S. Patent No. 1247520) [37]. However, this first concept of an UPSHP plant was never realized. In light of the rapid deployment of renewable energies, and in particular solar photovoltaics and (onshore and offshore) wind power, the idea became rediscovered and further developed [17-31].

2.2 Caverns as parts of classical PSHP plants

So far, only certain parts of PSHP plants are put underground, such as turbine houses, which are often placed in a subsurface cavern to protect the landscape. Consequently, also the pressure pipes going there have to be laid through pits and adits. An example for this is the PHSP plant in Goldisthal, currently the largest in Germany. While the upper and lower reservoirs are on the surface, the turbine and the generator house were built into a cavern in the mountain. During the construction of the Goldisthal PSHP plant, some 152,000 m³ of rock for the turbine house and entry tunnel and a further 32,000 m³ for the transformer cavern had to be excavated [39].
2.3 Expansion of the intra-day PSHP plant Nassfeld, Austria

The first-ever actually realized combination of a PSHP plant with a subsurface cavern for water in Austria was put into operation in 2006. The motivation for the construction of this plant was the plan to expand the lower reservoir of the PSHP plant Nassfeld erected in 1980-82 for reasons of economic attractiveness of such a measure. Due to various technical, landscape-related and legal considerations, however, it could not be realized through an expansion of the lower reservoir on-surface, which is why it was decided to establish a subsurface system of pipes. To this end, in less than six months of construction time, 160,000 m³ of rock were excavated and 1950 m of tunnel system with oval cross section (ca. 7.5 x 14.6 m) constructed (cf. Fig. 1). Because of the very advantageous sedimentary conditions, reinforcement of the construction with concrete or steel was largely unnecessary. The costs for this expansion amounted to approximately 8 M€ [40,41].

2.4 Abandoned UPSHP power plant project Ritten, South Tyrol, Italy

In 2009, in the village of Ritten in South Tyrol, Italy, the Austrian energy provider KELAG AG planned an entirely subsurface PSHP to be built into a mountain. The plan foresaw a turbine capacity of 250 MW. To utilize this capacity, water from an upper 0.6 Mm³ cavern should flow into a 900 m deeper cavern of the same size. The investment costs were estimated at 300 M€. After much protest of the local population, however, for which later primarily bad public relations work was made responsible, the project was abandoned with the argument put forward that the granting of a concession for construction would be very unlikely, i.e. regulatory uncertainty ([42,43]).
3. UPSHP concept

In the previous section we described how individual components were put underground in past PSHP projects. In this section, this trend is further developed into the idea of a totally underground PSHP (UPSHP) with special regard to abandoned coal mines in the Ruhr area in Germany. In a first step, we systematically collect and discuss the expected technical problems and questions raised. After that, we investigate the challenges in terms of possible technical options, cost-related aspects, and the available options for solving the problems. Figure 2 gives an overview of the UPSHP concept investigated.

![Figure 2. Illustration of a UPSHP concept with a rip-shaped design, own illustration.](image)

3.1 Technical overview

**Upper reservoir.** In contrast to a conventional PSHP plant, the upper reservoir of a UPSHP plant is, technically speaking, the smaller problem, as it can basically be established on-surface. If an abandoned coal mine is envisaged, the area of the former mine may be available for use (ranging from several dozens to, in some cases, hundreds of hectares of space [44]). In case that an on-surface lake is no feasible option, it would be technically possible to host the upper reservoir in one of the near-surface brines. However, this can be expected to cause significantly higher costs compared to an on-surface reservoir. Note also that in light of the obligation of the
mining companies to recultivate the land, and restore the water bodies, changed through the
mining activities, large parts of the costs related to land-use change are not additional, as these
would occur anyhow in one form or another, and thus do not have to be included in the
economic feasibility study.

**Lower reservoir.** The lower reservoir inevitably has to be established subsurface, the lower
the better. An obvious candidate solution is the use of existing cavities. As described in more
detail in [45], the dominant mining method in the Ruhr area is the long-wall mining technique,
which involves a controlled collapse of the sediments after the coal extraction. The only
remainders are the developed drifts that were established permanently for the transport of the
input materials, workers, and the coal as output, as well as the cavern halls, created for hosting
technical equipment.

The use of cavities remaining from coal mining must therefore be excluded as a main option,
essentially leaving the following three opportunities: (1) to excavate and secure additional
caverns; (2) to make use of existing drifts; or (3) to dig new drifts (for a detailed technical
description of these option in German, cf. e.g. [28]).

In the Ruhr area, already the excavation of small cavities, as they are e.g. required for coal
bunkers, is very lavish. On the one hand, the soft rock in this region is a geological issue. On
the other hand, this is due to the high rock pressure, especially in great depths [45].

Caverns planned for the admission of water need not necessarily be designed as a single room;
this leads to the concept of using existing drifts, which might be accessible at least partly after
abandonment of mining operations. These drift grids are sometimes very extensive and can
thus, at least potentially, offer a large total storage volume. Unfortunately, the remaining drift
grids are developed to various degrees. Hence it is very difficult to estimate whether these drifts
would indeed have a sufficient and steady downward slope in order to ensure the backflow of
the stored water in turbine operation.

The third option is to construct new drifts. Round-shaped tubes drilled, for example, by a
tunnel excavator are most cost-efficient for long-distance drilling. An optimal slope as well as
a solid development of the walls with steel and concrete can be realized. A self-contained
system like this would prevent a water exchange with the surrounding sediment which would
probably both reduce concerns of nearby residents and minimize technical issues such as water
inflow or washed-in particles. The study from Grunow et al. [16] mentioned earlier found that
while about 75% of the interviewed participants could well imagine a self-contained system in
their region, only 35% would welcome an open system. Finally, new drilling of tubes for a
lower basin could be arranged in an optimal structural concept, for example in a star- or a rip-
shape design.

**Drift advance and costs.** As we have to assume a new build of the drifts, we investigate the
expected costs for that next; the cost estimates will also be used for the economic valuation later
on in Section 4. Drifts for the mining operation were typically designed as semi-circles, the
plane floor being necessary for the below-surface traffic. In contrast, a new build drift for water
storage can also be designed as a circular tube. Comparatively fast tunnel drilling machines can
be used for the digging. A further benefit of a circular advance is the static advantage resulting
from the fact that the floor of the drift can be cladded, too. This prevents the floor from being
lifted into the drift and, therefore, can be assumed to significantly reduce the required
reworking. For further insights in drilling technology and an in-depth discussion for the
different tunneling options we refer to the dedicated literature on this topic (e.g. [28,45,46]).

While the optimization of the detailed layout of an UPSHP is left to future research, a crucial
aspect from an economic perspective are the expected (per-meter) unit costs for the tunneling
advance. The cost of a fully-fledged meter of drift (with the strongest wall enforcement, usually
made of steel and concrete) when doing the advance with a tunnel drilling machine for
conventional coal production were assessed to be at around 10–20 k€ m⁻¹ for deep mines in
Germany [47]. For 20 km of circular tube for a UPSHP, [23] estimated costs of about 13.6 k€
m⁻¹ (consisting of 59 M€ of fixed costs and about 10.6 k€ m⁻¹ as variable costs). These more
specific cost estimates range somewhere in the lower range of the conventional costs but the
authors referred to these as the “best-case”, and suggested to add around 10% of extra costs for
the usual “practical issues”. Therefore, we used 15 k€ m⁻¹ for the calculations in our standard
scenario, reflecting both the average per-unit cost value for conventional coal mining and
enhanced and more tailored estimation from more recent UPSHP investigations specifically for
the Ruhr area.

For a diameter of about 7.8 m, a so-called “open area” of about 48 m² results when considering
a circular extension, resulting in costs of about 312 € m⁻³. A plausible storage volume for a
UPSHP of 0.5 Mm³, for example, would require almost 10,500 m of drift. At 15 k€ m⁻¹ this
would amount to a total cost of roughly 160 M€.

**Conclusion for the expansion costs.** Whereas the building of an upper reservoir seems to be
comparatively easy to realize, the technical requirements and the costs for providing a lower
reservoir are significantly higher. While the excavation of larger cavities does not seem to be
reasonable, the new extension of fully cladded, circular drifts is a conceivable option. In the
last case, costs of approximately 200–420 € (m³)⁻¹ of storage volume would arise. Table 2 depicts a selection of exemplary scenarios based on these values.

<table>
<thead>
<tr>
<th>Drift extension [m]</th>
<th>Storable amount of water * [t]</th>
<th>Extension cost at 10 k€ m⁻¹ [M€]</th>
<th>Extension cost at 20 k€ m⁻¹ [M€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>96,000</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>5000</td>
<td>240,000</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>10,000</td>
<td>480,000</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>15,000</td>
<td>720,000</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>20,000</td>
<td>960,000</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>30,000</td>
<td>1,440,000</td>
<td>300</td>
<td>600</td>
</tr>
</tbody>
</table>

Note: * The storable amount of water is calculated in dependence of the developed drift, for an open drift area of 48 m².

Heads. The deepest coal pits in Germany reach depths of up to 1600 m, with typical depth of around 1250 m [48] (e.g. in Zeche Prosper-Haniel [49]), the vast majority of the pits in the Ruhr area, however, is only between 500-1000 m deep [50]. With heads of more than 700 m, Francis turbines for medium pressures are often replaced by Pelton turbines. The higher pressure of a Pelton turbine that results from increasing heads may render slight modifications necessary. This is in contrast to the pumping technology adopted. The world’s largest pumping head of a pump of 782 m has been realized in the Kanagawa plant in Japan [51]. Higher delivery heights, therefore, have to be realized in several stages. The required intermediate storage reservoirs, however, need not be very large and can likely be hosted relatively easily in the mid-range brines of the mines. Therefore, from a technical perspective, the pumps do not pose a limitation to the maximum possible head.

Energy quantity. The storable amount of energy depends on the head, the water mass moved, the efficiency of the turbine and the gravity, as depicted in eq. (1):

\[ E_{pot, stored} = h_{diff} \cdot m_{Water} \cdot \eta_{turbine} \cdot g. \]

The full-cycle efficiency considers all efficiency losses for a round trip, mainly determined by the efficiency of the pumps, the turbine and the flow through the pipelines, i.e.

\[ \eta_{full-cycle} = \eta_{Pump} \cdot \eta_{turbine} \cdot \eta_{pipelines}. \]

Table 3 reports on selected possible heads in relation to different masses of water plotted and the resulting capacity in each case with an assumed full-circle efficiency of 80%, as reported in [11,12] (Note that [20] estimated a slightly lower round-trip efficiency of between 73% and
76% for a UPSHP set up in Spain, due to higher losses caused by air pressure in the lower reservoir). Many of the plotted combinations do not seem to be realistic. Short heads as well as very small volumes can, also in the future, probably be realized more easily on-surface at lower cost. The necessary scenic interferences are fairly small and short differences in altitude of clearly less than 200 m can also be realized on surface in some places in the Ruhr area.

Table 3. Storage capacity (amount of energy) of a PSHP plant [MWh] for different heads and water masses

<table>
<thead>
<tr>
<th>Head [m]</th>
<th>0.1</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
<th>1</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>25.9</td>
<td>64.7</td>
<td>129.4</td>
<td>194.2</td>
<td>258.9</td>
<td>388.3</td>
</tr>
<tr>
<td>250</td>
<td>64.7</td>
<td>161.8</td>
<td>323.6</td>
<td>485.4</td>
<td>647.2</td>
<td>970.8</td>
</tr>
<tr>
<td>500</td>
<td>129.4</td>
<td>323.6</td>
<td>647.2</td>
<td>970.8</td>
<td>1294.4</td>
<td>1941.6</td>
</tr>
<tr>
<td>750</td>
<td>194.2</td>
<td>485.4</td>
<td>970.8</td>
<td>1456.2</td>
<td>1941.6</td>
<td>2912.3</td>
</tr>
<tr>
<td>1000</td>
<td>258.9</td>
<td>647.2</td>
<td>1294.4</td>
<td>1941.6</td>
<td>2588.8</td>
<td>3883.1</td>
</tr>
<tr>
<td>1250</td>
<td>323.6</td>
<td>809.0</td>
<td>1618.0</td>
<td>2427.0</td>
<td>3235.9</td>
<td>4853.9</td>
</tr>
</tbody>
</table>

Note: The shaded area is the range that would in principle be suited for an UPSHP. Computations account for the gravity constant (g=9.81) and a turbine efficiency of 95% [12].

Subsurface heads of more than 1000 m seem to be realizable in the Ruhr area only in few cases. Likewise, a volume (respectively storable mass: 1 m³ H₂O ≈ 1 t) of more than 1 Mm³ is technically questionable, because it would correspond to about 20 km of built drift grid. The range between around 250 and 1000 m head as well as volumes between 0.1 Mm³ and around 1 Mm³ seem to be promising, as shown in Table 3 (grey-shaded area). With these values, a plausible field of capacities between about 200 MWh and a maximum of 2500 MWh emerges. An UPSHP with a capacity in that range can hardly compete with the largest PSHP plants (e.g. Wehr, Vianden and Goldisthal, with up to 9300 MWh of capacity), but still ranks in the upper mid-range in comparison with the other German hydro storage plants.

**Plant design.** PSHP plants can, by variation of storage volumes and turbine water throughput, be configured for different operating times. The operation time at full load here is the time period when the turbine works at full capacity, until the entire available hydro storage capacity is depleted. In the case of conventional, on-surface PSHP plants, mostly the smaller upper reservoir is the limiting factor, which is in the end either empty or must not be depleted for environmental or technical reasons. In the case of the UPSHP plant, the maximal water volume is moved, if the (initially empty) lower reservoir reaches its highest filling level.

Most of the conventional PSHP plants are dimensioned for 5–9 hours of operation at full load (cf. [51]). Many of those power plants were designed during the 1970s and 1980s and
dimensioned at that time for the then prevailing framework conditions (transferring excess electricity production of slow ramping conventional plants from the night to noon hours). Intermittent production from renewables requires, besides the classical load-balancing between night and day, more and more short-term reserve energy capacities, which, up to today, can only be provided economically and at large scale by PSHP plants [52-54]. Longer power lines from remote renewable energy sources (e.g. offshore wind parks) also require reactive power which can additionally be provided by the (U)PSHP machinery [55,56]. Regarding the two last operation types, massive energy storage capacities are of a rather minor significance; more important seem short ramp-up times for pump and turbine operation, a high bandwidth of reserve energy at high efficiencies, and high peak loads of turbines and pumps. In the longer term, a dimensioning to shorter charging and discharging times seems likely. Therefore, in the considerations that follow, dimensioning for 5 hours of full-load operation per day will be assumed.

Assembling and structure. Can the drifts gather the pressure pipes? Important components for every PSPH plant are the pressure pipes between the upper and lower reservoir. The design of such pressure pits and adits with consideration of the inner pressure of the surrounded stones, the flow characteristics, the choice of material and much more, is highly complex and cannot be discussed in detail here. For the economic assessment, it is highly relevant whether such pressure pipe systems can be installed in the existing pits of the coal mines in the Ruhr area. Most of the shafts have been sunk with a diameter of 7–8 m. For constructional reasons, the clearance diameter of pressure pipes at PSPH plants is indicated in the literature to be about 2.4 m [57]. Larger diameters reduce the frictional loss but increase the construction costs. A good estimation of the pipe diameter can be based on the experience from the PSHP plant “Kopswerk II” in Vorarlberg, Austria, which has been in operation since 2008. The technical parameter values for this power plant are similar to the estimations made so far for possible UPSHP plants [58]. The pressure pits of the Kopswerk II, with a diameter of about 4 m, would be more than sufficiently dimensioned also for the largest conceivable UPSHP alternatives. The installation of comparable pressure pipes in the pits of old coal mines with 7-8 m in diameter seems to be possible with regard to the available space, without the need for any major retrofit.

A second question is whether the turbines and pumps are actually installable in an abandoned mine. The biggest problem will likely be the transport of these heavy and bulky components to the sub-surface machine and generator house (the ‘powerhouse’). A comparison with the Kopswerk II [58] in Vorarlberg, Austria, shows that the largest components, like for example
the pump spiral with a diameter of 7 m, only barely pass through the pits, with diameters of also around 7 m. Possible solutions might lie in the use of more but smaller components or in the disassembly before transporting and the reassembling of the components at their final location. Both alternatives come along with additional costs, and can only be estimated reasonably with available data and for a particular case. Based on the fact that numerous big machines were used for coal extraction we assume that there will be one way or another for installing the required components, and for putting the UPSHP into operation. This brings us to the economic considerations and investment and sensitivity calculations.

4. Cost assessment

4.1 Cost-determining characteristics

For an economic comparison of different UPSHP plants, two distinct properties are used frequently. The specific capacity costs are specified in € kW⁻¹. They provide a relation between the costs for the PSPH plant and the maximal power of the turbine. In contrast, the specific energy storage costs are specified in € kWh⁻¹, providing a relation between the costs and the storable amount of energy (in our study referred to as “energy storage capacity”, or shortly “capacity”).

By comparison of different energy storage plants, use of the above-presented capacity costs in € kW⁻¹ is very common so far probably because they can be determined easiest. This, however, is problematic: since the turbine power determines the parameter exclusively, but not the actually relevant energy storage capacity.

Due to the fact that in our investigation the focus is on the amount of storable energy using an underground basis (and not the installed capacity in terms of turbine power) we decided to use the energy storage cost in € kWh⁻¹ for the further calculations done. In order to allow for the comparability with other types of PSHPs, a compilation of our findings in terms of capacity costs will be presented at the end of this section.

4.2 Head-dependent costs

The UPSHP plant concept presented here features the realized head as an important success factor. This is due to the fact that while the capacity increases proportionately to the realized head, the costs derived by our model actually scale up much more gradually. A reason for this is that we imply the most solid type of tunnel support independent of the realized depth. So aside from some minor costs, for example, for longer and slightly stronger pressure pipes, the construction costs for the lower basin are, therefore, hardly influenced by the head.
In the following, the unit costs of newly excavated, fully lined drifts are assumed at 15 k€ m⁻¹, which results in 310 € m⁻³ for a tube of 7.8 m in diameter, as identified earlier. This, in turn, can be converted in dependence of the realized head into costs per kWh of energy storage capacity. We can conclude that substantial specific costs arise for the lower reservoir. Based on these numbers, we calculated that constructing reservoir space for 1 kWh of electricity costs €227 in a depth of 500 m, and €114 in a depth of 1000 m, respectively (for double the height one only needs to construct half the space).

4.3 Other costs

In contrast to the costs for the lower basin the costs for the powerhouse equipment (mostly generators and turbines), engineering works, real estate acquisition, the excavation of the powerhouse and the tunnels can be compared to those of a regular PSHP plant. Therefore, we aligned our values to those estimated in 2012 by the construction and consulting company “Black & Veatch” for the U.S.-American National Renewable Energy Laboratory (NREL). Black & Veatch estimate 2,230 US$ kW⁻¹ for a regular PSHP plant designed for 10 h of operation while featuring 500 MW of full load [59].

Converting these 2,230 US$ kW⁻¹, assuming an exchange rate of 0.8 € ≈ 1 US$ and the conversion from €/kW to €/kWh by assuming a 10-hour operation, we come up with a specific construction cost estimate of 178 € kWh⁻¹. Specifically, Black & Veatch estimate the cost shares illustrated in Figure 3: machinery incl. turbines 66.8 € kWh⁻¹ (37%), upper reservoir 33.6 € kWh⁻¹ (19%), construction costs 31.2 € kWh⁻¹ (17%), real estate costs 29.6 € kWh⁻¹ (17%), additional tunnels 10.8 € kWh⁻¹ (6%). In this estimation for a regular PSHP, no further costs for a lower reservoir were assumed. Under the heading “additional tunnels” the costs for the excavation of pressurized pits and adits between the upper reservoir and the turbine entry are taken together. Correspondingly, the pro rata cost for the construction of a subsurface cavern hall are subsumed in the category “machine- and generator cavern”.

The data for an ordinary PSHP plant shall now be applied to the concept of a UPSHP plant. As an example, we assume a maximum head that can be realized of 1000 m. For this constellation, the following assumptions were made:

The costs for an upper reservoir are markedly lower than for a conventional PSHP plant, as less storage infrastructure needs to be constructed. Contrary to a regular PSHP, no roads or electricity infrastructure has to be built into a remote mountain valley; and neither needs a huge dam to be constructed. At many mines, the plant operator is obliged to enable a re-use of the coal mining terrain by recultivation. As a lake is a low-cost option for achieving this, it can be
imagined that independently of an UPSHP plant project such a reservoir could be established under any circumstances (i.e. no extra cost if the UPSHP is realized). First studies also imply that a re-use of mining brownfields for UPSHP purposes might generally become accepted [16]. Considering all this we estimate costs of about 3 € kWh\(^{-1}\) for establishing an on-surface reservoir of an UPSHP.

A similar situation exists for the cost of the real estate. Since the above-ground part of the UPSHP plant would be erected on brownfields, only modest real estate costs can be expected. A further use of the mines is also in the interest of the operator, since he has to maintain and continuously pump out the existing subsurface mining buildings anyhow within the recultivation needs. Hence a further utilization of the mines offers an opportunity of partial refinancing of the eternal running costs.

For the construction costs we come up with an estimated 34 € kWh\(^{-1}\), which is somewhat higher than for a conventional PSHP plant. Although less engineering is required for the establishing of the upper storage reservoir (no large storage dam etc.), the construction of the subsurface lower reservoir is so far hardly proved and tested, which is why we assume the planning and total development costs to be significantly higher.

In the powerhouse, the machine park with turbines, generators, pumps and transformers are also assumed to be more expensive for the UPSHP plant. This can be expected, because the prospective plant size is slightly smaller than in the reference plant, which can be expected to further increase the relative costs. Furthermore, a dismounting in smaller components is presumably required which could raise costs to about 75 € kWh\(^{-1}\).

The considerably higher specific costs of 16 € kWh\(^{-1}\) estimated for the expansion of the machine and generator cavern are due to the more unfavorable circumstances. Particularly noteworthy are the soft rock under the Ruhr area, which make extensive safety measures necessary, and the high pressures, which result from the great depth. Provided that in the actual individual case existing caverns can be used (e.g. old coal bunkers), this portion of costs diminishes accordingly.

The construction costs of pressure pits and adits are assumed to be lower than for a conventional PSHP with 6 € kWh\(^{-1}\). This is because the existing mining buildings, and especially the pits, can be used so that only minor additional development works are assumed to be necessary.
The specific costs for the lower reservoir were calculated as described above in Section 4.2. Those are deduced for a head of 1000 m and of track extension cost of 15 k€ m\(^{-1}\), again considering 48 m\(^2\) of open area.

Combining all these estimations the cost shares shown in Figure 4 result. In comparison, a head of 500 m would lead to much higher specific costs of the lower basin (ca. 228 € kWh\(^{-1}\)), since the excavation costs would roughly be the same while the storable amount of energy is cut in half. The same applies to the specific “owner’s costs” of an “upper reservoir” (with “owner’s cost” referring i.e. to paid-up royalties, preproduction costs, inventory capital, and land costs, cf. [59]). In sum, this leads to much higher specific costs of about 360.5 € kWh\(^{-1}\) at a depth of 500 m. In Figure 5 the decreasing specific costs per kWh of storable amount of energy with increasing head is shown for heads ranging from 250–1250 m.

Figure 4. Unit cost share assumptions for an exemplary UPSHP plant with 1000 m head

Figure 5. Specific energy storage costs for different heads
4.4 Cost sensitivity analysis (Monte Carlo simulation)

The assumptions made for determining the specific costs in some cases are subject to large uncertainties. For testing how these characteristics react to the uncertainty of the individual variables, a Monte-Carlo simulation was run. In 100,000 runs, the values of the most influential parameters were varied symmetrically with respect to their assumed volatility (see Table 4).

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Cost variation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper reservoir</td>
<td>-100% / +30%</td>
<td>- No costs might occur, if an existing source of water could be used.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ A more complex reservoir construction might increase costs.</td>
</tr>
<tr>
<td>Lower reservoir</td>
<td>-40% / +20%</td>
<td>- Several requirements the tunneling for coal production had to meet can be neglected.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ The necessary cladding of the tunnels could prove a challenge.</td>
</tr>
<tr>
<td>Tunnels</td>
<td>+/- 30%</td>
<td>+ Extensive use of existing shafts can omit costs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- If these tunnels cannot be used in the individual case, costs might turn out similar to conventional PSH.</td>
</tr>
<tr>
<td>Powerhouse excavation</td>
<td>-20% / +50%</td>
<td>+/- The soft sediment in the Ruhr area poses a significant issue for excavating larger openings. For this reason, a mark-up of 2.5 for the costs compared to a conventional PSH were already factored in. However, even these costs are probably more likely to increase than to fall.</td>
</tr>
<tr>
<td>Powerhouse</td>
<td>+/- 30%</td>
<td>Powerhouse excavation is a huge task also in conventional PSH. These costs were already increased by about 12% for the standard case.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- These additional costs might be omitted in case of good accessibility (compared to hardly accessible mountainous terrain).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ If, however, access turns out to be especially difficult, costs might increase by another 30%.</td>
</tr>
<tr>
<td>Engineering</td>
<td>-15% / +30%</td>
<td>+/- Since UPSHP are a novel concept, the engineering budget was increased by about 10% in the standard case anyway Due to the many uncertainties this share is more likely to go up than down.</td>
</tr>
<tr>
<td>Owner’s cost</td>
<td>-100% / +10%</td>
<td>+ In the best case, a sensible after use for the mine is also in the interest of RAG as the owner, so no costs might apply for the allowance to operate.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Since hardly any serious other competing after use concept is foreseeable, only a moderate increase in the owners cost seem possible.</td>
</tr>
</tbody>
</table>

The results are shown in Figure 6. One can see the much wider variance at the lower head of 500 m and absence of a distinct peak value. Specific costs are most often in the range of about 300-380 €/kWh. The reason lies in the fact that the percentage changes of the very dominant cost share of the lower reservoir have a heavy impact on the result. For the larger head of 1000 m this effect diminishes, showing a unit cost value at around 240-250 €/kWh to be most likely. For even higher heads, the frequency distribution of the unit storage costs would eventually converge to a Gaussian distribution.

4.5 Absolute investment costs for UPSHP options

From the specific energy storage costs derived we can now move on to determine the absolute costs of an UPSHP project with a head of 1000 m and for variable storage size. Given the upper storage volume limit of 1 Mm³ envisaged in Table 2, we obtain an energy storage capacity of 2500 MWh. The total cost of ownership of the plant derived from that at specific costs of 253
€ kWh⁻¹ amounts to approximately 630 M€. Figure 7 shows further possible combinations of heads and storage reservoir volumes that result thereof.

Figure 6. Sensitivity analysis (frequency plots) for the specific storage costs estimated for a head of 500 m (upper plot) and 1000 m (lower plot)
4.6 Characteristic unit capacity costs

With regard to the completeness and further comparability, based on this data also the alternative characteristics for the supply of reserve capacity is supposed to be determined. As described above, it depends strongly on the turbine design and dimensioning. Figure 8 shows two curves. The first one assumes a turbine dimensioning in which the whole storage volume is filled after 5 h of full-load operation. The second curve assumes a less powerful turbine with lower flow capacity, for which the storage volume is only put through in 8 h. In order to better understand this data, some typical values for conventional PSHP are presented next. A study by dena [54] estimates a markedly lower value of 750 € kW⁻¹, whereas a study by the Deutsche Bank [60] estimates some 800-1300 € kW⁻¹. The specific costs of 2530 € kWh⁻¹ calculated in this study are based on the comparatively high cost levels estimated by Black and Veatch for PSHP (2230 US$ kWh⁻¹ or about 1784 € kWh⁻¹ (exchange rate € to US$: 0.8), which are, as expected, higher than these reference values.
Figure 8. Specific power cost, by head and number of full-load operating hours until the lower reservoir is full
Note: For the calculations made, the values for the full-load operating hours are assumed to be independent of the storage volume

5. Revenue assessment

Returns of a PSHP plant are generated primarily by three elements: (1) power transfer in times of excess power during peak hours; (2) reserve energy capacity; and (3) reactive power. In addition, the strategic operation of an individual PSHP plant plays an important role in realizing revenues. These operating strategies of a UPSHP plant would probably be quite similar to those of a conventional PSHP plant, which is why we refer to the relevant literature on the topic [9,10], [61,62].

5.1 Revenues from power transfer

The returns from energy arbitrage – i.e. the profits made by purchasing cheap electricity during off-peak periods for pumping and the production and sale of high-priced electricity during peak periods – strongly depend on the market situation and the resulting electricity price difference between base-load and peak-load. This realizable difference is very difficult to estimate for the mid-term future, because it is the overall outcome of a multitude of factors influencing the electricity markets – such as demand side management, micro-storage batteries for households, share of intermittent renewables etc. Kondziella and Bruckner [63] developed a complex market model which suggest a growing price spread between peak- and off-peak prices at the spot market from about 30 € MWh\(^{-1}\) in 2010 up to 75 € MWh\(^{-1}\) in 2030. With regard to the merit order curve, where the middle part, which has traditionally been occupied by nuclear and coal-fired power plants is increasingly occupied by renewable energy power
plants (with low marginal costs, at least for solar and wind power), and peaker-plants such as gas turbines (with high marginal costs), the authors of this study tend to follow this suggested trend. Should this come true, storage plants could realize wide arbitrage opportunities. For an in-depth discussion on estimations regarding future price spreads we refer to the existing literature. In order to get an idea of the impact of these uncertainties, three scenarios are considered in the following, where the price differences for the power transfer are 10 € MWh$^{-1}$, 50 € MWh$^{-1}$ and 100 € MWh$^{-1}$, respectively (analyzed for two different reservoir sizes: 0.5 Mm$^3$ and 1.0 Mm$^3$). As a guide for interpretation, electricity exchange prices from recent years as well as the price intervals between a running average of the highest and the lowest prices are depicted in Figure 9, showing that arbitrage potentials of 35-50 € MWh$^{-1}$ seem realistic as of today.

![Figure 9. Hourly electricity exchange prices and low and high price trends over 2 consecutive days. In recent years, the price volatility remained on a constant level, allowing for arbitrage deltas of around 35-50€/MWh. Source: Own illustration, based on market data from www.smard.de](image)

### 5.2 Revenues from a UPSHP plant

For the three scenarios mentioned we made some broad brushed computation of the expected annual revenues. In this computation, we account for the difference in price between power purchase and power sales (i.e. the arbitrage), the total efficiency of the UPSHP plant and the full-load hour equivalent [in h a$^{-1}$]. For the number of full-load hours, a study by dena [54] assumes 1000 h a$^{-1}$. This value in turn is partially averaged out of 741 full-load hours at PSHP in the neighboring countries (Switzerland, Austria) and on average 1140 full-load hours of
German PSHP plants. A total efficiency factor of 80% is assumed for a UPSHP plant, which is slightly higher than for existing PSHP plants (cf. [11,12], [51]). This can be reasoned by technical progress, efficiency advantages arising from high head heights, and the application of Pelton turbines.

For better comparability the turbines are designed for a maximum of 8 h of full-load operation. This duration depends on the head as well as on the size of the lower storage reservoir. In the following, therefore, we differentiate between a “small” storage reservoir with 0.5 Mm³ and a “large” storage reservoir with 1 Mm³ volume. The estimated returns for the three price scenarios considered, at 1000 full-load hours per annum and as a function of the head and size of the storage reservoir, can be seen in Figure 10. The exemplary dimensioning to 1000 m head, in the case of a 1 Mm³ lower reservoir and depending on the price scenario, would generate €2.8 million (10 € MWh⁻¹), €13.6 million (50 € MWh⁻¹) and €27.3 million (100 € MWh⁻¹) of proceeds per year. Note that this is in contrast to the estimated overall investment cost of 630 M€ reported in Fig. 8. It implies that the cost amortization through revenues gained by temporal arbitrage alone (i.e. power shifts from off-peak to peak hours) might take more than 20 years even under favorable conditions (i.e. a high head, large reservoir, low interest rate, and substantial off-peak/peak price spreads).

**Figure 10.** Estimated annual revenues from a UPSHP plant designed for an 8 h full-load operation in dependence of the head. Notes: Computed for revenue scenarios (10/50/100 € MWh⁻¹) and two underground water reservoir sizes (“small” = 0.5 Mm³, “large” = 1 Mm³), y-axis in logs

### 6. Discussion and conclusion

The sustainable energy transition towards a 100% share of renewables leads to an increase in volatile electricity generation. To ensure security of supply, energy storage facilities with fast
response times seem to be an indispensable element of any such transformation of the supply system. PSHP plants are perfectly suitable for both functions with no presently available or conceivable storage technology is able to store a comparably large amount of energy at similar system efficiencies [54]. Also, in contrast to e.g. battery technologies, the specific investment costs per unit of installed capacity of pumped-storage hydro power are relatively low for bulk storage.

Despite of all these advantages, the huge challenge is to find adequate locations. On the one hand, the number of technically suitable remaining sites is limited due to topological requirements and already existing usage. On the other hand, as discussed in the introduction, many projects had to be abandoned due to public resistance or because they did not receive permission by the authorities. This exploratory study investigates the techno-economic potential of underground PSHP plants in abandoned underground coal mine pits in the Ruhr Area in Germany as a possible solution to the development of further PSHP also in flat terrain and densely populated areas. The number of potential pits in the Ruhr area is large, whereas the negative impacts on humans and the environment seem rather low. The support of this concept could also be of political interest, because the construction and operation of such power plants offers new job opportunities as well as tax revenues in less developed regions, and enables to further push and facilitate the Energiewende towards a 100% share of renewables.

From our broad technical assessment, we conclude that the construction of a subsurface storage reservoir is in principle possible. While the geological conditions in the Ruhr area are suboptimal for the extraction of large caverns as hydro storage reservoirs, the use of tubular underground drift grids for the intake of waters appears to be an economically feasible option. The assembling of the plants of the subsurface turbine house was found challenging but generally possible.

The economic investigation reveals that profitability depends primarily on the realizable head. In the case of low heads, the cost rate for the extension of the lower reservoir dominates. The relative cost rate in comparison to the other expenses decreases with increasing heads. Based on a rough estimation, the expected investment costs turn out to be slightly higher compared to conventional PSHP plants, but not totally out of range.

The cost estimates made are obviously subject to significant uncertainty, especially with regard to the development of the lower reservoir. We used cost estimates derived from conventional mining but also found that costs might fall by waiving some of the restrictions previously set by the mining operation that might not be necessary for a storage basin.
Other costs assumed possibly do not have to be attributed to the investment costs of the project at all, such as e.g. the acquisition cost of the land and the construction of the upper reservoir. This can be justified on the ground that mining companies (in the Ruhr area primarily the company RAG in Essen) are obliged to make the abandoned coal mining terrain re-usable again for other purposes. The construction of a lake is an obvious option, which could possibly later be co-utilized at low cost for the PSHP plant operation.

Even if the favorable circumstances mentioned above occur, one can expect that a UPSHP plant features somewhat higher investment costs than the conventional type, with costs beginning at 1.3 k€ kW⁻¹ in realistic settings (also cf. [23], [28], [32]). Apart from the high construction cost of the lower reservoir this is caused by the expectedly higher maintenance and repair costs and the presumably lower service life. In favor of the subsurface variant, in contrast, are the large number of potential sites and the higher expected social acceptance.

Even at slightly higher costs than conventional PSHP plants, the cost turned out to be lower than for most other energy storage concepts. Especially the investment costs in the case of storage with hydrogen fuel cells (2.35 k€ kW⁻¹) or REDOX flow batteries (2.25 k€ kW⁻¹) are markedly higher. Only compressed air energy storage (CAES; adiabatic: 750 € kW⁻¹; diabatic: 600 € kW⁻¹) shows lower specific costs of energy storage. However, these are less well suited for reserve energy operation, since the fixed costs for each charging and discharging cycle are significantly higher than for PSHP facilities (€15 for CAES vs. €2 for PSHP, according to [54]).

In a liberalized electricity market, the same principle applies for electricity storage devices as for all other investments: sooner or later they have to gain a return. This is, however, the problem of most energy storage technologies. Whereas the technical use of storage options is rarely disputed, from an economic point of view there are only modest incentives to undertake the investment. Long-lived bulk energy storage devices are typically profitable only after decades, if at all. Political influences, such as the recently introduced (and then again abolished) grid use tariffs for storage power plants render such long-term investments additionally unattractive. Here possibly market-regulating incentives are needed in order to promote the development of storage capacity and to safeguard grid and supply stability in the long term.

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