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An exploratory economic analysis of underground pumped-storage hydro power plants in abandoned coal mines

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Abstract

In Germany, the mitigation of CO_2 emissions as well as the nuclear power phase-out are important political goals in the course of the sustainable energy transformation process (so-called “Energiewende”). The reduction in fossil- and nuclear-based energy supply has to be compensated by new renewable energies, especially wind power and photovoltaics. Most of the existing studies find that such an increasing contribution from volatile renewables calls for an intensified use of massive energy storage [1]. Conventional technologies for this purpose are pumped-storage hydro power (PSHP) facilities. Typically, these require a storage reservoir on top of a mountain and another one at the bottom. In Germany, unfortunately, suitable sites are quite rare and the constructional measures often have a negative impact on the landscape and the ecosphere, which often induces public resistance. A possible future solution might be the use of underground PSHP (UPSHP) plants, for example, in closed-down mines. This study constitutes an early attempt to model such plants, in order to assess and better understand the economic viability of such underground UPSHP power plants in closed down coal mines. First, we examine the topic from a technical perspective, which is followed by an economic analysis. In the technical assessment, we analyze the feasibility of building an underground reservoir, installing the pressure pipes in the main shaft and equipping the machine cavern with turbines and pumps. In the economic examination, the expected costs for building a UPSHP are calculated. A rough comparison between the costs of a classic and a UPSHP plant is made that also includes the costs of redesigning and reconstructing the underground reservoir. Based on the techno-economic evaluation, we conclude that under favorable conditions the realization of UPSHP plants seems both technically feasible and economically reasonable. More specifically, an extension of a tube system seems the most promising option. We also find that a PSHP plant in a mine shaft is probably slightly more expensive than a conventional one, an outcome that depends strongly on the feasible head. Also, the significant reduction of the adverse impacts on the landscape and local residents could be an advantage. In addition, the number of potential sites might be quite large compared to those for conventional PSHP plants.

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

Nomenclature

Abbreviations

dena	Deutsche Energie-Agentur GmbH
EE	Erneuerbare Energien
EEG	Erneuerbare-Energien-Gesetz
h	Height
KELAG	Kärntner Elektrizitäts-Aktiengesellschaft
PSHP	Pumped-storage hydro power
UPSHP	Underground PSHP

Symbols

η	Efficiency
η_{Pump}	Efficiency of the pumping process
η_{Turb}	Efficiency of the turbine process
η_{Total}	Total efficiency of the process

Subscripts

Pump	Pumping process
Turb	Turbine process

1. Introduction

Since the 1980s, the political will to reducing the dependency of nuclear and fossil energy sources has risen in Germany [2]. Renewable energy sources, such as hydro, wind, biomass, photovoltaics and geothermal energy, are considered as alternatives. The promotion of renewables is thus in the political interest also in Germany and hence pushed by a dedicated regulatory framework [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 subject to seasonal and weather-dependent variations. On the final energy consumer side, marked daily fluctuations in electricity demand occur as well. The balancing of electricity supply and demand, therefore, makes adequate reserve power generation and storage capacities indispensable [5]. In this respect, pumped-storage hydro power (PSHP) plants have been a popular choice in the past. In times of excess electricity, these pump water from the surface level to a level of higher altitude, typically a mountain. In the case of a lack of electricity, 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 about 20% minimum within one storage cycle.

The expansion of wind and solar power capacities also increases the need for storage capacity. However, in light of the limited number of remaining suitable sites, it seems hardly feasible to meet this increased demand by means of additionally constructed PSHP. Apart from geographical restrictions arising from the required elevation profile, in many cases there is considerable public resistance against the required construction measures. Especially the building of a storage reservoir on a hilltop or mountain typically requires to shave the peak, which often raises aesthetic or ecological concerns articulated both by the local population and nature protection groups.

A remedy to this dilemma between the desire of an uninterrupted power supply and the preservation of mountain peaks could be the idea of underground PSHP (UPSHP). Instead of pumping the water uphill in case of surplus capacity, it is pumped from 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 into the deeper ground. The advantage is obvious: on the surface, except for the provision of a (maybe already existing) storage reservoir, there is hardly any intrusion to the landscape. Also, the achievable altitude differences from the surface to the deepest brines in Germany can otherwise only be realized above ground in the high mountains of the Alps or Norway. The foreseeable end of coal production in the Ruhr area, as well as the about 20,000 pits that exist in that region alone, offer promising framework conditions for realizing such projects there. On the down side, however, there are also high technical and other requirements, as well as uncertainties and hard-to-compute costs and revenues.

The aim of this paper is to investigate and tackle some of these challenges from an investor’s perspective, to undertake an assessment of the technical feasibility, and to conduct a comparative economic analysis with existing technologies. More details can be found in [6].

The remainder of this paper is organized as follows. In Section 2, we briefly review the status quo of the conventional techniques used for hard-coal mining in the Ruhr area, starting with a description of the general structure of a mine, followed by selected process technologies for the drift advance, coal mining and mine aeration. In section 3, we describe the status quo of conventional PSHP, with emphasis on the requirements, tasks, functioning and technical components, as well as important parameters of existing PSHP. In section 4, we investigate for several examples to what extent there is already a trend towards subsurface construction measures for existing PSHP. In section 5, this trend is further developed into a PSHP concept that is totally realized underground as a UPSHP. To this end, the insights gained about coal mining and PSHP are used and combined with each other. We then analyze whether such a combination seems technically feasible. Subsequent to the technical considerations, we also perform an economic investigation. 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 revenues. 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 (see also [7]–[10]). 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) [11]. However, this first concept of an UPSHP plant was never realized and became forgotten (cf. [1]).

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. As an example, in our discussion we refer to Goldisthal, currently the largest PSHP plant 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 m^3 of rock for the turbine house and entry tunnel and a further 32,000 m^3 for the transformer cavern had to be excavated [12].

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€ [13].

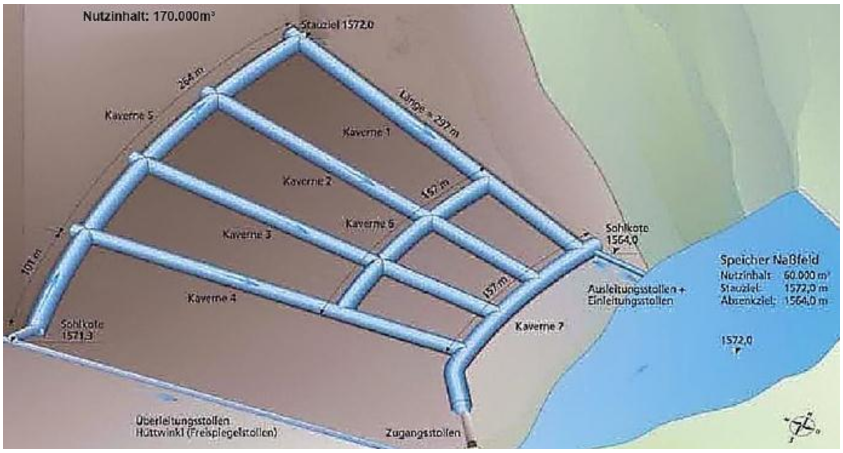


Fig. 1. Planned cavern structure for the extension of the intra-day PSHP plant Nassfeld, Austria [14]

2.4 Power plant 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 ([15]-[16]).

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). In a first step, we systematically collect and discuss the expected advantages of such a concept, but also the related technical problems and questions raised. After that, we investigate the challenges in terms of possible technical remedies, cost aspects, and the available options for solving the problems.

3.1 Advantages, problems and possible solutions

The expectations raised, however, meet numerous unanswered questions:

1. *Storage reservoir:* The first question that arises is how the storage reservoir can be realized. Which volumes are at disposal and how tedious would be the necessary construction measures?

2. *Head/penstock:* Since the amount of energy that can be stored depends on the head that can be realized, it must be investigated which heads are realistic.

3. *Amount of energy:* What amounts of energy need to be stored?

4. *Dimensioning:* In what time frame should the stored amount of energy be converted, and how powerful should the turbines thus be?

5. *Feasibility in terms of mining engineering:* In order to guarantee the sufficiently safe operation of the plant, mining engineering risks have to be minimized or ruled out.

6. *Technical feasibility of the construction:* Is it possible to successfully adapt the design of a PSHP to the local circumstances of a UPSHP plant? What preparations of the pits and drifts would be necessary?

7. *Economic viability:* Can the idea be realized at acceptable costs? How could such a plant be operated profitably / amortized?

Next, these challenges are investigated and evaluated in terms of possible remedies.

3.2 Determination of the real options value

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 (potentially large) area of the former mine may be available for use. In the generally densely populated Ruhr area, at least small- and medium-sized storage reservoirs on the surface may often be realizable without too much conflict with settlement areas. In case that for landscape protection or other reasons an on-surface lake is no feasible option, the possibility exists to host the upper reservoir in one of the near-surface brines. However, this can be expected to cause significantly higher costs than those for an on-surface reservoir.

Lower reservoir. The lower reservoir inevitably has to be established subsurface and in great depth. An obvious candidate solution is the use of existing cavities. As described in more detail in [6], the dominant mining method in the Ruhr area is the long-wall mining technique, which involves a controlled collapse of the sediments. The only remainders are the developed drifts that were established permanently for the transport of the input materials, workers, and the coal. The caverns that exist in reality were specially created for hosting technical equipment.

The use of cavities remaining from coal mining must therefore be excluded, leaving us with the following three options: (1) to excavate and secure additional caverns; (2) to make use of existing drifts; or (3) to dig new drifts.

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, this has geological reasons, due to the soft rock in this region. On the other hand, this is due to the high rock pressure, especially in great depths [10].

Caverns planned for the admission of water need not necessarily be designed as a single room; this leads to the use of existing drifts, which may be used at least partly after abandonment of mining operations. As described in the introduction, these drift grids are sometimes very extensive and can thus, at least potentially, offer a large total storage volume.

Next, the question arises how laborious the structural alteration works would be. The drifts below surface are developed to various degrees and with varying effort. Important segments that have to remain intact for a long time are secured in the completion stage with the highest achievable stiffness. While this procedure is time-intensive and thus also expensive, the walls cladded with concrete and steel can be used for many years without the need for major renovation / repairs. The often long tracks to the mining districts can be extracted at lower cost with steel reinforcements. The rib-shaped steel girders, so-called mine sticks, carry the rock pressure above the tunnel. In contrast, the floor is often not built up. The high pressure in the surrounded stones provokes that the ground quills from below into the drift. In the usual advance operation, continuous excavation operations are necessary, in which the ground is ablated by specific vehicles.

In view of the installation of a hydro reservoir for a PSHP plant in these drifts, such a regular reworking would hardly be feasible. If one makes do with a simple advance with steel partitions, the water flow would additionally wash out particles and rocks from the floor and the walls, which in larger quantities could jeopardize plant operation, or at least may render it less and less attractive over time. As each mine has a very individual drift grid, the question also arises how many drift kilometers there really are in pits close to the water. Finally, it remains an open issue whether these drifts then also would have a sufficient and steady downward slope in order to safeguard the backflow of the stored water in pumping operation.

Overall, these open questions regarding the use of the existing drifts lead to the conclusion that while, depending on the situation, individual drift sections could be reused, the construction of some new drifts will likely be indispensable. The excavation of such new construction works could either be used for filling up other cavities, or would be brought to the surface via the coal production systems and there be transported to a mining waste dump. The technical and legal circumstances would have to be investigated more thoroughly for the specific case.

Conclusion for lower reservoir. The use of natural caverns is not possible; the artificial extraction of large cavities is technically demanding and financially expensive and thus does not seem to be very reasonable. In certain cases, existing drifts may at least be partly usable, e.g. after additional extension measures. However, for a general concept, in the following, considerations have to be based on the fact that the drifts for a rib-shaped storage system in the completion stage would have to be built totally new.

Drift advance and costs. As we have to assume a new build of the drifts, we investigate the expected costs for that next. Drifts are up to now typically designed as semi-circles. The plane floor is required for the below-surface traffic. In contrast, a new build drift for water storage can also be designed as a circular tube. Tunnel drilling machines can be used for the digging. These proceed, especially in soft sediments, faster and at lower costs of wear-and-tear parts and personnel compared, for instance, to the roadway drivage by drilling and blasting. In this paper, however, we forfeit a detailed description of the driving process and instead refer to the dedicated literature on this topic [18]. 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.

The cost of a fully-fledged meter of drift when doing the advance with a tunnel drilling machine in the Ruhr area can be assumed to be at around 10–20 k€ m^{-1} ([17]–[19]). For a diameter of about 7.8 m, a so-called “open area” of about 48 m^2 results when considering a circular extension. Hence costs of about 208 € m^{-3} arise if we assume excavation costs of 10 k€

m^{-1}. Obviously, at 20 k€ m^{-1}, this value doubles. A short example calculation gives a better idea regarding the construction measures needed and the resulting costs. A volume of 0.5 Mm^3, for example, would require almost 10,500 m of drift. At 15 k€ m-1 (as average of 10 k€ m-1 and 20 k€ m-1) this would amount to a total cost of roughly 160 M€.

Conclusion for 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 between about 200-420 € $(m^3)^{-1}$ of storage volume would arise. Table 1 depicts a selection of exemplary scenarios based on these values.

Table 1

Development cost lower reservoir

Drift extension [m]	Storable amount of water* [t]	Extension cost at 10 k€ m^{-1} [M€]	Extension cost at 20 k€ m^{-1} [M€]
2000	96,000	20	40
5000	240,000	50	100
10,000	480,000	100	200
15,000	720,000	150	300
20,000	960,000	200	400
30,000	1,440,000	300	600

Note: * The storable amount of water is computed in dependence of the developed drift, calculated for an open area of the drift of 48 m^2.

Heads. The deepest coal pits in Germany reach depths of up to 1800 m [20]. In the Ruhr area, one can find pits with more than 1300 m depths (e.g. in Zeche Prosper-Haniel [21]), the vast majority of the pits in the Ruhr area, however, is only between 500-1000 m deep [17]. 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 [22]. 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 and the water mass moved. Table 2 reports on selected possible heads in relation to different masses of water plotted and the resulting capacity in each case for the efficiency assumed. 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 and at lower cost. The necessary scenic interferences are fairly small and short differences in altitude of clearly less than 200 m can be realized in some places in the Ruhr area.

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 m^3 $H_2O \approx 1$ t) of more than 1 Mm^3 is technically questionable, because it would correspond to about 20 km of built drift grid. The area between around 250 and 1000 m^3 head as well as volumes between 0.1 Mm^3 and around 1 Mm^3 seem to be promising, as shown in Table 2 (grey-shaded area). With these values, a plausible field of capacities between about 200 MWh and a maximum of 2500 MWh emerges. Approximately, it turns out that an UPSHP with a capacity of between 200 MWh and 2,500 MWh, as calculated above, can indeed not 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 plants.

Table 2

Storage capacity (storable amount of energy) of a PSHP plant [in MWh] for different heads and water masses

Head [m]	Water mass [Mt]					
	0.1	0.25	0.5	0.75	1	1.5
100	25.9	64.7	129.4	194.2	258.9	388.3
250	64.7	161.8	323.6	485.4	647.2	970.8
500	129.4	323.6	647.2	970.8	1294.4	1941.6
750	194.2	485.4	970.8	1456.2	1941.6	2912.3
1000	258.9	647.2	1294.4	1941.6	2588.8	3883.1
1250	323.6	809.0	1618.0	2427.0	3235.9	4853.9

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%.

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. [22]). Many of those power plants were designed during the 1970s and 1980s and dimensioned at that time for the then prevailing framework conditions, which have changed considerably over the last decades. The extension of the hard-to-predict power generation from wind parks requires, besides the classical load-balancing between night and day, more and more short-term reserve energy capacities, which can so far only be provided economically and at large scale by PSHP plants. The provision of reactive power is also of increasing importance (cf. section 3.2; [23]). 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 operation will be assumed.

Realization with mining methods. Over the last decades, the originally severe subsurface dangers mostly became controllable due to technical progress and improved security measures adopted. Security measures against dangers like spontaneous combustion and droppings are approved and reliable. However, new problems and questions arise in the case of an extension to the UPSHP plant.

- *Slope:* The drift to be flooded needs a continuous downward slope to the deepest point, in which the water is collected before it is brought to the surface again by means of pumping. At existing tracks it has to be estimated individually whether the inclination, which is usually provided to collect the leakage water, suffices. In the case of the new build tracks, a realization of a sufficient slope would presumably not be a major problem.
- *Tunnel water tightness:* Mine water, which ingresses in the empty reservoir of the lower reservoir, must additionally be pumped to the surface, as otherwise it reduces the available volume in the pumping mode. This leads, in any case, to decreased plant efficiency. Moreover, there is a danger that sediment will be washed into the system, which again constitutes a potential danger for the plant. The above-described full development of the drifts indeed seems to represent an efficient counteraction, due to the fact that the amount of intruding mine water is minimized and less input of sediments expected than in the case of conventional PSHP plants located in the mountains with natural, sediment-rich inflows.

- *Stability:* The existing drift grid, which is mostly secured by the long-wall support, cannot provide long-term stability. Even in the case of full-blown tracks occasional repair works must be expected, based on experience from the construction of railway or road traffic tunnel constructions, but which can be considered as technically and economically manageable.

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 [24]. 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 [18]. 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.

Are the turbines and pumps installable? The possibilities of assembling the pumps and turbines below ground are difficult to assess. The biggest problem will likely be the transport in the subsurface machine and generator house. Another comparison with the Kopswerk II [25] shows that the largest components, like for example the pump spiral with a diameter of 7 m, in the case of a pit diameter of also about 7 m hardly be able to bring subsurface through the existing pits. If the possibility to assemble is stretched to its limits, there is the possibility to either disassemble bulky components and reassemble them underground or, alternatively, to use smaller pumps and turbines in the first place. Both alternatives come along with additional costs, and can only be estimated reasonably with available data and for a particular case. In the further considerations, we assume that the possibility of assembling exists.

4. Cost assessment

4.1 Cost-determining characteristics

For an economic comparison of different UPSHP plants, at least two important parameters can be used. 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. 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 storages, use of the above-presented capacity costs in € kW^{-1} is very common so far. This, however, is problematic: since the turbine power determines the parameter exclusively, but not the actually relevant energy storage capacity, the results are often only partly meaningful. Put another way, the parameter can be “sugarcoated”, e.g. by assembling a bigger turbine, instead of a smaller one, for modest additional costs. Also as a result from this it is observable how the assembly of a more powerful turbine leads to a slight increase in the total costs of the project, but generates an attractive price per kW of installed capacity.

Because the critical questions in the case of an UPSHP plant are not how much turbine power can be installed below ground, but how much energy in the conceivable tracks of the lower reservoir is storable, this work is focused on the parameter of the specific energy storage costs. We also compute the specific capacity costs for reasons of comparability.

4.2 Head-dependent costs

The UPSHP plant concept presented here features the realized head as an important success factor for at least two reasons:

(1) As mentioned above, the storage capacity increases proportionately with the head;

(2) The costs only rise slowly with increasing head.

Certainly, a greater pit drift has to be furnished with pressure pipes, turbines have to withstand higher stresses and also the assembling becomes slightly more difficult with increasing depths, although those cost increases are relatively small.

Note that for the costs arising from extending the tracks for the lower reservoir, we assume no correlation with the depth in which those tracks would have to be excavated. This is reasonable, because the extension costs assumed for these tracks are, at 10-20 k€ m^{-1} (cf. section 3.2), already set for the almost maximal degree of extension. Given the assumption of depth-independent advancing costs, the costs of the lower reservoir, i.e. mainly those for the excavation and lining of additional drifts, only depend on the extracted volume.

In the following, the unit costs of newly excavated, fully lined drifts is assumed at 15 k€ m^{-1} (mean value of the cost range 10-20 k€). For the case of an open surface area of about 48 m², costs of about 310 € m^{-3} result. This, in turn, can be converted in dependence of the realized head into costs per kWh of energy storage capacity (cf. [6]). Hence 1 m^3 of water can double the amount of energy when doubling the head height. Since the construction costs of the lower reservoir do not increase, the doubling of the storable amount of energy theoretically leads to a reduction in the specific costs by 50%.

We can conclude that already for the lower reservoir substantial specific costs arise. These decrease, however, with rising head or increasing depths. In the following considerations, we use 227 € kWh^{-1} for a lower reservoir in 500 m depth and 113 € kWh^{-1} at 1000 m depth as illustrative benchmark values.

4.3 Other costs

Besides the costs of a lower reservoir, certainly other costs come up by constructing an UPSHP plant. In our study, these turn out to be difficult to determine, due to the fact, for example, that the prices for plant components of this magnitude are always dependent on the actual assignment, and that it is barely possible to find any serious benchmarks. Other cost components, such as the extension of the upper reservoir or the construction costs of subsurface caverns for machines and generators, can be determined only in specific cases. In order to nevertheless come up with a rough cost estimate for a complete UPSHP plant project, the residual costs that occur, in comparison to the building of a conventional PSHP, need to be estimated somehow. As a basic parameter value, general cost estimates for PSHP plants are used, calculated in 2012 by the construction and consulting company “Black & Veatch” for the U.S.-American National Renewable Energy Laboratory (NREL). The data shown in the figure are for a PSHP plant that is constructed for 10 h of operation and featuring 500 MW of full load.

For a conventional exemplary 500 MW PSHP plant, and based on [26] (exchange rate 0.8 € = 1 US$); conversion from €/kW to €/kWh by assuming a 10-hour operation, which implies a conversion factor of 0.1), we come up with a specific construction cost estimate of 178 € kWh^{-1} (for details see [5]) and the following cost shares: 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. Hence the components in the turbine house, and especially the turbines, pumps, generators and transformers required, account for the largest cost share of 37%, while roughly equal cost shares arise for the land, the upper reservoir and the engineering expenditures required for the planning and construction of the plant. 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”. For simplicity, we assume that an existing reservoir can be used without any additional investment cost.

The data for an ordinary PSHP plant shall now be applied to the concept of a UPSHP plant. As an example, we assume a realistic head 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 fewer storage facilities need to be constructed. At many mines, the plant operator is obliged to enable a re-use of the coal mining terrain. 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 (i.e. cost-free).
- A similar situation exists for the cost of the real estate. Since the largest part of a UPSPH plant would be erected on-site where the mine is, or subsurface, 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 re-cultivation needs. Hence a further utilization of the mines offers an opportunity of partial refinancing of the eternal running costs.
- The construction costs assumed at 34 € kWh^{-1} are 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.), as the construction of the subsurface lower reservoir, however, is so far hardly proved and tested, the planning and development costs are presumably 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 usually increases the relative costs. Furthermore, a dismounting in smaller components is presumably required.
- The considerably higher specific costs 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, because the existing mining buildings, and especially the pits, can be used so that only minor additional development works seem to be necessary.
- The specific costs for the lower reservoir were, as the only one, not extracted from the comparison with an exemplary PSHP, but are based on the calculations detailed in [6]. 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 (Figure 3).

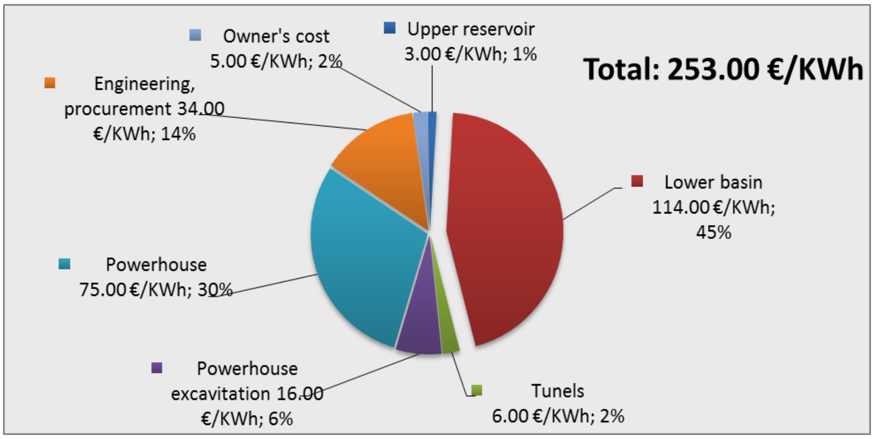


Fig. 3. Unit cost shares for an exemplary UPSHP plant with 1000 m head

In comparison to the depth of 1000 m a UPSHP with 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 stay 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”. In sum, this leads to much higher specific costs of about 360.5 € kWh^{-1}. For more information see [6]. In Fig. 4 the decreasing specific costs per kWh of storable amount of energy with increasing head is shown for heads ranging from 250–1250 m.

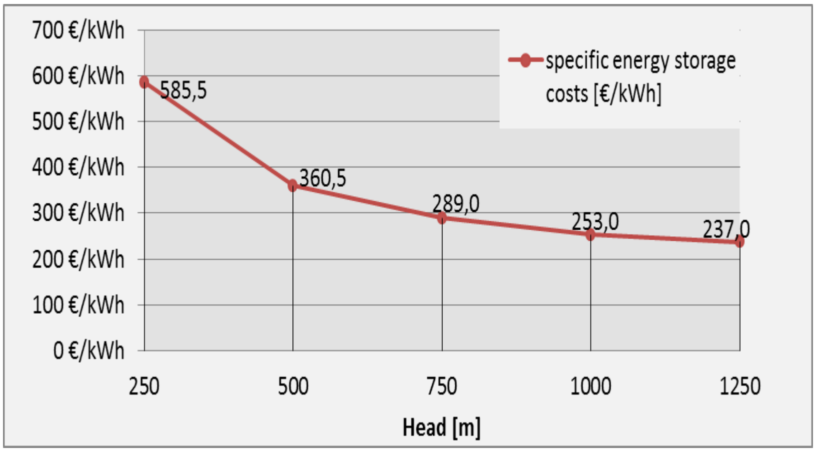


Fig. 4. Specific energy storage costs for different heads

4.4 Cost sensitivity analysis

The assumptions made for determining the specific cost contain in some cases large uncertainties. For testing how this characteristic reacts to the insecurity of the individual variables, a Monte-Carlo simulation was run. In 100,000 simulation runs, the values of the most influential parameters were varied up and down. The results are shown in Fig. 5. One can see the wide variance at the lower head of 500 m. The reason lies in the fact that the percentage changes of the very dominant cost share of the lower reservoir have a hefty impact on the result. For the larger head of 1000 m this effect diminishes, and eventually converges to a Gaussian distribution.

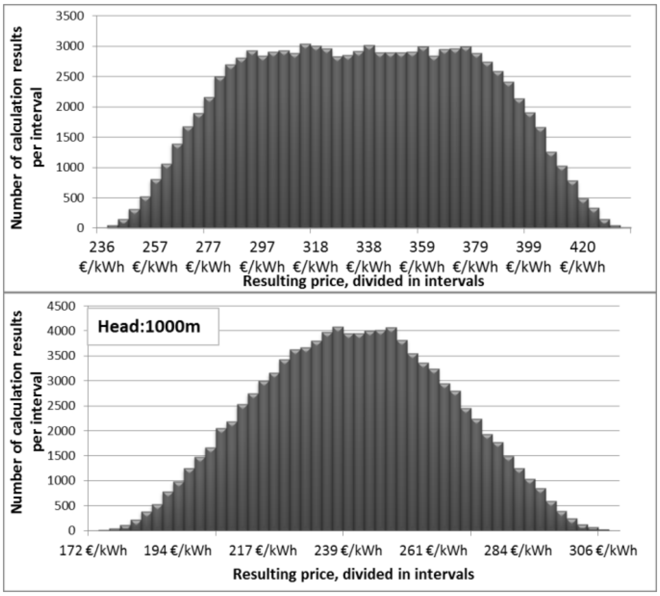


Fig. 5. Sensitivity analysis for the specific cost for two different heads (500 m and 1000 m)

4.5 Absolute investment costs for UHPPS options

From the specific energy storage costs derived we can now move on to determine the absolute costs of an UHPPS 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 cost of the plant derived from that at specific costs of 253 € kWh^{-1} amounts approximately 630 M€. Fig. 6 shows further possible combinations of heads and storage reservoir volumes that result thereof.

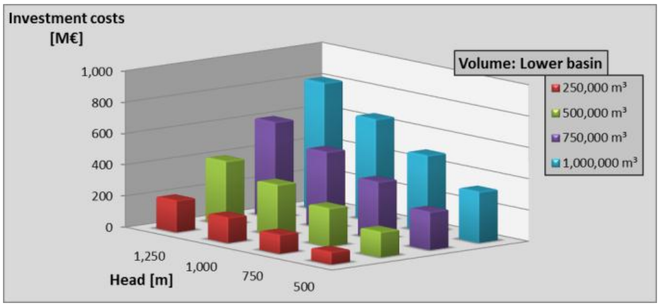
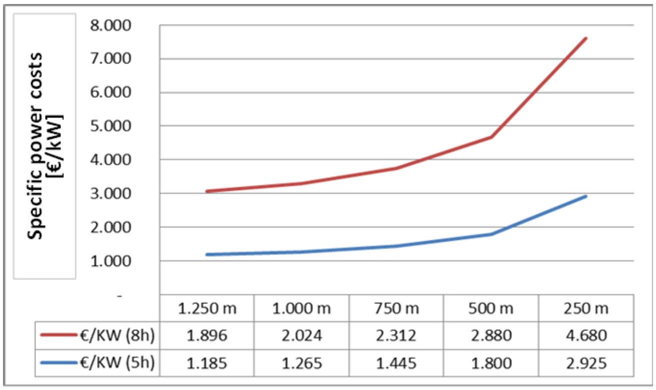


Fig. 6. Investment cost of an UPSHP plant, by head and volume of the storage reservoir; assuming unit costs of capital of 253 € kWh^{-1} (following Fig. 3)

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. Fig. 7 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. The American study, which was used in the beginning as the basis for our own calculations, estimates the specific capacity cost at 2230 US$ kW^{-1} (or 1784 € kW^{-1}, using an exchange rate of $1 ~ €0.8). A study by dena [23] estimates a markedly lower value of 750 € kW^{-1}; while a study by the Deutsche Bank [27] estimates some 800-1300 € kW^{-1}.



	1.250 m	1.000 m	750 m	500 m	250 m
€/KW (8h)	1.896	2.024	2.312	2.880	4.680
€/KW (5h)	1.185	1.265	1.445	1.800	2.925

Fig. 7. Specific power cost, by head and number of full-load operating hours until the lower reservoir is full

Note: For the assumptions made, the values for the full-load operating hours are independent of the storage volume

5. Revenue assessment

The monetary return from a PSPH plant in a liberalized electricity market cannot be calculated directly, but depends on multiple factors. 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.

5.1 Revenues from power transfer

The returns from power transfer strongly depend on the market situation and the resulting electricity price difference between night and day. At least two alternative future scenarios can be thought of regarding the development of this difference.

Scenario 1. Future price differences will markedly diminish. In Germany, in times of high nuclear power generation, the price difference was relatively high, because nuclear power plants can neither be shut down in the off-peak hours at night nor be ramped up in the midday peak hours. But this market situation is changing due to the EEG and the nuclear phase-out. With the end of nuclear power generation, a significant baseload component disappears. Simultaneously, the peakload in the midday peak hours coincides with the peak production of the photovoltaic power plants, which usually feed in most energy at noon (cf. [28]). As a result, it can be expected that nighttime electricity will become more expensive and the full-load price might be lower.

Scenario 2. Future price differences will further divert. In this scenario, we assume that more extensive use of renewables will be linked to a further expansion of wind power usage. The power supply from the wind power plants is indeed strongly volatile. Besides a great amount of short-term regulation capacities, a central role will be the energy storage about multiple hours or even days. The load compensation is no longer necessarily led by demand, from the night hours to the midday hours, but rather led by supply, from times with much wind and a high power output to times with dead calm and accordingly low power output ability. Because most of the renewable energy sources, and especially wind power plants, produce electricity at low marginal costs, in this scenario with excess power supply the power can be bought at low prices. In cases of unfortunate weather conditions, power supply from PV, wind and hydro power plants falls short, which can lead to very high electricity prices (cf. [28]).

The actual development probably depends strongly on the political frameworks and the development of the other energy sources, above all combined-cycle power plants as well as coal-fired power plants. To take these uncertainties into account, three scenarios will be considered in the following, where the price differences for the power transfer are 10 € MWh^{-1}, 50 € $MWh^{-1}$and 100 € MWh^{-1}.

5.2 Revenues from a UHPPS plant

For the three scenarios just mentioned we now conduct a first crude computation of the expected annual revenues. In this computation, we account for the difference in price between power purchase and power sales, ΔP, the total efficiency of the UHSPH plant, η_{total}, and the full-load hour equivalent H [in h a^{-1}]. As the number of full-load hours, a study by dena [23] assumes 1000 h a^{-1}. This value in turn is partially averaged out of 741 full-load hours at PSHP in the neighboring outland 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. [6],[22]). 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 four 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 Fig. 8. So, finally, the returns in the four estimated price scenarios, at 1000 full-load hours per annum and as a function of the head and size of the storage reservoir can be seen in Fig. 8. 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 M€ (10 € MWh^{-1}), 13.6 M€ (50 € MWh^{-1})and 27.3 M€ (100 € MWh^{-1}) of proceeds per year. Note that this is in contrast to the estimated investment cost of 630 M€ reported in Fig. 6.

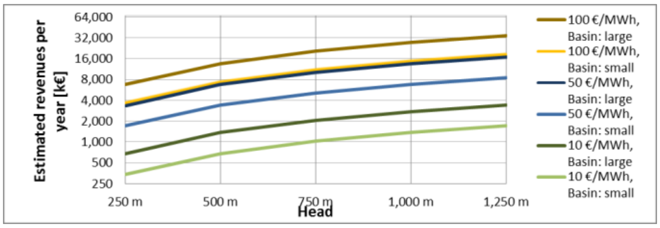


Fig. 8. Annual revenues from an UPSHP plant designed for an 8 h full-load operation in dependence of the head
Notes: Computed for revenue scenarios (10/50/100 € MWh^{-1}) and two storage sizes ("small" = 0.5 Mm^3, large = 1 Mm^3), y-axis in logs

5.3 Reserve capacity and reactive power revenues

As in many other studies, the returns from the provision of reserve energy and the supply of reactive power, unfortunately, could not be determined in our study either. The returns from controlling power range are partly included already in the returns from the power transfer. This is based on the fact that the assumed 1000 full-load hours per year include the operating time in the regular operation mode as well as the time for the power transfer. The attainable results for the reserve power bandwidth turn out to be significantly higher than the ones for the power transfer alone. If the higher prices for the controlling power range were integrated in the price for the power transfer, those would be increasing. So this effect leads to a higher capacity price scenario.

Similarly to the returns from the controlling power range it also seems to be the case for reactive power. The prices for supplying positive or negative reactive power are not publicly traded, but mostly directly traded between the grid operator and the supplier. The returns that would result here are rather minor in comparison to the aforementioned ones, which is why ignoring them will not have much impact on the overall results.

6. Discussion and conclusion

Currently, it is a political target to phase out nuclear electricity generation and to mitigate CO_2 emissions by wasting less fossil energy in electricity generation. In contrast, the share of renewable energy generation shall be increased. Wind and solar energy play a key role in this respect, but are very volatile. To ensure security of supply, energy storage seems to be an indispensable part of the transformation. Thereby an energy storage for multiple hours or days is required as well as a short-term load regulation in the range of seconds and minutes. PSHP plants are perfectly suitable for both functions. An extensive study of dena [23] on energy storage options concludes that no presently available or conceivable storage technology is able to store a comparable energy amount with similar efficiency factors almost loss-free. Also the investment costs needed for pumped-storage are relatively favorable.

Despite of all these advantages, the main remaining challenge is to find adequate locations. The number of technically suitable sites is very limited. Moreover, many projects had to be abandoned, due to public resistance or because they did not receive permission by the authorities (cf. section 2.3). Additionally geographic limitations come along. Whereas many scenarios predict a great future especially for wind power production alongside or in front of, German coastlines, the local, flat topography there is not suitable for conventional PSHP plants. The large differences in level needed are mainly found relatively far away in the Alps or in Norway.

A possible solution to this problem is provided by the idea to install an underground PSHP plant in abandoned pits [5]. The number of potential pits is large, whereas the negative impacts on human and environment seem very 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. In this study the idea of a UPSHP plant in abandoned coal mines of the Ruhr area was analyzed. The focus was firstly on the technical and secondly on the economic feasibility.

From our broad technical assessment we can conclude that the construction of a subsurface storage reservoir is in principle possible. Still, the geological conditions in the Ruhr area are suboptimal. Due to the soft sediments, the extraction of large caverns as storage reservoirs is very expensive and, thus, might be uneconomical. Nonetheless, 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 seems generally possible. Possibly a space-saving disassembling of the components is required for the installation, whereby the expenses and, therefore, also the costs would rise. The penstock between upper and lower reservoir, in the case of a conventional dimensioning, should find enough space in the existing pits. From a technical viewpoint we can conclude from these estimations that realization of such a project appears generally possible. The economic consideration concludes the estimation that profitability firstly depends 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 are 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, whose cost were estimated by using typical values from mining. The goal for the extension of the drift grid in mining is another one as for the development of a lower reservoir for a PSHP. In mining the drifts are designed such that distances can be vanquished at minimum effort, especially concerning material extraction. For the storage reservoir of a PSPH plant, in contrast, the goal is mainly to create a maximum free volume. Longer distances to the entry pit are disadvantageous. From these considerations, the hypothesis results that a drift extension that does not follow any spatial goal but that is more concerned with a maximum volume creation possibly can be realized at lower cost. Hence, in certain cases, the costs for this could also be lower than assumed.

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 RAG) 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 an UPSHP plant features higher investment costs than the conventional type (see also [29]). 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 social acceptance hoped for. In comparison with other energy storage concepts, even the handicap of the high investment and operation and maintenance costs is a relative one. Except for conventional PSHP plants the required expenditures for energy storage devices seem to be somewhat higher than the costs computed in this study. As derived in section 4.6, for an UPSHP plant we can expect specific capacity costs of ca. 1.3 k€ kW^{-1} (5 h design) and 2 k€ kW^{-1} (8 h design), respectively. These results correspond with the results found by the University of Clausthal in 2011, where the costs of a UPSPH plant in a closed down ore mine were estimated to be about 1816 € kW^{-1}. [30] In contrast to dena [23], which assumes 750 € kW^{-1} for conventional PSHP plants, other studies have sometimes reported even higher values (cf. section 4.6); 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, note that 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 (i.e. €15 for CAES vs. €2 for PSHP, according to [20]).

Political framework conditions. In a liberalized electricity market, the same principle applies for electricity storage devices s as for all other investments: sooner or later they have to gain a return. This is, however, the problem of most storage technologies. Whereas the technical requirement for the development of storage options is rarely disputed, from an economic point of view there are only modest incentives to undertake the investment. 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.

An extension of the energy storage capacities in Germany for maintaining grid stability seems indispensable. However, this also depends strongly on the political framework conditions. As soon as the decision in favor of a huge extension of the storage capacity is made, UPSHP plants could play a central role due to their relatively high economic attractiveness in comparison to other large-scale storage options.

The insights gained from our preliminary study can only be used as rough guidelines. For the actually, thorough economic planning more detailed studies are required. Especially the scientific estimation of the expected utilization rate of the subsurface storage capacity, and also a more precise investigation on whether the technical components can be installed below ground, leaves plenty of scope for future research.

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