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

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Abstract: This study researches 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, 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), and cost uncertainty is dealt with by means of a Monte Carlo simulation for two distinct head heights. The findings regarding costs and acceptability are compared with those of a classic (on-surface) pumped-storage hydro power plant in a mountainous area. Based on a techno-economic evaluation we conclude that under favorable conditions the realization of underground pumped-storage hydro power (UPSHP) plants seems both technically feasible and economically reasonable. More specifically, an extension of a tubular system seems the most promising option. A UPSHP plant in a mineshaft is probably slightly more expensive than a conventional one, an outcome that depends strongly on the feasible head height. However, the significant reduction of the adverse impacts on the landscape and on 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 sites where underground mining is being abandoned.

Keywords: hydro power; pumped storage; coal mining; reservoir engineering; massive energy storage; economic viability; temporal arbitrage; Germany

1. Introduction

Since the 1980s, the political will to reduce dependency on nuclear and fossil energy sources has risen in Germany [1]. As a consequence, renewable energy sources, such as hydro, wind, biomass, and solar, have become the pillars of its sustainable energy transition (so-called "Energiewende"). The promotion of renewables is thus also in the political interest of the German federal government and is 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 wind and solar power are intermittent and subject to strong seasonal and weather-dependent variation. Furthermore, daily 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 power storage capacities. Numerous technical alternatives for energy storage and supply side (e.g., grid expansion) or demand side (e.g., smart meters and gateways) management options are currently being discussed, and their individual strengths and weakness evaluated. Much literature on these topics has been published elsewhere [3–10]. The focus of the present study is on pumped-storage hydro power (PSHP) plants, and the techno-economic viability to install them under ground in abandoned coal mines, even in densely populated and industrial areas (i.e. energy load centers) such as the Ruhr area in Germany. PSHPs are the most common storage technology and a well-established storage option. In times of excess electricity, PSHPs pump water from surface level to a level of higher altitude, typically a basin in mountainous terrain. In times when electricity supply 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 about 20% within one storage cycle [11,12].

A current problem is the limited number of potential sites. This is caused by the technical need for sufficient vertical heights, by comprehensive ecological requirements, as well as by distinct public resistance ("Not in my backyard!"), where the latter led to several project terminations in the past (for example, at the Rursee lake near Aachen). In particular, the building of a storage reservoir on a hilltop or in a mountain valley typically requires massive changes to the landscape, which often causes aesthetic or ecological concerns to be articulated by both the local population and nature protection groups [13,14].

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 seems to be unfortunately very limited in Germany. A possible future solution might be the use of underground PSHP (UPSHP) plants, for example, in closed-down coal mines. Instead of pumping the water uphill in the case of electric surplus capacity, it is pumped from an underground storage, 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 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 (on the conversion of open pit mines to semi-underground PSHPs, see [15]). The operating companies are obligated to reestablish the areas formerly used (i.e., put in a degraded state) for coal processing, for which a lake could be a low cost option and could also gain high public acceptance. Grunow et al. [16] investigated public opinion concerning the after-use of the mining districts in the Ruhr Area and found that over 80% of the interviewed favor recreation areas, while 63% could also well imagine an industrial/commercial after-use. Furthermore, it was found that about 70% of the interviewed persons gave positive consideration to the after-use in the form of UPSHPs. Moreover, the achievable altitude differences from the surface to the deepest shafts in Germany of up to 1600 m can otherwise only be realized above ground in the higher mountains of the Alps or in Norway. The end of hard coal production in the Ruhr area (in 2018), as well as the approximately 20,000 pits that exist in that region alone, offer promising framework conditions for realizing such projects there. On the downside, 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 is well established but has only really become a subject of interest for research and media in recent years, due to the increasing necessity of storage and the simultaneous phase-out of mining activity in many regions of the world. Table 1 provides a brief overview of important seminal as well as recent studies.

The aim of this paper, which is a revised and updated version of [17], 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. The research question is whether UPSHP can be operated cost effectively. As far as we are aware of, this is the first study of its kind, and thus of an exploratory character only. The data used and assumptions made bear high uncertainties, which is why we have made an extensive sensitivity analysis regarding the costs and revenues that determine profitability.

Table 1. Brief overview of the most relevant underground pumped-storage hydro power literature (in reverse chronological order).

Author	Year	Country	Contribution	
Kitsikoudis et al.	2020	Belgium	UPSHP in an abandoned slate mine with focus on hydraulics and economic implications regarding volatile electricity prices	[18]
Menéndez et al.	2020	Spain	Impact of changes in air pressure in UPSHPs on global efficiency	[19]
Pujades et al.	2020	Belgium	Interaction between a UPSHP in an abandoned slate mine and ground water flow	[20]
Carneiro et al.	2019	Portugal	Screening of potential locations for different underground energy storage options in Portugal	[21]
Matos et al.	2019	Portugal	Development of geological screening criteria for various underground energy storage technologies, i.e., UPSHP	[22]
Menéndez et al.	2019	Spain	(I) Development of tunnel designs and (II) air pressure simulation	[23]
Schauer	2019	Germany	Techno-economic assessment for a UPSHP in the Ruhr area	[24]
Niemann et al.	2018	Germany	State of play and prospects for the pilot UPSHP plant Prosper-Haniel in the Ruhr area	[25]
Kaiser et al.	2018	Germany	Comparison of compressed air and UPSHP regarding technical and economic aspects	[26]
Alvarado Montero et al.	2016	Germany	Comprehensive case study for a pilot UPSHP plant in the mine "Prosper-Haniel" in the Ruhr area	[27]
Olsen et al.	2015	Denmark	Concept study of a pumped hydro storage in a water pocket only a few meters below the surface	[28]
Perau et al.	2014	Germany	Geological and technical aspects regarding a UPSHP	[29]
Luick	2013	Germany	Holistic comparison of different UPSHP sites in the Ruhr area	[30]
Pickard	2012	USA	Summary of the research on UPSHP	[31]
Beck et al.	2011	Germany	Comprehensive analysis of UPSHP in German hard rock formations in closed iron ore mines	[32]
Min et al.	1984	The Netherlands	Increasing turbine efficiency for UPSHP concepts	[33]
Coates	1983	USA	Suitability of rock formations in Illinois for a UPSHP	[34]
Willett et al.	1983	USA	Overview of the development of the UPSHP concept	[35]
Tam et al.	1979	USA	Exploratory techno-economic study of the UPSHP concept in the USA	[36]
Sorensen	1969	USA	One of the first general investigations of the UPSHP concept	[37]
Fessenden	1917	USA	Patent granted on the idea of underground pumped hydro storage	[38]

The remainder of this paper is organized as follows. In Section 2, we investigate for several real-world examples the trend towards subsurface construction measures for existing PSHP. In Section 3, this trend is further developed into a PSHP concept that is realized completely 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 4.7. Finally, all insights gained from our study are summarized, evaluated, and discussed in Section 5, leading to some preliminary conclusions in Section 6 as to whether the realization of the developed concept seems feasible.

2. On the History of Underground Pumped-Storage Hydro Power Plants

2.1. Rediscovery of an Old Idea

The idea of using underground reservoirs for energy storage is not new, cf. [33–38]. Already back in 1917, the famous radio pioneer Reginald A. Fessenden patented a "system of storing power" below ground (U.S. Patent No. 1247520) [39]. However, this first concept of a UPSHP plant was never realized. In light of the recent development of renewable energies, the idea has been rediscovered and further developed [18–32].

2.2. Caverns as Parts of Classical PSHP Plants

So far, only certain parts of PSHP plants are placed under ground, such as turbine houses, which are often contained in a subsurface cavern in order to protect the landscape. Consequently, also the pressure pipes (penstocks) leading there have to be laid through pits and adits. An example of 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 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 [40].

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 in Nassfeld (in the Austrian province of Salzburg). For economic profitability reasons, the plan was to expand the lower reservoir of the original PSHP plant (built in the early 1980s). Due to various technical, landscape-related, and legal considerations, however, this construction 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 m^3 of rock were excavated and 1950 m of tunnel system with an oval cross section (ca. 7.5×14.6 m) were constructed (cf. Figure 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€ (M€ = million euros) [41,42].

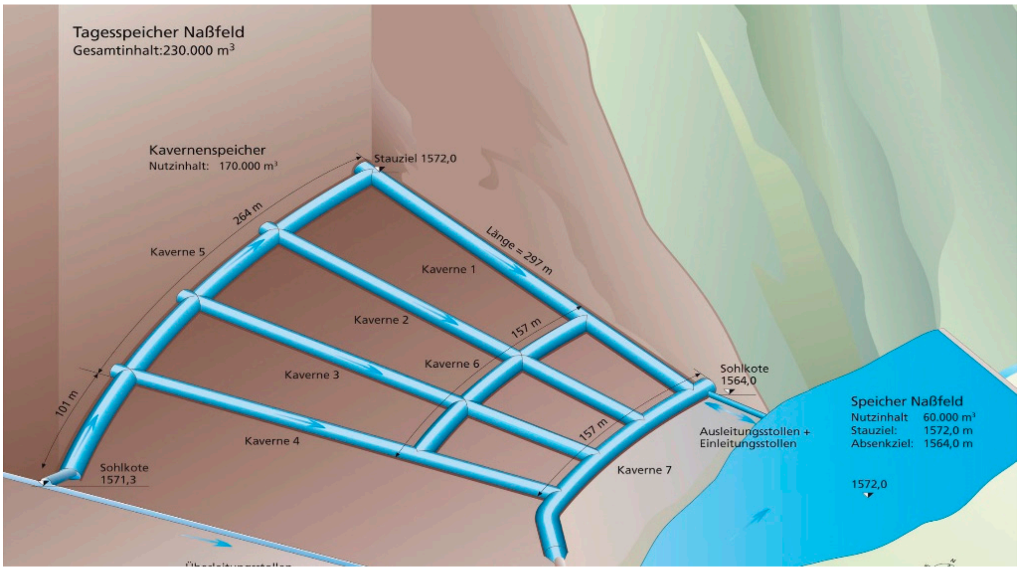

Figure 1. Planned cavern structure for the extension of the intra-day pumped-storage hydro power (UPSHP) plant Nassfeld, Austria [42].

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 Mm^3 cavern was to flow into a 900 m deeper cavern of the same size. The investment costs were estimated at 300 M€. After much protest from the local population, however—for which primarily bad public relations work was later held 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 [43,44].

2.5. Technical Feasibility Study for an UPSHP in the Abandoned Coal Mine of Prosper Haniel, Germany

The feasibility of an UPSHP concept for the concrete example of the abandoned deep coal mine Prosper Haniel in the Ruhr area in Germany is subject to recent investigation [25,27,29]. Research indicates that the intended layout for a plant size of about 800 MWh and 200 MW of maximum power output would be technically feasible, and by and large publicly accepted [16], but that current market and regulatory conditions are not sufficiently favorable.

3. Methodology for a Techno-Economic Analysis of the 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 completely underground PSHP (UPSHP) with special regard to abandoned coal mines in the Ruhr area of Germany. In a first step, we systematically collect and discuss the expected technical problems and questions to be raised. After that, we investigate the challenges in terms of possible technical remedies, cost aspects, and the available options for solving the problems. Figure 2 gives an overview of the concept.

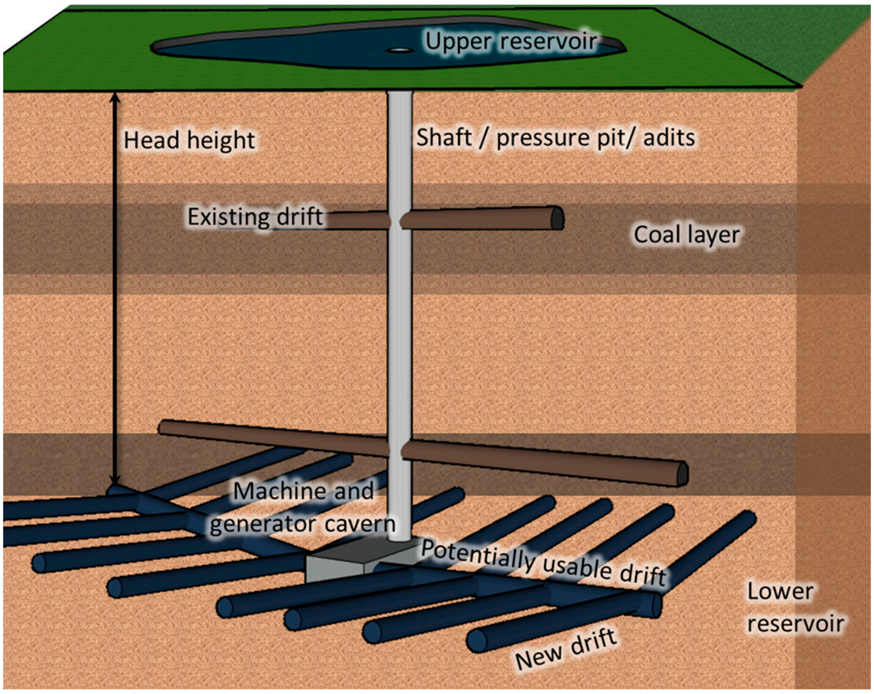

Figure 2. Illustration of a UPSHP with a rib-shaped design; own illustration.

3.1. Technical Considerations and Assumptions Made

3.1.1. 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 [45]). In the case where an on-surface lake is not a feasible option, it would be technically possible to host the upper reservoir in one of the near-surface adits. However, this can be expected to cause significantly higher costs compared to an on-surface reservoir.

3.1.2. Lower Reservoir

The lower reservoir inevitably has to be established subsurface (the lower the better, since the storable amount of energy increases linearly with the realized difference in height). An obvious candidate solution is the use of existing cavities. As described in more detail in [46], the dominant mining method in the Ruhr area was the long-wall mining technique, which involves a controlled collapse of the sediments after coal extraction. The only remainders are the developed drifts that were established permanently for the transport of the input materials, of workers, and of 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 language, cf., [29]).

In the Ruhr area, even the excavation of small cavities, such as, for example, required for coal bunkers, is very laborious. The instability of the soft rock in this region is a geological challenge that even gains in impact with increasing rock pressure in greater depths [46].

Caverns planned for the admission of water need not necessarily be designed as one single enclosed space; this leads to the concept of using existing drifts, which might be accessible at least partly after the abandonment of mining operations (Figure 2). These drift grids are sometimes very extensive and can thus, at least potentially, offer a large total storage volume. Unfortunately, the remaining drift grids have been 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 during turbine operation.

The third option is to construct new drifts. Round-shaped tubes drilled, for example, by a tunnel excavator are highly 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 by Grunow et al. [16] mentioned earlier found that while about 75% of the interviewed participants could well envisage 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 rib-shaped design (Figure 2).

3.1.3. Drift Advance and Costs

As we have to assume, at least partly, 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 into drilling technology and an in-depth discussion of the different tunneling options, we refer to the dedicated literature on this topic (e.g., [29,46,47]).

While the optimization of the layout of a UPSHP is left to be the subject of other investigations, a crucial aspect from an economic perspective are the per-meter costs to be expected for the tunneling advance. The costs of a fully-fledged meter of drift (i.e., with a maximal degree of reinforcement, using standard steel and concrete materials) when undertaking the advance with a tunnel drilling machine for conventional coal production were assessed to be at around 10–20 k€ m^{-1} (k€ = thousand euros) for deep mines in Germany [48]. For 20 km of circular tubing for a UPSHP, [24] 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 estimations fall somewhat more in the lower range of the conventional costs but the relevant authors referred to these as "best-case" and suggested extra costs of around 10% for the usual "practical issues". Therefore, we opted for 15 k€ m^{-1} in our reference scenario, reflecting both the average in conventional coal mining and the realistic estimation of the more recent UPSHP investigation for the Ruhr area.

For a diameter of about 7.8 m, a so-called "open area" of about 48 m^2 results when considering a circular extension, resulting in costs of about 312 € m^{-3}. A plausible storage volume for a UPSHP of 0.5 Mm^3, 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€.

3.1.4. Conclusion for the Expansion Costs

While 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 € $(m^3)^{-1}$ of storage volume would arise. Table 2 depicts a selection of potential scenarios based on these values.

Table 2. Development costs lower reservoir.

Drift Extension (m)	Storable Amount of Water * (t)	Extension Costs at 10 k€ m^{-1} (M€)	Extension Costs 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 calculated in dependence of the developed drift for an open drift area of 48 m^2.

3.1.5. Head height

The deepest coal pits in Germany reach depths of down to 1600 m, with typical depths of around 1250 m [49] (e.g., in Zeche Prosper-Haniel [50]). The vast majority of the pits in the Ruhr area, however, are only between 500 and 1000 m deep [51]. With head heights of more than 700 m and the resulting high pressures, Pelton turbines typically become the preferred option (instead of Francis turbines used for medium pressures). The higher pressure of a Pelton turbine that results from increasing the head height may render slight modifications necessary. This is in contrast to the pumping technology adopted. The world's largest pumping head height of a pump of 782 m has been realized in the Kanagawa plant in Japan [52]. 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 adits of the mines. Therefore, from a technical perspective, the pumps do not pose a limitation to the maximum possible head height.

3.1.6. Energy Quantity

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

$$E_{pot,\ stored} = h_{diff} \cdot m_{Water} \cdot \eta_{Turbine} \cdot g. \tag{1}$$

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

$$\eta_{full-cycle} = \eta_{Pump} \cdot \eta_{Turbine} \cdot \left(\eta_{pipelines}\right). \tag{2}$$

Table 3 reports on selected possible head heights in relation to different masses of water plotted and the resulting capacity in each case with an assumed full-cycle efficiency of 80%, as reported in [11,12] (note that [21] estimated a slightly lower round-trip efficiency of between 73 and 76% for a UPSHP setup in Spain due to higher losses caused by air pressure in the lower reservoir). Many of the depicted combinations in Table 3 do not seem to be realistic. Short head heights 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 head heights and water masses.

Head Height (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 a UPSHP. Computations account for the gravity constant (g = 9.81) and a turbine efficiency of 95% [12].

Subsurface head heights of more than 1000 m seem to be realizable in the Ruhr area only in a few cases. Likewise, a volume (or 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 range of between around 250 and 1000 m head height as well as volumes of between 0.1 Mm^3 and around 1 Mm^3 seem to be promising, as shown in Table 3 (gray-shaded area). With these values, a plausible field of capacities of between about 200 MWh and a maximum of 2500 MWh emerges. A 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.

3.1.7. 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 finally either empty or must not be depleted due to environmental or technical reasons. In the case of a 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 h of operation at full load (cf. [52]). 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 [53–55]. 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 [56,57]. Regarding the two last operation types, massive energy storage capacities are of rather minor significance; more important seem to be 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 h of full-load operation per day are assumed.

3.1.8. Assembling and Structure

Important components for every PSHP plant are the penstock (pressure pipe) between the upper and lower reservoir as well as other shafts. The design of such penstocks with consideration of the inner pressure of the surrounding rock, 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 though 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 [58]. 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 potential UPSHP plant projects [59]. The pressure pipes 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 a 7–8 m diameter seems to be possible with regard to the available space, without the need for any major retrofit.

An issue 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 [59] in Vorarlberg, Austria, shows that the largest components, such as, for example, the pump spiral with a diameter of 7 m, only barely pass through the shafts, with diameters of also around 7 m. Possible solutions are the use of more but smaller components or the disassembly before transporting and reassembling at the 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. Economic Analysis

4.1. Cost-Determining Characteristics

For an economic comparison of different UPSHP plants, two distinct properties are used frequently. The specific capacity costs are given in € kW^{-1}. They provide a relation between the costs for the PSPH plant and the maximal power of the turbine. In contrast, the 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, in short, "capacity").

By comparison of different energy storage plants, the use of the above-presented capacity costs in € kW^{-1} has been very common so far, probably because they are the easiest to determine. This, however, is problematic, since the turbine power determines the parameter exclusively, but not the actually much more 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 costs in € kWh^{-1} for further calculations. In order to enable comparability with other PSHPs, a compilation of our findings in terms of capacity costs is presented at the end of this section.

4.2. Head-Height-Dependent Costs

The UPSHP plant concept presented here features the realized head height as an important success factor. This is due to the fact that while the capacity increases proportionately to the realized head height, 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 (independently of the realized depth). Therefore, aside from some minor costs, for example, for longer and slightly stronger pressure pipes, the construction costs for the lower basin are hardly influenced by the head height.

In the following, the unit costs of newly excavated, fully lined drifts are assumed to be 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 height into costs per kWh of energy storage capacity.

We can conclude that substantial specific costs will arise for the lower reservoir. Based on these numbers, we calculated that constructing a reservoir space for 1 kWh of electricity will cost €227 in a depth of 500 m and €114 in a depth of 1000 m, respectively (for double the head 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, and 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 and Veatch for the U.S.-American National Renewable Energy Laboratory (NREL). Black and Veatch estimate 2230 US$ kW^{-1} for a regular PSHP plant designed for 10 h of operation while featuring 500 MW of full load [60].

Converting these 2,230 US$ kW^{-1} by assuming an exchange rate of 0.8 € ≈ 1 US$ and the conversion from € kW^{-1} to € kWh^{-1} by assuming a 10-h operation, we come up with a specific construction cost estimate of 178 € kWh^{-1}. Specifically, Black and Veatch estimate the cost shares illustrated in Figure 3: Machinery including 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%), and 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 is subsumed in the category "machine and generator cavern".

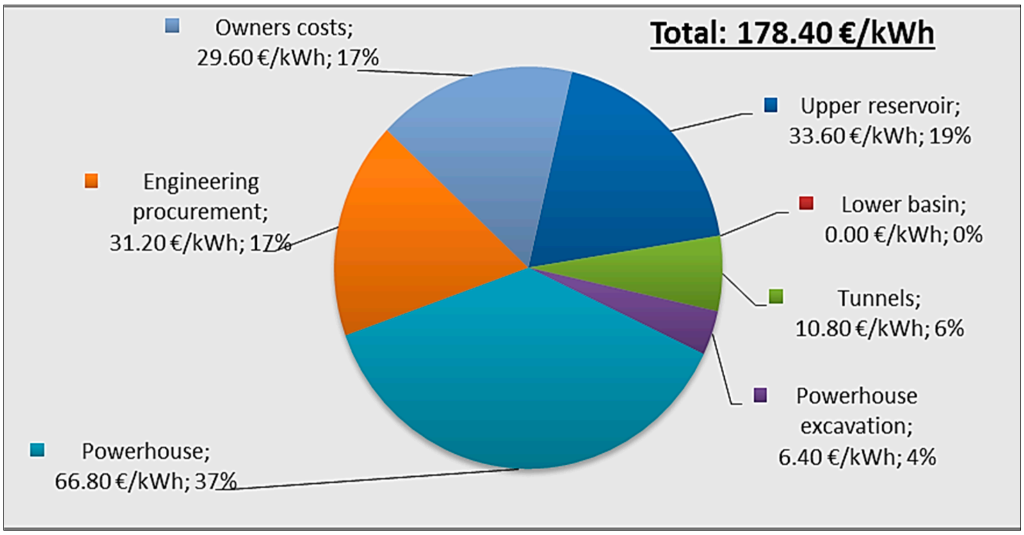

Figure 3. Cost shares for a regular PSHP plant, as calculated by Black and Veatch [51].

The data for an ordinary PSHP plant are next applied to the concept of a UPSHP plant. As an example, we assume a maximum head height 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 have 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 a UPSHP plant project, such a reservoir could be established under any circumstances (i.e., at 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 water reservoir of a UPSHP plant.

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 anyway within the re-cultivation needs. Hence a further utilization of the mines offers an opportunity of partial refinancing of the eternal running costs.

For the construction costs we estimate 34 € kWh^{-1}, which is somewhat higher than for a conventional PSHP plant. While less engineering is required for the establishing of the upper storage reservoir (no large storage dam, etc.), the construction of the subsurface (lower) reservoir has so far barely been proved and tested, which is why we estimate 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 usually increases the relative costs. Furthermore, a dismantling into 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 less favorable circumstances. Particularly noteworthy is the soft rock under the Ruhr area, which makes 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 plant 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 height of 1000 m and for 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.

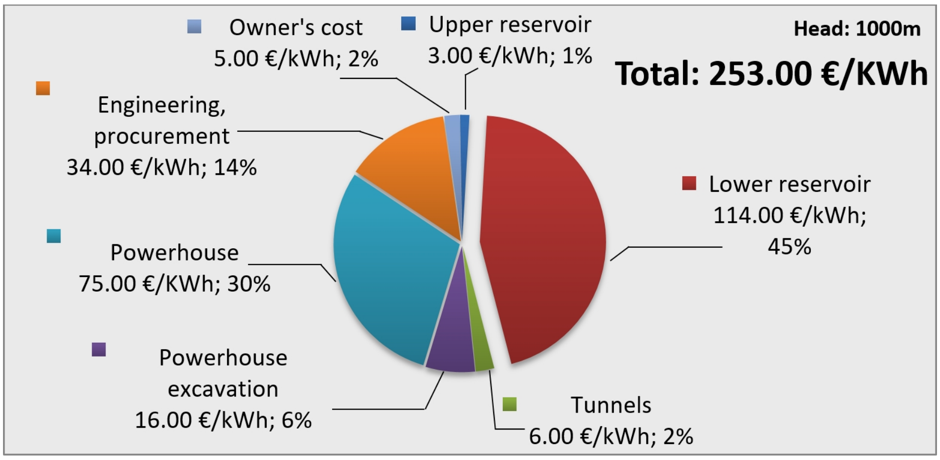

Figure 4. Unit cost share assumptions for a potential UPSHP plant with 1000 m head height.

In comparison, a head height of 500 m would lead to much higher specific costs for the lower reservoir (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 costs” referring, i.e., to paid-up royalties, preproduction costs, inventory capital, and land costs, cf. [60]). 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 height is shown for head heights ranging from 250 to 1250 m.

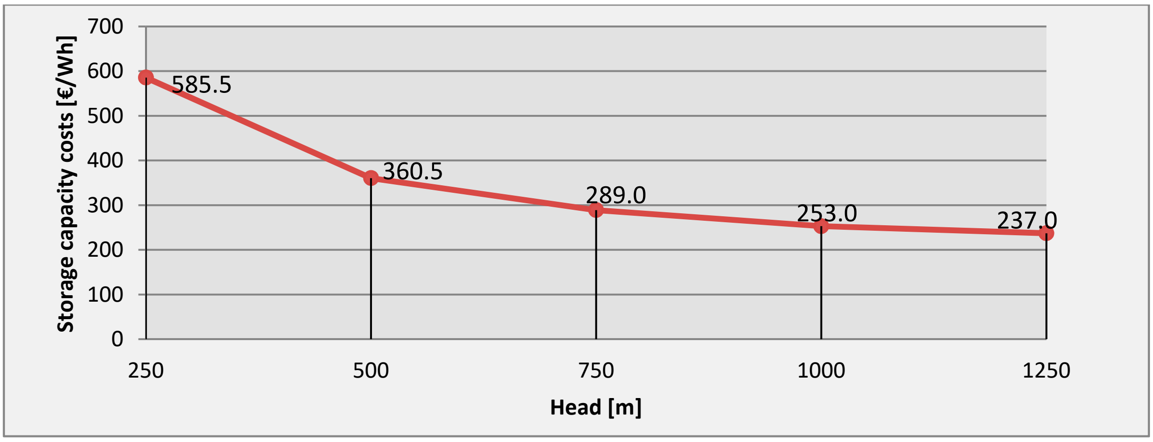

Figure 5. Specific energy storage costs for different head heights.

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, as shown in Table 4.

Table 4. Brief overview of the assumptions made for the sensitivity analysis.

Cost Component	Cost Variation	Comments
Upper reservoir	−100%/+30%	− No costs might occur if an existing source of water can be used. + A more complex reservoir construction might increase costs.
Lower reservoir	−40%/+20%	− Several requirements that the tunneling for coal production had to meet can be neglected. + The necessary cladding of the tunnels could turn out to be a challenge.
Tunnels	+/−30%	+ Extensive use of existing shafts can avoid costs. − If these tunnels cannot be used in the individual case, costs might turn out similar to conventional PSHP plant.
Powerhouse excavation	−20%/+50%	+/− The soft sediment in the Ruhr area poses a significant issue for excavating larger openings. For this reason, a cost mark-up factor of 2.5 (250%) compared to a conventional PSHP plant were already factored in. However, even these costs are probably more likely to increase than to fall.
Powerhouse	+/−30%	Powerhouse excavation is a huge task also in conventional PSHP plant. These costs were already increased by about 12% for the standard case. − These additional costs might be avoided in the case of good accessibility (compared to barely accessible mountainous terrain). + If, however, access turns out to be especially difficult, costs might increase by another 30%.
Engineering	−15%/+30%	+/− Since UPSHP is a novel concept, the engineering budget was increased by about 10% in the standard case. Due to the many uncertainties involved, this share is more likely to go up than down.
Owner's costs	−100%/+10%	+ 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. − Since hardly any other serious competing after-use concept is foreseeable, only a moderate increase in the owner's costs seems possible.

The results are shown in Figure 6. One can see the much wider variance at the lower head height of 500 m and absence of a distinct peak value. Specific costs are highest from about 300 to 380 € kWh^{-1}.

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 height of 1000 m, this effect diminishes, showing a peak unit cost value at around 240–250 € kWh-1. For even higher head heights, this would eventually converge to a Gaussian distribution.

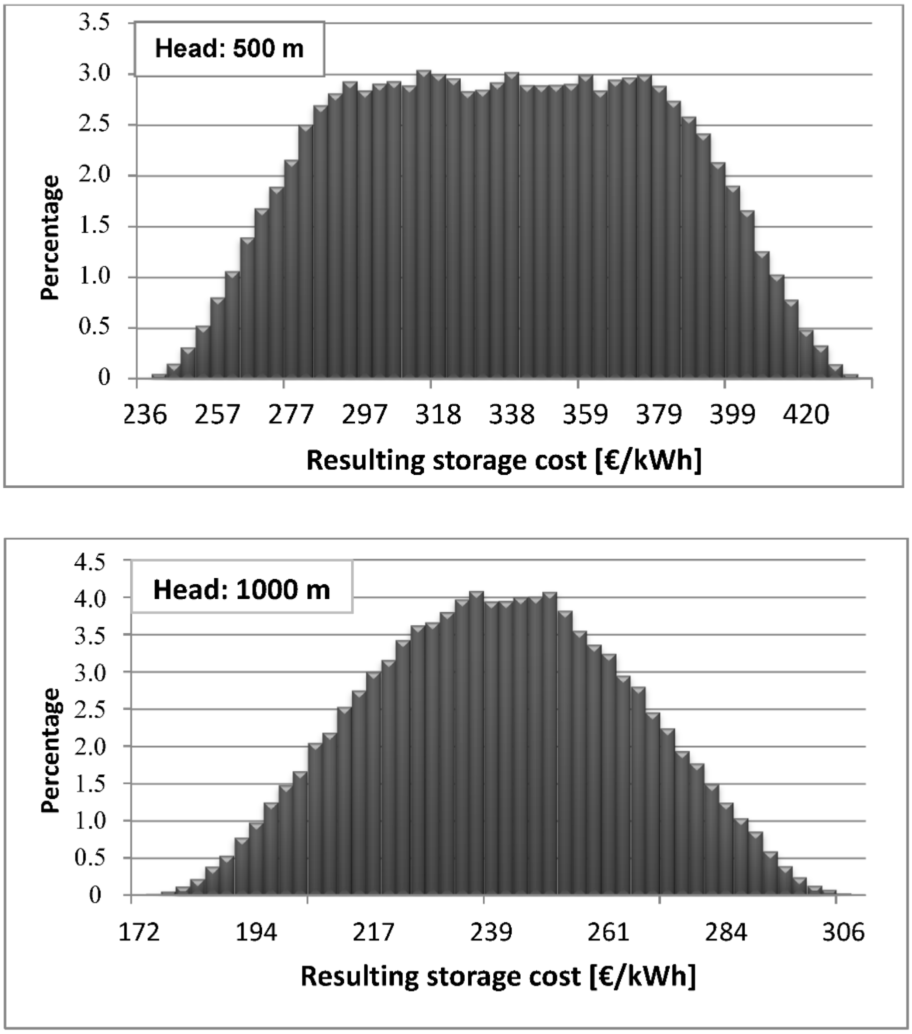

Figure 6. Sensitivity analysis for the specific costs for two different head heights ((**upper**) plot: 500 m, (**lower**) plot: 1000 m).

4.5. Investment Costs for UPSHP Plants with Different Head Heights and Lower Reservoir Volumes

From the specific energy storage costs derived, we can now move on to determine the absolute costs of a UPSHP project with a head height of 1000 m and for variable storage size. Given the upper storage volume limit of 1 Mm^3 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 therefrom.

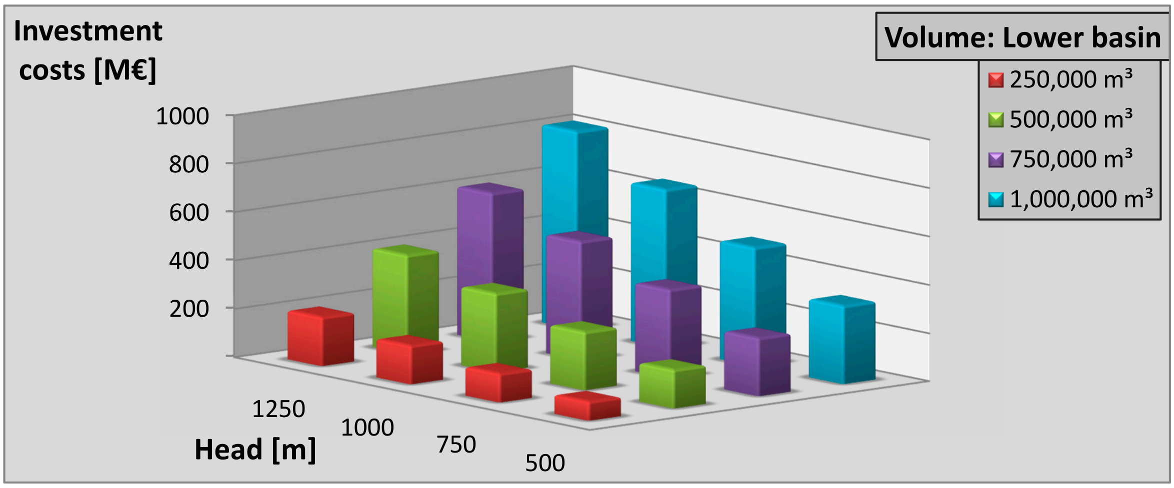

Figure 7. Estimated total investment costs of a UPSHP plant, by head height and volume of the subsurface (lower) water reservoir; assuming unit costs of capital of 253 € kWh^{-1} (following Figure 4).

4.6. Characteristic Unit Capacity Costs

With regard to completeness and further comparability, based on these data also the alternative characteristics for the supply of reserve capacity should 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 these data, some typical values for conventional PSHP plants are presented next. A study by dena [55] estimates a markedly lower value of 750 € kW^{-1}, whereas a study by the Deutsche Bank [61] 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 plants (2230 US$ kWh^{-1} or about 1784 € kWh^{-1} (at an exchange rate € to US$ of again 0.8), which are, as expected, higher than these reference values.

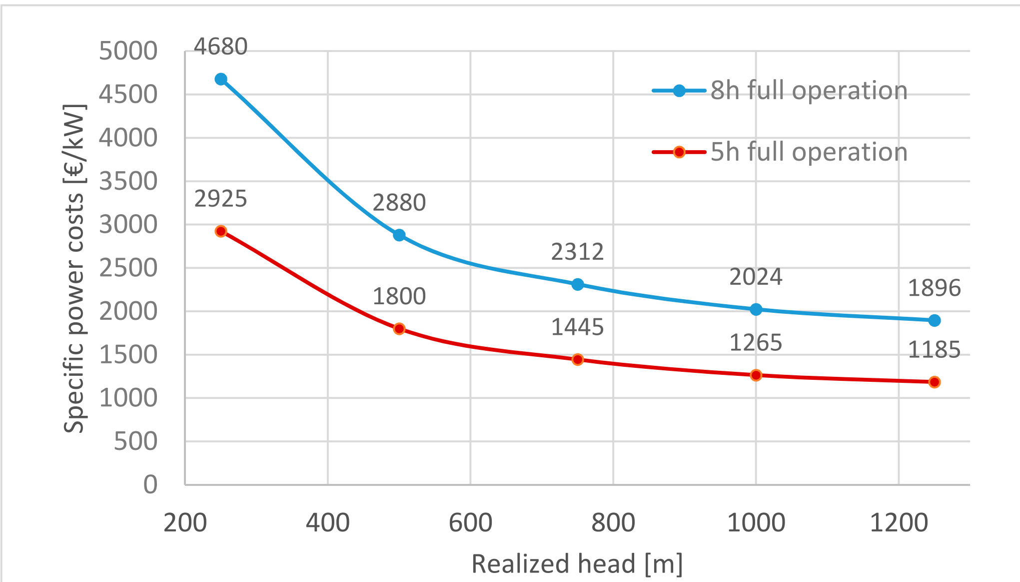

Figure 8. Specific power costs, by head height and number of full-load operating hours until the lower reservoir is full. Note: For the calculations made, the values for the full-load operating hours are assumed to be independent of the storage volume.

4.7. Revenue-Determining Characteristics

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 [9,10,62,63].

4.7.1. Revenues from Power Transfer

The returns from energy arbitrage 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 private households, share of intermittent renewables, etc. Madlener and Lohaus [64] investigate temporal arbitrage in spot market electricity prices in the context of well drainage management in abandoned coal mines owned by RAG in Germany. The authors show that electricity prices may vary significantly between consecutive years and that the economic potential for temporal arbitrage is indeed sizable. Kondziella and Bruckner [64] develop a complex market model which suggests 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 the present study follow this argumentation regarding cost and price spread development. Should this materialize, storage plants could realize wide arbitrage opportunities. For an in-depth discussion on estimates of 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 guidance for interpretation, electricity spot market 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 today.

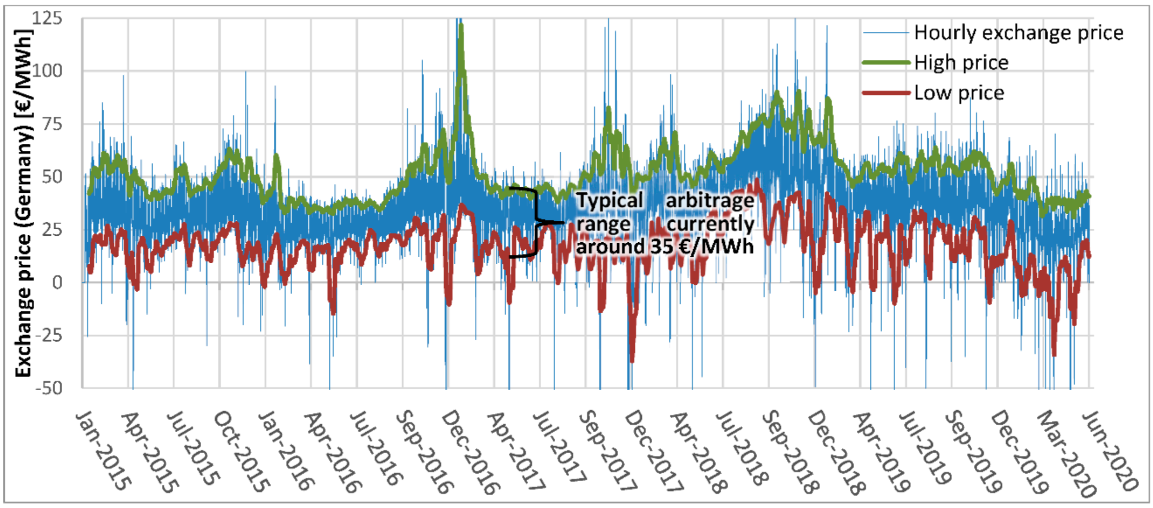

Figure 9. Hourly electricity exchange prices (EPEX spot) and low and high price trends over two days. In recent years, price volatility remained on a constant level, allowing for arbitrage deltas of around 35–50 €/MWh. Own illustration based on market data from www.smard.de.

4.7.2. Revenues from a UPSHP Plant

For the three scenarios mentioned, we did some broad-brushed computations 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 [55] assumes 1000 h a^{-1}. This value in turn is partially averaged out of 741 full-load hours at PSHP plants 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. [11,12,52]). 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 height 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 Mm^3 and a "large" storage reservoir with 1 Mm^3 volume. The estimated returns for the three price scenarios considered, at 1000 full-load hours per annum and as a function of the head height and size of the storage reservoir, can be seen in Figure 10. The exemplary dimensioning to 1000 m head height, in the case of a 1 Mm^3 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 costs of 630 M€ reported in Figure 8. It implies that the cost amortization through revenues gained by temporal arbitrage business 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).

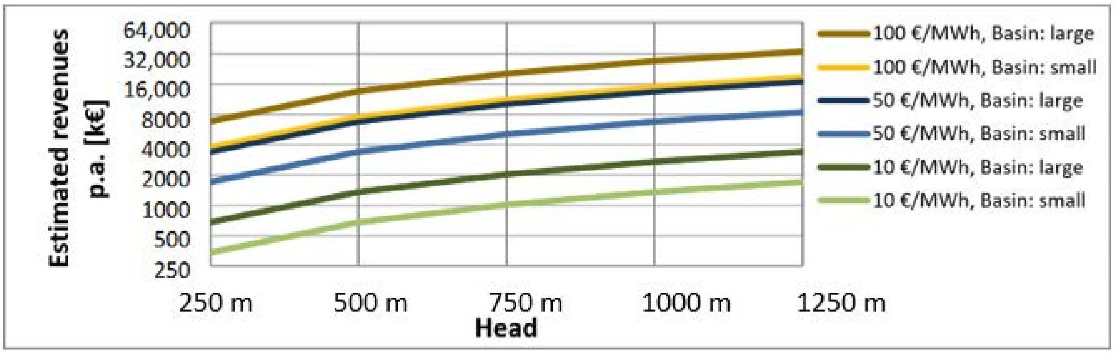

Figure 10. Estimated annual revenues from a UPSHP plant designed for an 8 h full-load operation in dependence of the head height. Notes: Computed for revenue scenarios (10/50/100 € MWh^{-1}) and two subsurface water reservoir sizes ("small" = 0.5 Mm^3, "large" = 1 Mm^3), y-axis in logs.

5. Discussion of Results

The sustainable energy transition towards a 100% share of renewables is leading 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, as no presently available or conceivable other storage technology is able to store a comparably large amount of energy at similar system efficiencies [55]. Moreover, 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 were not granted 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 of Germany as a possible solution to the development of further PSHP plants 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 exactly in those regions that have been subject to recent major structural change caused by the end of coal production, enabling the country to further push and facilitate the Energiewende towards a 100% share of renewables.

Some costs assumed in the analysis 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 (see also [24,29,33]). Apart from the high construction costs 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 per unit costs turned out to be lower than for most other energy storage concepts. In particular, 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, this is 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 [55]).

6. Conclusions

From our broad technical and exploratory assessment, we can 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 water appears to be an economically feasible option. The assembling of the plants of the subsurface turbine house was found to be challenging but generally possible.

The economic investigation reveals that profitability depends primarily on the realizable head height. In the case of low head heights, the cost rate for the extension of the lower reservoir dominates. The relative cost rate in comparison to the other expenses decreases with increasing head heights. 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 subsurface (lower) water 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 water storage reservoir.

In a liberalized electricity market, the same principle applies for electricity storage devices as for all other investments: sooner or later they will have to gain a positive return. This is, however, the problem with most energy storage technologies today. While the technical need and usefulness of bulk storage options is rarely disputed, from an economic point of view there are only modest incentives to undertake such a long-term investment under high uncertainty, and the long-term evolution of the temporal arbitrage potentials are at least questionable in light of the many other flexibility options. 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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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

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

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