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Thomas Kempka et al.

Best-practice guidelines on Hybrid Pumped Hydropower Storage of excess energy in open-pit lignite mines

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An interdisciplinary feasibility study on Hybrid Pumped Hydropower Storage of excess energy in open-pit coal mines

Public report

Best-practice guidelines on Hybrid Pumped Hydropower Storage of excess energy in open-pit lignite mines

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GFZ Helmholtz-Zentrum Potsdam · GIG National Research Institute · CERTH Centre for Research & Technology Hellas · ΔΕΗ · PGE Górnictwo i Energetyka Konwencjonalna S.A. · TU berlin

Cover Picture

The lake of the closed and flooded open-cast lignite mine of Amynteon (Western Macedonia, Greece). Source: Public Power Corporation of Greece.

Scheduled decommissioning of lignite mining in Europe requires innovative and economic strategies to support coal regions in transition. ATLANTIS assessed the feasibility of transforming open-pit coal mines into hybrid energy storage projects. This involved repurposing open-pit mines for hybrid pumped hydropower storage (HPHS) to store excess energy from the electric grid and renewable sources. The project aimed to contribute to the EU Green Deal, while increasing the economic value, stabilizing the regional job market, and enhancing EU energy supply security. The main objective of ATLANTIS was to elaborate a technical and economic feasibility study on HPHS in open-pit coal mines.

Imprint

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About this report

This report was written, edited and produced by the EU-RFCS ATLANTIS project consortium.

For further information on the ATLANTIS project, kindly refer to the project's website:
https://www.atlantis-project.eu

All figures have been created as part of the ATLANTIS project, unless referenced otherwise.

Best Practice Guidelines

Executive Summary

Energy storage is a key pillar in the energy transition to make use of excess energy from wind and solar power and stabilise the grid when energy production does not meet the current demand. Pumped hydropower storage (PHS) is currently the only proven, large-scale energy storage technology readily available. Suitable PHS locations in the EU are limited due to its specific topographic demands. Decommissioned open-pit lignite mines can help leverage the PHS potential, as they meet the requirements by using the former mining open-pit as lower reservoir, while the existing infrastructure will minimise potential environmental impacts and costs. By integrating renewable energies with this technology, the resulting Hybrid Pumped Hydropower Storage (HPHS) plants become pivotal in securing and stabilising EU energy supply, while offering new prospects for coal regions in transition.

The present report disseminates the key findings of the ATLANTIS project on the feasibility of transforming open-pit lignite mines to HPHS sites to leverage the EU energy storage capacities. The guidelines specifically address the current status of HPHS, site selection criteria, HPHS design, optimal HPHS operation, its integration with the electric grid, as well as environmental and economic considerations relevant to the two study areas of the project: the Bełchatów-Szczerców complex in Poland and Kardia mine in Greece. A geographic analysis was conducted to identify suitable locations for upper reservoirs, and a multi-criteria decision-making approach was used to determine feasible HPHS designs for both study sites. Additional aspects such as HPHS operational management, efficiency optimisation and power grid integration are also discussed. Major concerns associated with the implementation of HPHS projects are related to environmental impacts: these mainly include hydrochemical effects such as water acidification as well as the release and migration of waterborne contaminants into adjacent groundwater aquifers. Additionally, maintaining stability of mine slopes throughout the entire lifecycle of a HPHS project is crucial. Consequently, specific environmental risks were identified and rated in a dedicated risk assessment. Predictive hydrochemical modelling was conducted to identify suitable measures to mitigate hydrochemical impacts on the surrounding local aquifer systems. The stability of mine slopes and waste dumps was addressed in a detailed quantitative investigation of different scenarios during lake filling, fluctuating water tables during HPHS operation, seismic activity, and climate change using geotechnical modelling approaches. Mitigation and monitoring measures were proposed to manage the environmental risks and ensure safe and sustainable HPHS operations. Mathematical techno-economic models were applied to determine the overall economic viability of HPHS deployment projects and to assess potential economic risks. In assessing the socio-economic footprint, the wider context of the changes that may take place in the coal regions in transition was captured, in particular the changes expected as a result of the HPHS technology implementation.

Each section of the guidelines concludes with recommendations based on the relevant research findings to support the activities of decision makers, regulatory bodies, mining authorities, stakeholders and HPHS operators. The overarching findings are summarised in the Conclusions chapter.

Current Status of Hybrid Pumped Hydropower Storage (HPHS)

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According to the Paris Agreement, global warming is to be limited to 1.5 °C above pre-industrial levels. An important contribution to this goal is to make energy production greener in the sense of carbon reduction, e.g., by improving efficiency and increasing the capacities for renewable energy generation. The increase in renewable energy generation capacity induces a higher demand for energy storage, especially at the large scale. This is particularly important, as a large disbalance exists between the development of renewable energy production and storage capacities in Europe. At the current stage, only a few existing energy storage technologies have the potential for large-scale implementation over a longer operational time. Among them, battery energy storage systems (BESS), compressed air energy storage (CAES), and pumped hydropower storage (PHS) are profitable. The PHS storage technology is the most commonly accepted one, where large experience regarding planning, implementation, and operation exists. Besides, it can provide important capacities for grid balancing and black start.

In parallel, the scheduled decommissioning of lignite mining in Europe requires innovative and economical strategies to support the coal regions in transition. In the ATLANTIS project, the feasibility and risks of transforming open-pit coal mines into hybrid energy storage projects have been investigated. Hereby, repurposing of open-pit mines for Hybrid Pumped Hydropower Storage (HPHS) of excess energy from the electric grid and renewable sources will contribute to the EU Green Deal, while increasing the economic value, stabilising the regional job market, and contributing to EU energy supply security. The main objective of ATLANTIS was the elaboration of a technical and economic feasibility study on HPHS in open-pit coal mines. The main advantages of this concept are that different requirements and economic aspects can be combined without producing conflicts. Established transformation strategies, such as the conversion of mine areas into solar parks and wind farms are not limited by HPHS implementation but complement each other. Furthermore, existing power plants and grid infrastructure can be complemented by HPHS, and the integration in national power grids is granted due to the already existing connection and capacities. Consequently, repurposing of open-pit mines in abandonment as HPHS is a promising approach to help enable the energy transition in Europe while supporting coal regions in transition. Economic re-utilisation of former open-pit mines can substantially contribute to land rehabilitation and environmental protection as well as to the public perception of transformation processes.

The present report has been prepared to summarise and disseminate the ATLANTIS project research and its key findings on the feasibility of using open-pit lignite mines as HPHS sites to leverage the energy storage potential in the EU, as well as to support the activities of decision-makers, regulatory bodies, mining authorities, and stakeholders. The guidelines address in particular the current status of HPHS, site selection, HPHS design, operation, power grid integration, and environmental and economic considerations using the examples of two mines in Poland and Greece. Each section of the guideline concludes with recommendations intending to help end-users make informed decisions on how best to establish an HPHS operation in an open-pit coal mine in the phase of decommissioning and rehabilitation from an economic and environmental perspective during planning, implementation, and for future operation.

The focus of the guidelines will be given on the following items:

- The role of HPHS as an energy storage resource/technology in the European energy market, addressing the challenges and opportunities for energy storage in open-pits of abandoned coal mines, considering the regulatory framework.
- The importance of design, operation, and power grid integration of HPHS as well as the implementation potential in the Member States as success factors. Factors and solutions have been assessed and key findings will be presented within the guidelines.
- Environmental considerations as key challenges that must be addressed in the early stages of planning, of which hydrochemical and geotechnical impacts and their subsequent effects have been identified as most important.
- Economic considerations and their modelling, addressing in particular energy supply and requirement, cost and finance analysis, economic risks, and the socio-economic footprint of projects.
- Quantification of also socio-economic or societal effects as important aspects of large projects, which allows all responsible and interested parties to understand decision-making and to assess options.

Development of Pumped Hydropower Technology in Recent Years

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Motivation

Generation capacities of renewables to achieve a carbon-neutral, climate-resilient energy transition significantly increased in the past years. However, to achieve these goals, sufficient availability of energy storage facilities is required, especially at large scale. Hydropower is the most established and largest renewable energy technology, as its history began more than 2000 years ago (Quaranta et al., 2023). Global installed capacity and annual electricity generation have increased steadily in recent years, reaching 1397 GW and 4408 TWh in 2022, respectively, which corresponds to more than 15% of the global electricity demand (IHA, 2023).

Processes

There are four types of hydropower technologies: storage/dam hydropower, run-of-river hydropower, hidden hydropower in water infrastructures, and pumped hydropower storage (PHS; Quaranta et al., 2023, IHA, 2022a). Hereby, PHS is a proven technology with an exceptional lifespan of more than 60 years compared to batteries, which ranges between 20 and 30 years (Energy storage, 2023), and already contributes 96% of installed global storage power capacity. Larger storage capacities (>100 MW) to store surplus energy for short and long-term can be realised, and total round-trip efficiencies of up to 85% are some of the many advantages of this technology (Javed et al., 2020; Jinyang et al., 2020). In 2022, 270 PHS power plants were in operation worldwide with a total installed turbine power capacity of 175 GW, an increase of more than 10 GW compared to the previous year. By 2030, a further increase of almost 50% to about 240 GW is expected, as several sites are envisaged for the construction of new PHS plants worldwide (Fig. 1, IHA, 2023; IHA, 2022b, Quaranta et al., 2023).

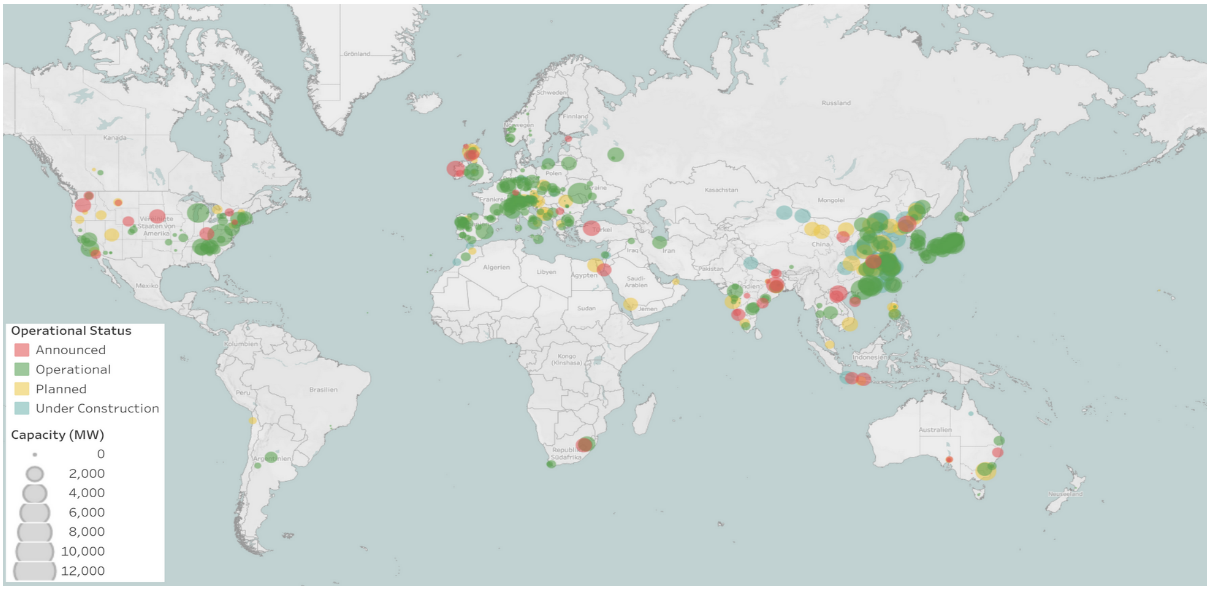

Fig. 1: World map with locations for existing and planned pumped storage projects and their capacities (IHA, 2022b).

Investigations

To date, 160 PHS power plants with an overall turbine capacity of 55 GW operate in Europe (Quaranta et al., 2023). With the exception of China, Europe (including Turkey) recorded the largest increase in hydropower capacity (almost 3 GW) worldwide in 2022, to which PHS contributed 1780 MW due to the commissioning of three notable projects in Switzerland, Portugal, and Turkey. In recent years, Europe has taken on a global leading role in the field of hydropower alongside China and has produced the largest share of exports, high-value inventions and scientific publications (Quaranta et al., 2023). This makes hydropower a key sector for strengthening the EU's competitiveness in tackling the challenges of the energy crisis, climate change, the green and digital transitions, and the competitiveness of emerging economies (IHA, 2023, Quaranta et al., 2023). Due to significant improvements over the past years, modern PHS plants can achieve technical storage efficiencies between 65-85% and a cycle efficiency between 75-80% (Pujades et al., 2017; Voith, 2024). In hybrid combinations by integrating fluctuating energy sources (e.g., wind and solar), hybrid pumped hydropower storage plants (HPHS) contribute to cost-effective, flexible, and sustainable management of electricity generation decoupled from demand (Mongird et. al., 2019). In the areas related to the ATLANTIS project, the installed turbine power capacity of PHS is estimated at 0.7 GW (Greece) and 1.8 GW (Poland) to date, which, including other hydropower technologies, corresponds to a total share of 10.9% and 1.7% of electricity generation, respectively (Quaranta et al., 2023).

Recommendations

- Economic, environmental, and social factors play a decisive role in the assessment of hydropower potential. For an in-depth understanding of hydropower potential, including all system and process-relevant economic, environmental, and social factors, a comprehensive, objective, and standardised quantification needs to be carried out at global and continental level (IHA, 2023).

- Long construction times and high investment requirements for new PHS projects can entail additional risks, particularly for large power plants. Further, hydropower planning and approval processes typically take more than five years (IHA, 2023). For the EU in particular, it is recommended that market regulations and authorisation procedures be introduced that are robust, transparent and shortened to counteract any further concerns among operators, investors, and interest groups.

- It is recommended to make use of the EU's leading role in scientific research, technological innovation, export, and market development, to strengthen market stability, long-term technology improvement, and visibility also among the public domain (Quaranta et al., 2023). However, hydropower capacity cannot be increased through market forces alone. To achieve a more balanced system, policymakers will further need to develop mechanisms that reward flexibility (IHA, 2023).

The Role of HPHS as an Energy Storage Technology

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Motivation

A continuous, sustainable, and clean power supply is hardly conceivable without the option of intermediate energy storage. Several studies indicate that PHS as a cost-effective source of flexibility has remarkable attributes such as higher storage and energy production capabilities, long-term storage potential, and exceptional operational efficiencies (Nikolaos et al., 2023). According to IEA (2023), PHS systems have a technology readiness level of 11/11, i.e. proof of stability has been reached and predictable growth is expected. Therefore, PHS has the potential to play an key role in the energy transition in Europe. Combining different renewable energy sources into hybrid energy solutions is a key pillar in counteracting energy shortages and the associated supply uncertainties caused by, e.g., the intermittency of renewable sources availability and a lack of grid capacity, and in maintaining a high level of grid resilience. In a hybrid power plant, the same electrical infrastructure can be used, thus lowering overall costs (Quaranta et al., 2023).

Processes

The functionality of an HPHS power plant is based on the principle of converting electrical energy into gravitational energy and vice versa. A plant requires an upper water reservoir, located relatively near but separated vertically by a considerable height to a second lower water reservoir. Excess electricity from renewables such as photovoltaic and wind turbines, can be used to pump water into the upper reservoir via penstocks (Fig. 2), which is then released into the lower reservoir as required, whereby electricity is generated by means of hydroelectric turbines during high-peak demand periods.

The water can then be stored in the lower reservoir and system-related electricity surplus allows it to be pumped back through the penstocks into the upper reservoir again. By rapidly releasing or pumping the water, pumped storage power plants are extremely effective in compensating for the problems of electricity system caused by fluctuating electricity generation from renewable energy sources (Breeze, 2019). The entire system can be isolated from the grid or developed in a grid network.

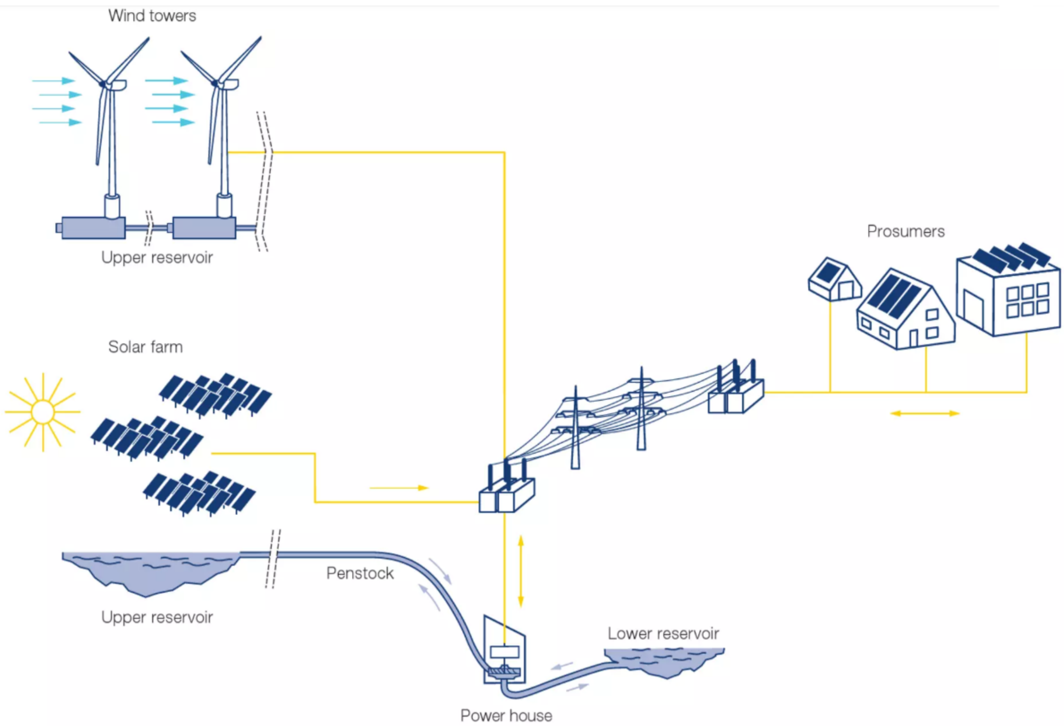

Fig. 2: Schematic of HPHS in water pumping and releasing modes (Voith, 2024).

Investigations

Hydropower storage and PHS are currently the only established technologies for long-term (e.g., days, weeks) energy storage, and if their components are correctly dimensioned, large water reservoirs can also store energy (and water) seasonally (Quaranta et al., 2023). The optimal size of the hybrid system for renewable energy depends on key factors such as capital costs, suitable topography and climatic changes, and requires an evaluation through numerical simulations based on specific mathematical models and the management of system components to find the best solution. For example, in some locations, solar and wind resources are anti-correlated, complement each other, and together generate less fluctuating output than independently (Simão and Ramos, 2020; Ramli et al., 2018). For hybrid power supply systems, the most important planning objectives when dimensioning and designing the power plant are therefore to minimise the costs of power generation, to purchase energy from the grid (if it is connected), to reduce emissions, to lower the overall lifecycle costs and to increase the reliability and flexibility of the power generation system (Sawle et al., 2018).

Recommendations

- A comprehensive identification of sites potentially suitable for hybrid use of PHS, including systematic mapping and assessment of existing and potential hydropower sites is strongly recommended to advance sustainable infrastructure development and improve energy policy decisions.
- The potential for hybridisation with other energy technologies should be exploited to a much higher degree and the integration of intermittent renewable energy sources with PHS plants should be promoted. Accelerating the expansion of

renewable energies through more rapid authorisations and can have a positive impact on this process.

- As the potential for hydropower capacity expansion is limited, the modernisation of hydropower infrastructure can bring additional benefits and is recommended together with the exploration of alternative rather unconventional sites for the implementation of PHS, i.e. decommissioned open-pit mines, to overcome capacity and topographical constraints.

Challenges and Opportunities of Abandoned Coal Mines for Energy Storage

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Motivation

Depending on the topographical and ecological conditions, modern PHS projects usually require the construction of at least one of the two water reservoirs. Huge open-pit mining excavations usually remain unfilled even after mining activities have ceased, thus significantly impairing the ecological and aesthetic values of the landscape (Menéndez and Loredo, 2019; Wessel et al., 2020). Due to costs, the residual material is stored in the form of mine dumps adjacent to the open-pit mine, while the excavations are generally flooded and become pit lakes. The ongoing closure of open-pit mines under the EU Green Deal agreement and the challenges in selecting suitable sites, which are constrained by a number of environmental parameters, offer the opportunity to use precisely these areas for the realisation of a PHS power plant. Hereby, the avoidance of further excavations by re-using and rehabilitating former mining sites, significantly reduces potential environmental impacts in the absence of sufficient topographical and ecological conditions, and at the same time HPHS in former open-pit mines can create new employment prospects for former mine workers, increasing the socio-economic value of the region and promoting public acceptance. Cost advantages besides the significant reduction in costs of constructing the two required storage reservoirs due to the presence of the open-pit result from the presence of transport infrastructure and electricity transmission facilities at the former mining and coal-fired power plant sites.

Processes

The concept of PHS in an abandoned open-pit mine is based on the use of an artificial lake in the former mining excavations as the lower reservoir in combination with the mine dump at which an upper reservoir is built to store electricity. Both reservoirs may be connected via subsurface or surface-based penstocks. Powerhouse facilities with turbines, transformer, and a connection to the electricity grid are usually located in the subsurface or above ground close to the lower reservoir (Fig. 3, Wessel et al., 2020). One advantage is that many of the coal mines to be decommissioned have a good spatial correlation with existing wind and solar parks, and many of such parks are in the development phase on the grounds of former lignite mines, as these will be required to transition their primary energy production to renewable energies in the coming years as part of the EU Green Deal agreement and energy transition, thus offering the possibility of hybrid solutions.

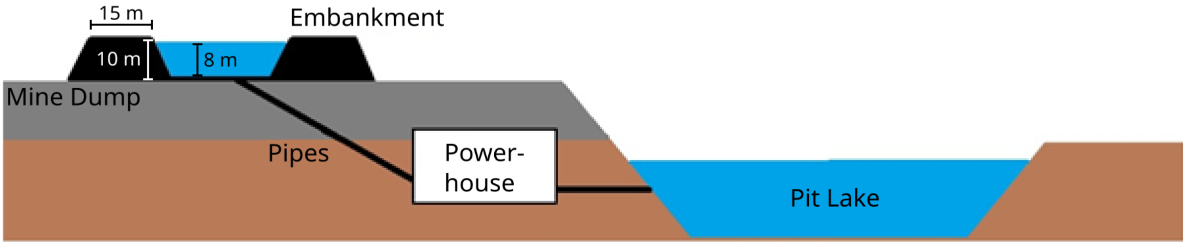

Fig. 3: Schematic of a technical concept for an open-pit PHS plant (Wessel et al., 2020).

Investigations

The storage capacities worldwide for PHS in open-pit mines would be enormous. Europe has a large number of open-pit mines that have already been abandoned or will be abandoned in the near future. The Australian National University has identified 904 mining sites in 77 countries worldwide that are suitable for implementing PHS (ANU, 2024). Several international projects have already passed the planning and feasibility phases for PHS in former open-pit mines, partly in hybrid combination, such as

- Silvermines Mountains – Tipperary, Ireland
- Kidstone Goldmine – New South Wales, Australia
- Marmora iron ore mine, Ontario, Canada
- Tent Mountain Mine – Southwest Alberta, Canada
- Muswellbrook Mine – New South Wales, Australia

Nonetheless, the requirements for a successful HPHS system implementation in abandoned open-pit mines are high. A substantial understanding of the geological and hydrogeological conditions is important to manage the risk of, e.g., pit slope failure as well as vertical ground displacements during the first filling of the storage reservoirs as well as in the context of fluctuating reservoir levels during operation. However, compared to conventional pumped storage plants, the latter allows for more flexible control and operation by variable pumping technologies (Breeze, 2019; Hunt et al., 2020). A major challenge is that open-pit mines are rarely isolated. Consequently, groundwater flows in and out, which may endanger adjacent groundwater bodies in case of remobilised coal residues and associated pH variations, and can affect the efficiency of the plant (Jiang et al., 2021; Pujades et al., 2016; Pujades et al., 2017; Rehmann et al., 2015). Groundwater exchange depends largely on the porosity and hydraulic conductivity of adjacent groundwater aquifers, the characteristics of the lower reservoir, the relative elevation of the groundwater table compared to that of the lower reservoir, and the envisaged pumping/injection cycles (Kitsikoudis et al., 2020). Pujades et al. (2016) found that groundwater exchange between the lower reservoir of the PHS plant and the local aquifers increases at higher hydraulic pressure variations due to the pumping and injection rates per cycle. If the stored water volume in the subsurface reservoir is much higher than the pumped and injected water volume during each cycle, groundwater flow impacts will be negligible, which can be taken into account for ongoing operations. The slopes must also be able to withstand the initial filling of the basin and the fluctuating water levels at all times during operation. Hydropower plants in the EU must comply with the requirements of several environmental directives, which require project developers to identify and assess the significant environmental impacts and risks, and propose appropriate preventive measures (Quaranta et al., 2023). Hence, HPHS plants using abandoned open-pit mines as reservoirs need to achieve a good balance between electricity generation, impacts on ecosystems and benefits on society, supporting the achievement of the EU Green Deal targets and objectives of renewable energy and water policies. However, the most common challenge cited by stakeholders is also the lack of policy incentives for upfront investments (IHA, 2023).

Recommendations

- Since the available capacities for the realisation of PHS in former open-pit mines in the EU are enormous due to the successive closure of many coal mining sites, a screening of the available sites is required to determine the true potential. The screening should include nearby installed or planned renewable energies and corresponding energy infrastructure.

- One of the main concerns of HPHS in open-pit mines is an exchange of water between the reservoir and its surrounding geological porous media that may affect the groundwater environment, as coal deposits contain various minerals whose oxidation and release can have a significant impact on water chemistry, and thus water quality. Hence, a thorough hydrogeological and hydrogeochemical assessment of the site is recommended prior to the start of construction and should be supported by numerical modelling to understand groundwater flow patterns, aquifer characteristics, local hydrochemistry and the potential impacts of the project on local groundwater resources.

- To pave the way and unlock the potential that abandoned open-pit mines offer for the implementation of HPHS, governments and policy makers must also incentivise sustainable hydropower development by creating financial and market mechanisms that reward flexibility, accelerating renewable energy development through simplified permitting and licensing regulations, and embedding sustainable hydropower practices in government regulations (IHA, 2023).

Current Regulatory Framework

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Motivation

There is no EU legislation specifically for HPHS, however, there are a number of EU directives, guidelines and other documents that support the implementation of HPHS systems. It is important to note that PHS and consequently HPHS are not only considered as renewable energy sources, but also as a very important energy storage solution, both technically and legally.

Processes

Project developers must identify assess and mitigate any environmental impacts of project implementation and propose environmental protection measures before licenses are granted by the competent authorities. Further assessment procedures are required if the projects are to be located in Natura 2000 areas. In the case of funding from the Recovery and Resilience Facility, member states must comply with the European Commission's Do No Significant Harm (DSSH) criteria, which include six environmental objectives (Quaranta et al., 2023).

Investigations

Although it is not a piece of legislation, the “Guidance on the requirements for hydropower in relation to EU Nature legislation” published in 2018 is an important document outlining how hydropower can be in accordance with the requirements of various European Directives, as described below, via the examination of best-practice case studies. According to the European legislation, hydropower plants must comply with the requirements of the following directives: the Environmental Impact Assessment (EIA) Directive (Directive 2011/92/EU and amendment 2014/52/EU), the Habitats and Birds Directives (Directives 92/43/EEC and 2009/147/EC) and the Water Framework Directive (Directive 2000/60/EC). Another important piece of legislation is the Renewable Energy Directive (amended 2018/2001/EU), which sets a target of 32% renewable energy for the EU by 2030 (Papadakis et al., 2023), which significantly promotes the use of hydropower and other renewable energies, such as solar power. The share of renewable energies is expected to rise to 42.5% in the new version of the directive (Quaranta et al., 2023). Additionally, the Regulation 2019/941 on risk-preparedness in the electricity sector requires member states to be able to utilise national energy sources and promotes energy storage and flexibility procurement. Hydropower is the most flexible renewable energy source and exhibits the highest water-energy storage capacity (Quaranta et al., 2023).

One of the most useful and recent documents related to energy storage is the "Commission Recommendation of 14 March 2023 on Energy Storage – Underpinning a decarbonised and secure EU energy system 2023/C 103/01", which promotes energy storage in multiple forms. Most of energy storage in the EU (95%) is provided by hydropower and part of that is provided by PHS (EU holds 25% of PHS global turbine capacity), therefore documents such as this could accelerate the use of PHS in the coming years (Quaranta et al., 2023).

Recommendations

- A detailed and clear legal framework on PHS is required on EU level, as this technology is considered both a renewable energy source and a storage solution. So far, there are only directives that indirectly refer to PHS. HPHS is not mentioned in the EU Directives. Therefore, more specific laws should be established both for PHS and the different types of HPHS (solar, wind, etc.).
- Although hydropower is promoted in EU recommendations, it seems to be underestimated as a renewable energy source and more importantly, as an energy storage technology, even though it is the most widespread in Europe. EU legislation should continue to promote it as an important and sustainable energy storage solution, especially with regard to HPHS systems, and facilitate the construction of new plants in the member states via relevant directives.

Design, Operation, Power Grid Integration and Implementation Potentials of HPHS

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The design of an HPHS system requires the definition of a wide variety of factors, ranging from optimal site selection for construction to the technical design of the system according to the desired energy storage requirements. After additional safety and environmental measures, former open-pit mines can be the ideal choice for the lower reservoir of an HPHS system, depending on their size and depth. This is followed by the optimal site selection for the construction of the upper reservoir, which will be located in the vicinity of the lower reservoir. In the framework of ATLANTIS, two case studies were examined, the Kardia lignite open-pit mine (Western Macedonia, Greece) and the Bełchatów-Szczerców lignite open-pit mine (Łódź Basin, Poland), which will serve as lower reservoirs for the prospective HPHS systems. The site selection of the upper reservoir was conducted by utilising advanced GIS and Multi-Criteria Decision Making (MCDM) techniques, coupled with a preliminary energy storage capacity calculation for each selected site, and identifying design properties for the specific energy storage unit based on previously selected site characteristics, as well as energy market demands, Renewable Energy Sources (RES) capacity and performance, region-specific boundary conditions and efficiency of the system. All the studied parameters of the HPHS system of the ATLANTIS project, from design factors to environmental and techno-economic aspects were integrated in the final feasibility study.

Infrastructure

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Motivation

The transition to clean energy and eventual decarbonisation refers to the phasing out of lignite units, the closure of the mines and the installation of renewable energy facilities. Thus, the mining industry target is achieving effective post-mining land use transition. Within this framework, the feasibility of implementing a PHS facility is examined in two case studies, the Kardia lignite open-pit mine (Western Macedonia, Greece) and Bełchatów-Szczerców lignite open-pit mine (Łódź Basin, Poland), where PPC and PGE are respectively planning to use the PHS technology coupled with renewable energy sources to support the transition to climate neutrality by 2050 in line with European objectives.

Processes

RES such as solar photovoltaic (PV) panels and wind farms (WF), developed on mining land and its surrounding areas, can be combined with the PHS technology. The conceptual idea is to utilise the pit lake as a “lower reservoir” and to create another reservoir in the perimeter of the pit or generally at higher altitudes that will serve as an “upper reservoir”. The aim is to take advantage of the head difference between the pit lake and the upper reservoir and use the hydropower potential. In a grid-connected hybrid RES/PHS energy system, excess power produced by RES can be used to pump the water from the lower reservoir to the upper reservoir. Subsequently, when the power produced by RES is not sufficient to satisfy the entire load of the grid, the deficit power can be provided to the grid by the PHS system by releasing the stored water from the upper reservoir to pass through the turbines in the powerhouse located at the lower reservoir (Fig. 2).

Compared to other energy sources, RES are characterised as fluctuating energy sources due to their main setback of producing energy only in certain hours, as they are weather-dependent technologies. The PHS facility could work as an energy storage unit, uplifting and storing water quantities to higher elevation levels during low-power demand periods, and releasing power during high-power demand periods, thus filling in the valleys and lopping off the peaks (Fig. 4), providing grid stability and security of supply. Therefore, it is essential to consider the intermittent power outcome of RES technologies in each study area.

In practice, only a portion of the energy surplus is stored due to energy losses that depend on the length of the penstock (pipes or tunnels), the water flow velocity, and characteristics of turbines and generators. Other changes in balance are also taken into account, such as evaporation losses and water inflows into the reservoirs, depending on the characteristics of each study area. Thus, some additional water can be stored in the upper reservoir of the plant to compensate for the energy losses. The diameter of the penstock should also be evaluated to meet the requirements for the maximum flow rate prospected to cover the storage demands.

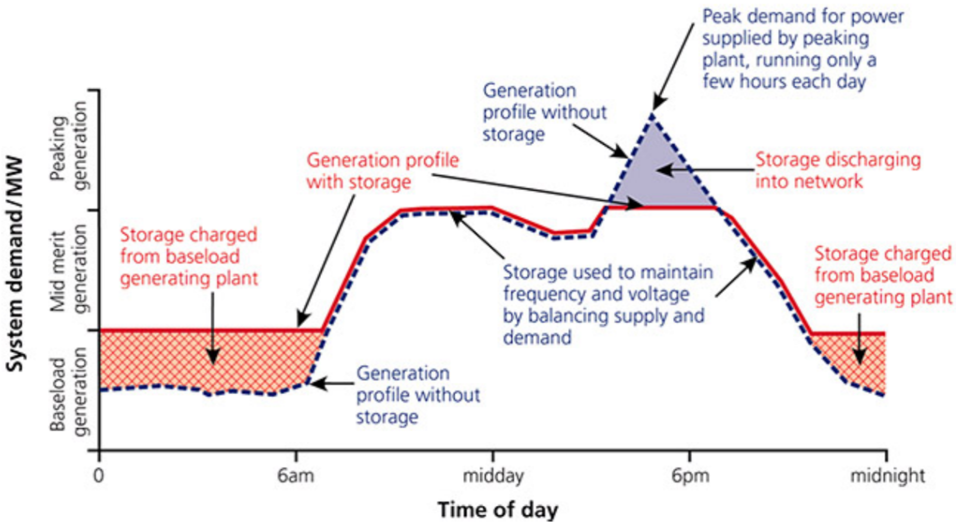

Fig. 4: Simplified scheme of electricity demand and use of energy storage (Wittingham, 2012).

Investigations

The efficient and reliable supply of electricity hinges on a complex system of power generation, transmission and distribution. In Poland, electricity is predominantly generated by coal and lignite-fired thermal power plants and its transmission to customers involves extensive networks that incur losses, mitigated by increasing transmission line voltage. In this context, implementing HPHS systems offers a promising solution to enhance energy stability and efficiency.

The Kardia mine provides an ideal setting for combining HPHS with PV systems, leveraging the region's abundant solar resources, to store excess energy and stabilise the grid. Conversely, the Bełchatów-Szczerców field, one of Europe's largest lignite mining areas, shows the potential of coupling HPHS with PV systems and wind farms, tapping into substantial wind resources to facilitate the transition from fossil fuels to renewables.

Recommendations

- Open-pits comprise large areas that could store significant amounts of water, and thus provide considerable energy storage capacities for large lower reservoirs. They can also provide a significant head elevation difference between the lower and the upper reservoir, which is a crucial parameter considered in the HPHS design.

Therefore, pit lakes could be utilised as RES support mechanisms, by transforming them into energy storage units.

- PHS is also considered a reliable option for effective post-mining land use transition and the transformation of abandoned open-pits into post-mining assets, and is in line with the European objectives for the transition to climate neutrality by 2050.
- The findings reveal that both sites present viable opportunities for HPHS implementation, which can significantly reduce carbon footprints, improve power supply reliability, and minimise energy transmission losses.

Technical Concept and Design Criteria for HPHS in Open-Pit Coal Mines

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Motivation

To explore an innovative repurposing of the Kardia and Bełchatów-Szczerców open-pit lignite mines in Greece and Poland for HPHS to support renewable energy storage according to the EU Green Deal, a technical concept including the selection of the most suitable areas within the mining license boundaries for the HPHS upper reservoir had to be developed for both mining regions.

Processes

The implementation of advanced GIS and Multi-Criteria Decision Making (MCDM) techniques facilitated the assessment of preliminary suitability for the construction of the upper reservoir, essential for the operation of HPHS, with an emphasis on specific topographic and proximity criteria. Eventually, the most suitable area at each site had to be identified, satisfying all the set criteria. The energy storage potential was included in this consideration, resulting in two locations for each study area with the highest-ranking scores.

Investigations

Geospatial Workflow Development: A semi-automatic geospatial workflow was designed to evaluate potential sites for HPHS in open-pit mines, considering topography, proximity to infrastructure, and environmental constraints.

Preliminary Suitability Evaluation: Utilising the Analytic Hierarchy Process (AHP) for weighting criteria based on expert judgment, seven regions within the Kardia mine as suitable for the upper reservoir, with capacities ranging from 0.6 to 4.8 GWh (Fig. 5).

Innovative Application: An innovative strategy for renewable energy storage is presented, providing a framework for transforming decommissioned mines into valuable resources for the energy transition, consistent with sustainability and regional economic stability objectives. The results for the Kardia mine indicated that 9% of the area has very low suitability, 16% has low suitability, 24% has moderate suitability, 25% has high suitability, and 26% has very high suitability for constructing an upper reservoir. The Bełchatów-Szczerców open-pit was also evaluated, indicating that 13% has very low suitability, 13%

low, 22% moderate, 33% high and 18% very high suitability for the construction of the upper reservoir.

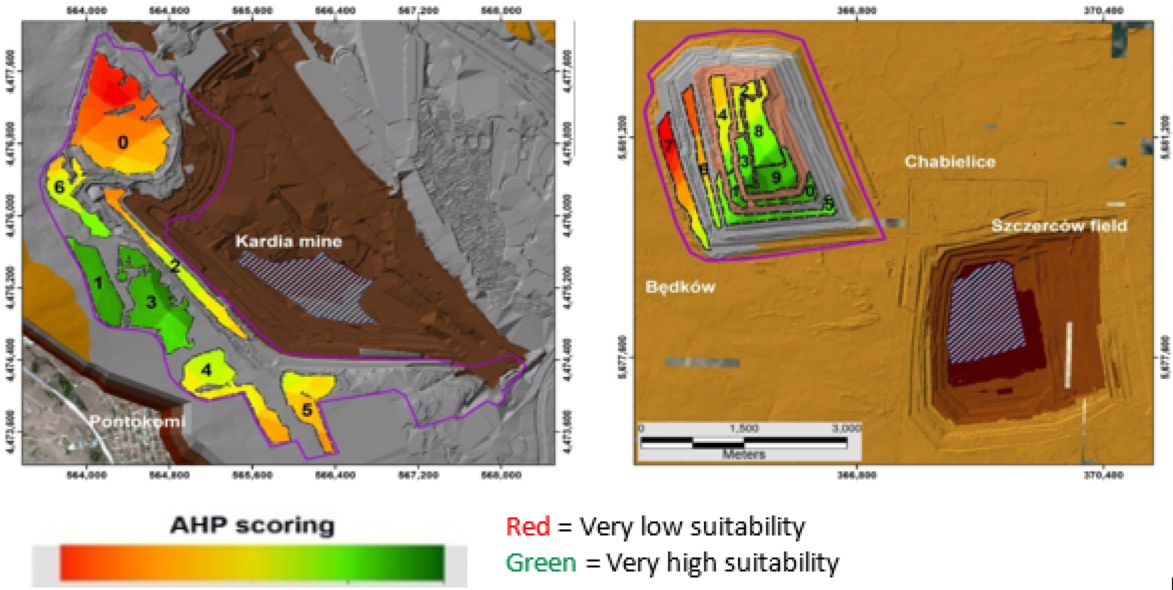

Fig. 5: Colour-coded areas assessing site suitability for upper reservoirs in Greece's Kardia mine (left) and Poland's Bełchatów-Szczerców field (right), based on AHP scoring. Suitability ranges from red (very low) to green (very high), with defined lower reservoir outlined in purple.

Energy Storage Potential: The identified sites offer a significant potential for energy storage, contributing to the stability of the regional power supply and supporting renewable energy integration. It is important to emphasise that regarding the locations deemed most suitable from preliminary feasibility studies, comparisons of efficiency and storage capacity were conducted for both areas. This involved identifying and assessing various alternative surface areas based on topographical suitability criteria, specifically for the implementation of the HPHS upper reservoir within the confines of the open-pit mines. Within the context of the Greek mine, two sites that were identified using the applied methodology have been highlighted in recent pre-feasibility studies, which are currently underway (Krassakis et al., 2023).

Recommendations

- It is recommended to use a Multi-Criteria Decision Making (MCDM) approach integrated with a Geographical Information System (GIS) to find the optimum topological conditions for the open-pit mine under investigation. Hereby, the criteria on the average head elevation difference and energy storage capacity play the most important role.

- A spatial analysis and expert opinions are also crucial for the preliminary selection of the most suitable locations of the upper HPHS reservoir. The spatial analysis should take into account land repurposing planning including agricultural purposes and active and passive recreation (such as biking trails, recreation forest parks, road access networks to the lake, entertainment facilities, etc.).

HPHS Operational Management, Efficiency Optimisation and Power Grid Integration

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Motivation

The PHS facility aims to work as an energy storage unit due to the fluctuating performance of the RES units. Therefore, one main objective was to identify design properties for the energy storage unit based on selected site characteristics, especially energy market demands as well as RES capacity and performance, and region-specific boundary conditions. Also, the probable bandwidth of HPHS operation parameters and its efficiency for each study area under consideration were required, i.e., the Kardia mine in Greece and the Bełchatów-Szczerców mine in Poland, where RES will be coupled with the PHS technology, utilising pit lake water.

Processes

A holistic approach was considered for the HPHS design by defining the HPHS operational management, efficiency optimisation and power grid integration. Basic input data (i.e., RES production, grid stability conditions, available energy budget and demands, topography restrictions, and legislation restrictions) were considered, and different operational scenarios were analysed to identify the fundamental technical concept and design properties for the HPHS facility in the Kardia and Bełchatów-Szczerców exhausted lignite mines. The methodological approach is presented briefly in Fig. 6, illustrating the modelled processes. Different scenarios of optimum conditions were deployed for the optimal planning of the hybrid PHS system, and a sensitivity analysis of the operation schedule optimisation results was performed to deduce conclusions on the design parameters.

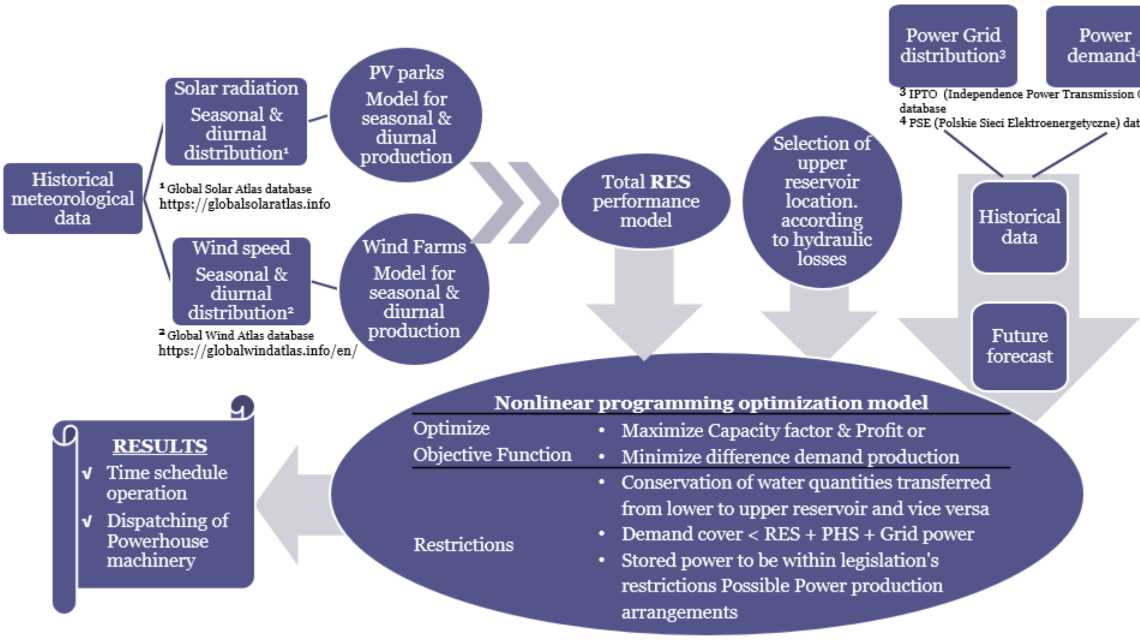

Fig. 6: Flowchart of the methodological approach.

Investigations

In the context of a preliminary feasibility study, an efficiency and storage capability comparison investigation was carried out for the two regions of Kardia and Bełchatów-Szczerców. The following aspects were considered in the scenarios undertaken for both regions: a) specifics of different RES capacities (PV parks and wind farms) prospected to be realised and different feasible portions of this capacity to be supported by the HPHS unit, b) specifics of each study area concerning the suitability criteria for the upper reservoir's location, c) specifics concerning the water level of the lower reservoir and its fluctuation, and d) specifics of different types and dimensions of penstocks.

In the numerical simulations undertaken, the power supply (available and predicted excess energy in the power grid) was considered, as well as the diurnal and seasonal energy demands distributions, the open-flow system, hydrodynamics status (HPHS system provision) based on the geometry of the prospective pit lakes for both study areas and the power supply day-ahead distribution. Diurnal and seasonal distributions of the local power grid and national power grid (corresponding to national demand) were also considered.

The hourly statistical characteristics of solar radiation and wind velocity were analysed to evaluate the diurnal and seasonal variations in the performance of the foreseen RES for each case study. It is derived that the PV output (nominal power) can potentially support a capacity of photovoltaic electricity of 270 MW_p, in the Greek case, and 700 MW_p in the Polish case. Based on the mean wind speed in the Bełchatów-Szczerców mining area and the turbine power output, 46 MW average monthly power output was estimated for the wind farms foreseen.

The potential energy storage per unit m of the daily water level fluctuation (MW/m water fluctuation) is then estimated in relation to the elevation and volume of the pit lake, due to limitations in water level fluctuation in the lower reservoir. According to the results, in the case of the Kardia mine (for a specific pit water level at +540 m a.s.l.) and the alternative of increasing the total head difference by 30 m (placing the upper reservoir in a position outside the excavation), the estimated potential energy storage is increased by about 25%. Additionally, in the case of the Bełchatów-Szczerców mine (for a specific pit water level at +170 m a.s.l.), the estimated potential energy storage was increased by about 20% if the total head difference is increased by approximately 50 m (placing the upper reservoir at +419 m a.s.l. compared to placing it at +373 m a.s.l.).

Different scenarios of optimum conditions were deployed in the non-linear programming optimisation models, where the maximum day-ahead peak performance of RES was considered, and consequently the maximum surplus of RES energy was adopted in the simulations. Therefore, different schemes for the HPHS plant operational schedule during daytime hours were produced for the study areas. As a result, HPHS operational management, efficiency optimisation and power grid integration were realised.

Recommendations

- The HPHS facility should be connected directly to the grid, preferably, via an Ultra High Voltage Centre (UHVC), instead of connecting it to the RES facility. Also, it is recommended that an enhanced optimisation model is used in combination with Neural Network day-ahead predictions and automatisation (Programmable Logic Controller) to cover dynamic calculations in real-time conditions.

- The HPHS facility in the Greek case (Kardia mine) can support 270 MW_p capacity, based on the optimal HPHS design characteristics. To further support the significantly higher prospective RES capacities with the planned PV parks of 1180 MW_p coverage in the Ptolemais area, additional HPHS facilities in the Mavropigi Mine and/or South Field Mine have to be evaluated.

- The HPHS facility characteristics in the Bełchatów-Szczerców field show an advantage over the Greek case due to higher head difference, requiring less storage support demand, and consequently resulting in small fluctuation in the pit lake's level, only. Therefore, it is recommended that the Greek case should consider placing the upper reservoir outside of the open pit to increase the head difference, and hence the stored potential energy. This would also confine the fluctuation of the pit lake's water level and improve the overall geotechnical slope stability.

Potentials for HPHS Implementation in Open-Pit Coal Mines

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Motivation

Decommissioning of lignite mines in the course of phasing-out electric power generation from fossil fuels in the European Union (EU) is one of the strategic key pillars to reduce net greenhouse gas emissions by 55% compared to the 1990 levels until 2030, and achieving climate-neutrality by 2050. This transition involves replacing coal-based energy production with 69% and 80% of renewable energy by 2030 and 2050, respectively (EC, 2020). The need for large-scale energy storage increases with the power production from renewable energy sources. In order to achieve 100% intermittent renewable generation by 2050, more storage projects are required to increase the available share of renewables (EC, 2020). Potentials for the implementation of HPHS need to be investigated along with a technical, economic and environmental assessment of HPHS in the two study areas, taking into account the specific geographical and climatic conditions of each site. The evaluation approach will serve a basis for assessing the HPHS potential for other coal-dependent regions in the European Union in a multi-step and comprehensive site analysis.

Processes

PHS is currently the only large-scale energy storage that has reached full maturity. However, its potential is still limited by the availability of sites which can be overcome by repurposing and implementing PHS in former open-pit mines for excess energy from the electric grid and renewable sources and substantially contribute to energy supply and the overall transition process. Climate goals, energy security, economic diversification and environmental concerns are the key drivers for the transition and should be critically addressed. The HPHS system design criteria depend on site characteristics and energy market demands. These information provide the required insights to develop the fundamental technical concepts and define required installed capacity, storage capacity as well as environmental aspects. Key technical parameters include the dynamic hydraulic head difference, volumetric flows, volume of upper reservoir as well as pump and turbine selection. Therefore, a comprehensive analysis to identify suitable sites for HPHS installations is the first step in the implementation process. This involves assessing factors such as (hydro-)geology, topography, technical and economic feasibility by identifying existing infrastructure and determine the financial viability of nice HPHS system to be implemented. Investigation of hydrogeochemical influences, slope stability within the pit-lake, and land-use conflicts, among various other factors, are site-specific and necessitate comprehensive evaluation for each individual location.

Investigations

Potentials for HPHS implementation in EU coal regions in transition were evaluated using a dynamic potential assessment model developed to determine additionally feasible storage and power production capacities that can be realised from open-pit lignite mines. The model describes the energy storage in terms of both, power production capacity and energy storage capacity by applying theoretical and technical criteria. The investigation was carried out in open-pit lignite mines with a depth of at least 50 m and an areal size above 1 km^2. The minimum power generation had to exceed 50 MW and the total combined pumping and discharging cycle time should be 24 hours in maximum. Potential capacities vary from country to country. Germany has higher potentials due to the presence of larger and deeper mines compared to other countries. An increase of almost 50% in installed power and 90% of storage capacities are feasible by PHS in German open-pit lignite mines. In total, 118 GWh of energy storage potential and about 9.32 GW in the EU (129 GWh and 10.25 GW including calculations for Montenegro, North Macedonia and Serbia which are not yet EU member states) can be realised in open-pit lignite mines, which will be abandoned until the end of the next decade (Fig. 7). That is an increase of about 20% to the currently installed power and more than 45% in the EU storage capacities. With these additional potential installed power capacities, 5% of the 200 GW energy storage capacity that the EU aims to achieve by 2030 (EC, 2023) can be realised by PHS installation in open-pit lignite mines. Depending on the energy policies in place, the model can be optimised for higher storage capacities or power production.

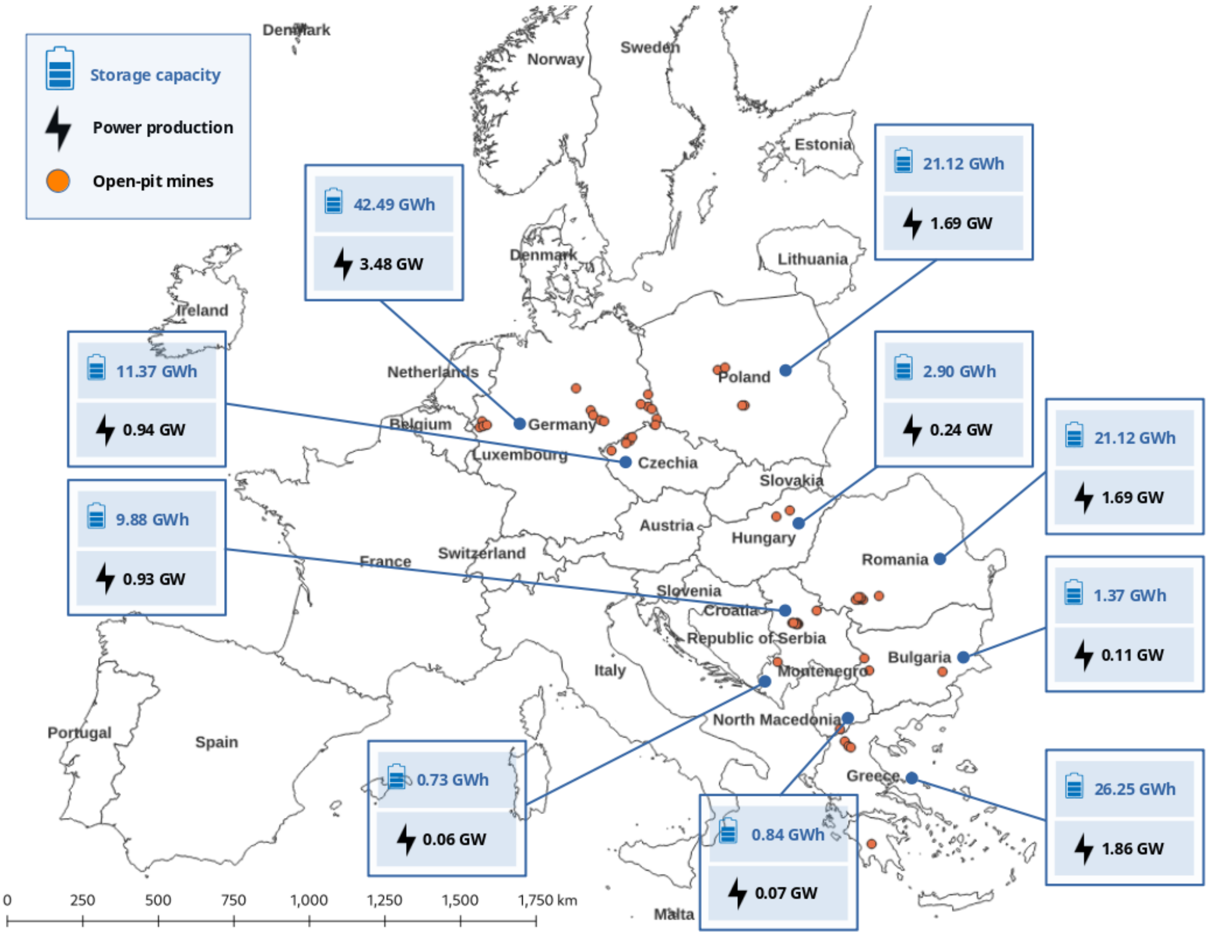

Fig. 7: Distribution of open-pit lignite mines investigated in Europe and the calculated potential energy storage and production capacities per country.

Recommendations

- To obtain accurate estimates of the potential of open-pit mines for HPHS implementation, it is recommended to use data that capture the current mining characteristics as well as planned activities, e.g., mine areal size, mine depths, internal or external dumps, (temporal) flooding planning or other planned restoration measures, etc.
- When using data sourced from existing databases, it is crucial to conduct a thorough verification process to ensure the consistency of the data. This step is essential due to instances where the energy storage metrics, specifically the capacity of energy that can be stored in a reservoir in the form of gravitational potential energy, may be erroneously conflated with the annual energy generation of a PHS system.
- To assess the HPHS potential in a country, data provided at country level should be used whenever possible. If this is not feasible or if no/hardly any data is available, reference data with comparable characteristics can be used and verified against data from other sources, as the data varies from country to country.

Environmental Considerations

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The implementation of the HPHS technology in closed open-pit mines may, under certain circumstances, have a potentially negative impact on the environment. The two main possible environmental risks that should be taken into account when planning the construction of HPHS systems are potential changes in the local groundwater chemistry and geotechnical impacts related to the stability of the reservoir slopes. Both impacts are crucial in the comprehensive quantification of environmental risks for the HPHS systems.

Flooded open-pit mines are usually connected to unconfined aquifers and one of the main concerns of HPHS at such sites is the water exchange between the reservoirs and the surrounding porous medium. Contact of mine water with oxygen during the storage or successive pump and discharge cycles in the open-pit reservoirs may trigger the oxidation of lignite deposit minerals, which consequently may lead to alterations in reservoir hydrochemistry. The wide range of minerals occurring in lignite deposits may change under more oxidative conditions, e.g., pyrite oxidation and sulphate production may occur. This in turn may result in pH variations that can mobilise certain metal elements. Maintaining sufficient water quality during HPHS operations is of paramount importance as future sites must ensure that local groundwater meets relevant national and EU quality standards.

Another important aspect of the environmental assessment of the HPHS systems are potential geotechnical impacts. Those are cross-linked to local hydrogeology, and therefore need to be studied with regard to fluctuating reservoir and groundwater levels. These assessments include the investigation of the embankments with regard to their stability as well as erosion of the bank sediments and of the reservoir subsurface, subsidence processes due to consolidation in the surrounding areas, which are affected by groundwater level changes, and the investigation of the geomechanical interactions in view of induced seismicity.

In the ATLANTIS project, a comprehensive quantification of the environmental risks has been undertaken and recommendations for the region-specific environmental monitoring elaborated for the selected HPHS locations in Poland and Greece including generic ones are listed in the following.

Hydrogeochemical Impacts of HPHS Operation Due to the Potential Release and Migration of Waterborne Contaminants

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Motivation

The flooding of former open-pit lignite mines is often accompanied by the influx of acidic mine waters and elevated metal and sulphate concentrations. These hydrochemical contaminants result from pyrite oxidation in mine dump sediments that have been exposed to oxygen as a result of the mining activities. HPHS operations may cause additional pyrite oxidation in the respective sediments due to the influx of oxygen-enriched waters during pumping and injection cycles, and thus increase the leaching potential of pyrite oxidation products. Acidic reservoir water can enhance the corrosion of metal and carbonate bearing infrastructure used for the PHS plant, such as steel pipes, turbines, or the concrete sealing of the upper reservoir. Also, increased metal and sulphate concentrations pose environmental threats in the reservoirs and adjacent groundwater bodies. Thus, a thorough hydrochemical assessment was carried out for the Kardia mine (Greece) and the Bełchatów-Szczerców field (Poland).

Processes

Pyrite is an iron disulphide that often forms under environmental conditions that favour the deposition of lignite. Due to this mineral's instability under oxidising conditions, the dissociation of the mineral results in the release of acid, iron and sulphate, particularly in the unsaturated zones of the mine dump. Mine flooding and increasing groundwater tables mobilise the contaminants in the mine sediment pore water and transport them into the pit lake and adjacent water bodies. During the HPHS operation, oxygen-rich waters oscillate in the interface layer between the lower reservoir and adjacent (dump) sediments. This enhances subaqueous pyrite oxidation in the reservoir-dump interface layer and leaches the oxidation products into the reservoir.

Investigations

A novel reaction path modelling framework was developed to assess the temporal and final contaminant concentrations in the systems of both investigated sites. Therefore, data obtained during the sampling campaign and the subsequent laboratory work was used. The data comprised chemical compositions of rainwater and groundwater as well as leachates generated during leaching experiments. Additionally, geochemical data from sediment samples were used. The different components of the hydrochemical system were simulated in hydrochemical batch reactors, which were coupled in a reactor network derived from site-specific conceptual models. This enabled a continuous quantification of relevant mineral reactions and balancing the temporal progression of masses and concentrations for all system components. The framework is highly adaptable to site-specific conditions and enables the simulation of several hydrogeochemical scenarios with an efficient calculation method and efficient computational times. The hydrochemical assessment carried out for the Kardia mine (Greece) and Bełchatów-Szczerców field (Poland) shows that the risks associated with the operation of HPHS as well as the potential release and migration of waterborne contaminants mainly include elevated sulphate concentrations in the reservoirs. For the Kardia site, the sulphate concentrations are limited to the reservoir, since there is no contact between the reservoir and its adjacent aquifers (Fig. 8).

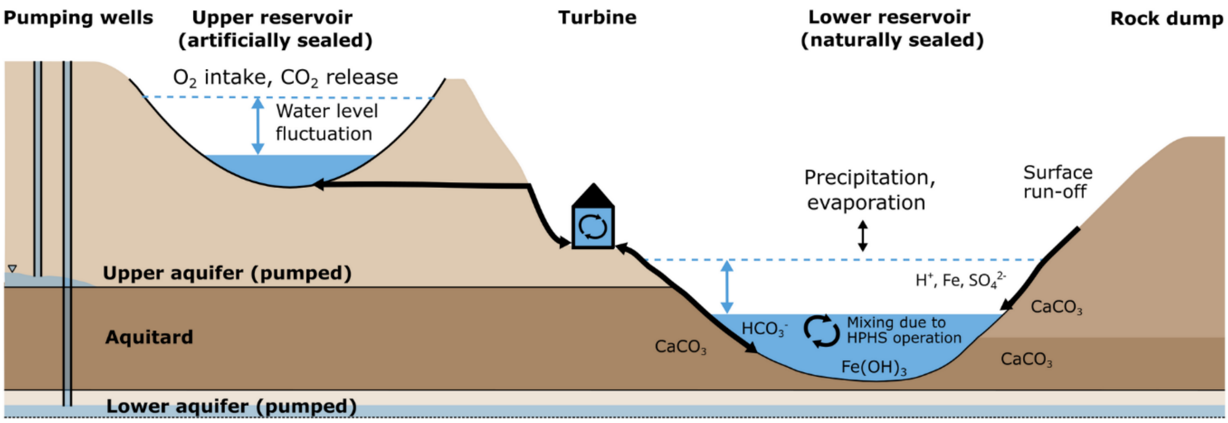

Fig. 8: Conceptual sketch of all hydrogeochemical processes considered in the simulation framework for the Kardia lignite mine. The water balance for Kardia considers surface run-off, precipitation, and evaporation. Around 60% of the water from the lower reservoir is pumped to the upper aquifer, thus a water level change of 6.5 m in the lower reservoir per complete cycle is to be expected. Discharging the water from the UR will lead to a complete mixing in the lower reservoir.

At the Bełchatów-Szczerców mining complex (Poland), the sulphate concentrations are mainly depending on the pyrite availability, pyrite oxidation grade, and the contact between the reservoir and pyrite-bearing formations (Fig. 9). A generic study on different hydrogeological scenarios deduced from data of mainly German lignite mines reveals that the iron and sulphate concentrations can range from 10^{-5} to 10^{3} mg/l and 10^{-1} to 10^{4} mg/l, respectively (Schnepper et al., 2024).

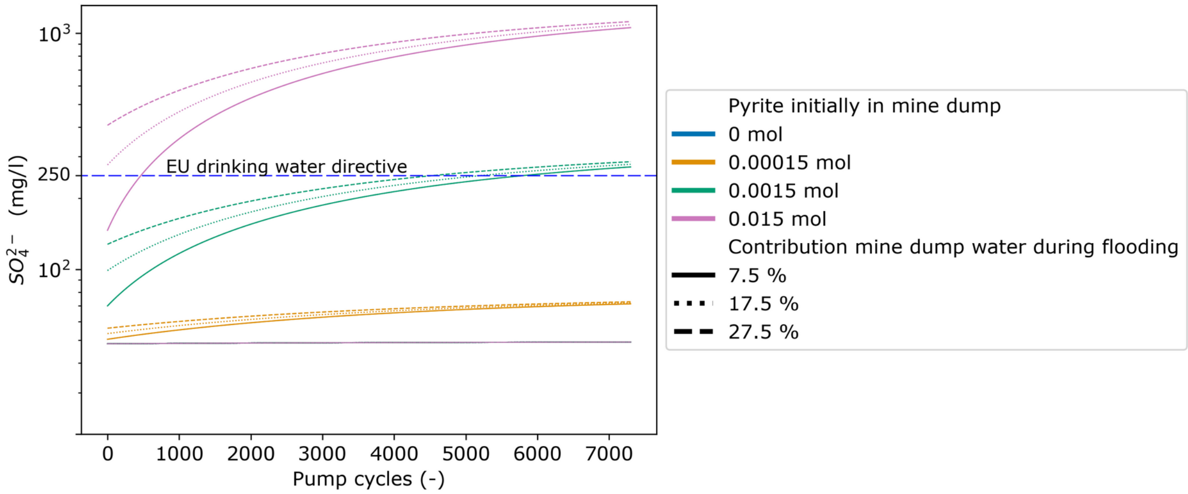

Fig. 9: Development of the SO_4^{2-} concentrations in the lower reservoir of the Bełchatów-Szczerców field considering different initial pyrite concentrations after 7300 pumping cycles.

Recommendations

- The hydrochemical system of the flooded open-pit lignite mine is determined by the local geochemical conditions such as pyrite and carbonate concentrations in the lignite-bearing sediments as well as in the overburden and bedrock. A comprehensive hydrochemical investigation, supported by numerical modelling, is therefore recommended prior to the commencement of HPHS operations to assess potential site-specific impacts on local groundwater resources from waterborne contaminants.

- The impact of the HPHS operation depends on the volume of the water oscillating regularly in the interface layer between the lower reservoir and dump sediments relative to the reservoir size. The simulation results imply that the volume of the oscillating water and amount of pyrite additionally oxidised by HPHS is too small to impact the overall water quality. However, a comprehensive assessment of the mineral composition and penetration depth of the oscillating water and potential atmospheric oxygen in the reservoir-mine dump interface layer is recommended to assess the impact of the HPHS operation on the water quality.

- Hydrochemical impact of pyrite oxidation products can be reduced by limiting the oxygen availability in the pyrite-bearing sediments during excavation and deposition. Sealing the respective sediments with low-permeable sediments or artificial materials is recommended to limit the oxygen availability and the influx of water. Liming the sediments in the discharge area has no influence on the sulphate concentration of the leachate, but can be recommended to buffer the pH value of the leachate.

Geotechnical Impacts of HPHS Operation on Slope Stability, Surface Displacements and Erosion

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Motivation

The imperative shift from fossil fuels to renewables marks a pivotal chapter in energy strategy, heralding a decline in global carbon emissions through the expanded use of wind and solar power. Within this framework innovatively converting disused open-pit mines into HPHS facilities (Fig. 10) offers a dual benefit: bolstering energy storage during low-demand periods and reinvigorating post-mining landscapes. Such transformations require meticulous geotechnical planning, particularly for slope stability under fluctuating water conditions, ensuring safe operation of these sites and seamless integration into the modern energy infrastructure.

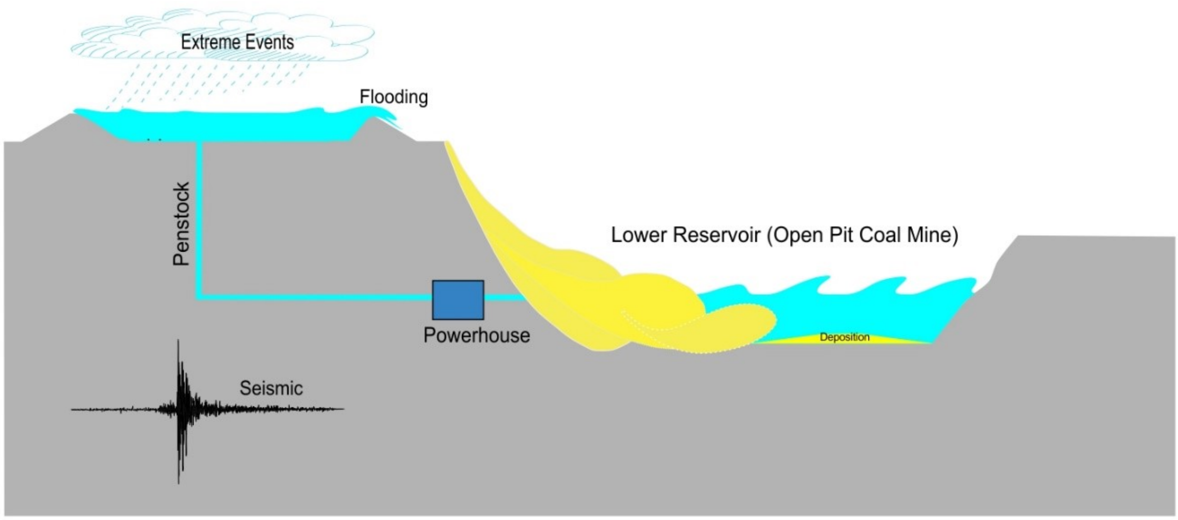

Fig. 10. Conceptual diagram of HPHS in the area of open-pit coal mine and geotechnical risks.

Processes

A main concern in hydropower construction is the safety of the reservoirs with its embankments, dams, and installations, which are mainly controlled by slope stability and bearing capacity in the different operational phases. The main aspects are the stability of the slopes during construction and the stability of the designed slopes for different operational states. Especially the hydrostatic and pore pressures, and their interaction with a controlled groundwater level are besides adequate slope angles the main parameters affecting the geotechnical safety of a HPHS project. Furthermore, the large unsealed lower basin and huge open slope areas, together with basin currents might affect material transport processes at the reservoir slopes and in the reservoir, which must be controlled.

Application of the Finite Element Method (FEM), conducted with well-established commercial software packages, provided a quantitative analysis of potential structural deformations, stress distributions, and displacements within the geological strata. It allowed for the examination of how soil layers of different strength in a stratified geological environment behave under varying load conditions, which is vital for both predictive analyses and the design of interventions. With careful consideration of boundary conditions to reflect the real-world scenarios, the FEM analysis was crucial in visualising the kinetic responses of slopes during both static conditions and potential seismic activities resulting from HPHS operation.

The robustness of these methodologies lies in their capability to address complex geotechnical challenges, including variability in material properties and the intricate interactions between soil layers, hydraulic pressures and seismic forces. This allows to investigate the geotechnical safety of the site as well as geotechnical constructions considering future situations and intermediate stages. The research was grounded on comprehensive geological surveys, providing essential data for the accuracy and reliability of the slope stability evaluations. The analytical processes were rigorously tested against the dynamic conditions associated with reservoir filling, operational demands, and seismic influences, ensuring the safety and longevity of the repurposed mine sites.

Investigations

In assessing the stability of slopes for pumped hydropower storage systems, two geotechnical methods were employed: the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM). LEM determines the Factor of Safety (FoS) by evaluating the balance of driving and resisting forces along potential failure surfaces, essential for pinpointing the minimum safety factor, or Global Minimum Factor of Safety (GFoS). This method was adeptly applied to both the Bełchatów-Szczerców and Kardia mine sites, accommodating their diverse soil conditions and failure surface geometries. The process included adapting to Eurocode 7 standards by calculating the Partial Factor of Safety (PFoS), which accounts for the uncertainties inherent in load and material strength estimates. This alignment with the probabilistic approach of the upcoming revision of the Eurocode 7 yields results that are comparable in accuracy and reliability, thereby enhancing confidence in the structural safety assessments.

The Bełchatów-Szczerców mine presented a complex picture, where both external and internal dump slopes showing remarkable stability against seismic challenges, reaffirming the importance of adept water level management and seismic analysis in ensuring long-term slope stability.

The flow velocity of water pumped by hybrid pumped hydropower storage (HPHS) systems is critical in determining erosion rates, with high velocities generating shear stress that destabilises slopes, especially in low-cohesion soils. This erosion is more pronounced in sandy materials and can result in significant sediment transport across the lake, impacting downstream areas and the broader lake environment. The outcomes from both sites confirm the feasibility of maintaining slope stability during the transition of former mining operations to HPHS facilities.

Recommendations

- Implement comprehensive drainage systems at the Kardia mine to manage groundwater levels and mitigate hydrostatic pressure on slopes. Techniques such as deep well pumping and horizontal drains should be utilised to control groundwater and reduce erosion risks. For both Kardia and Bełchatów-Szczerców mines, careful modulation of lake water levels can strengthen slope stability and prevent erosion.

- Construct foot protection dams or place additional weight at the slope's toe at Kardia to counteract underwater erosion forces. At Bełchatów-Szczerców, compacting internal dump materials is essential for minimising void spaces, thereby enhancing resistance to erosion and ensuring the long-term consolidation of underwater slope sections.

- Design erosion-safe outlets from the penstock/powerhouse to handle high flow rates. Utilise concrete structures, boulders, gravel, and geotextile reinforcements to protect areas prone to higher currents. Regularly monitor slopes for condition changes to proactively address erosion, particularly at Kardia due to greater lake level fluctuations and the smaller water body, necessitating further investigation in conjunction with the power house and lower basin outlet designs.

Quantification of Environmental Risks for Selected HPHS Locations and Recommendations for Region-Specific Environmental Monitoring

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Motivation

Quantifying environmental risks at HPHS locations is crucial for ensuring sustainability as well as minimising ecological impacts and costs. Environmental risks associated with utilising abandoned open-pit mines for HPHS are for instance related to failure of slopes, the upper reservoir or waste dumps, erosion, seismic activity, climatic extreme events and climate change, hydrogeology, hydrogeochemistry, HPHS operation, or self-ignition of lignite in dumps. The possible risks must be identified, assessed, and properly managed to ensure safe and feasible HPHS operation.

Processes

In an approach adopted from the NASA guidelines for risk management (NASA, 2022), a risk assessment was executed in iterative steps. In a first step, relevant environmental risks associated with utilising abandoned coal mine pits for HPHS were identified in a workshop. These were analysed and quantified in a survey, receiving expert ratings of 49 votes for Poland and 34 for Greece. Risk estimation scores were calculated by multiplying the likelihood and consequence scores for each identified risk. Since some risk scores were identical, a priority ranking system for each risk was implemented (Fig. 11), categorising them into low, medium, and high. Analysing over two thousand risk matrices for each study area was required for the overall risk assessment.

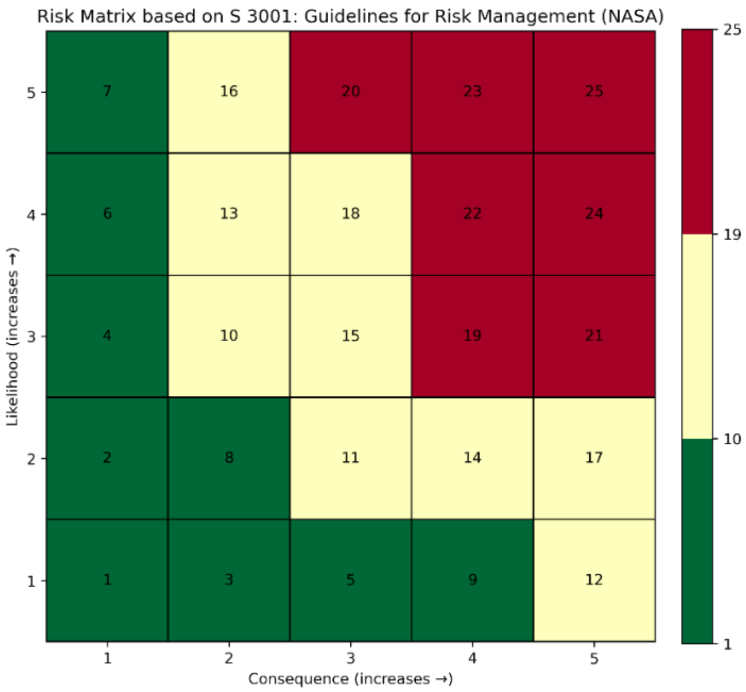

Fig. 11: Three risk levels (low-green, medium-yellow, high-red) based on priority rank.

Investigations

In the comprehensive study, environmental risks were meticulously analysed at two distinct HPHS sites: Kardia mine in Greece and Bełchatów-Szczerców mine in Poland. A thorough examination led to the identification of 60 unique risks, organised into twelve categories according to their characteristics and potential impacts. These risks were further classified as low or medium; the Kardia mine was more susceptible to medium-level risks, whereas the Bełchatów-Szczerców mine predominantly faced risks classified as low. In Greece, the most significant risk identified was slope failure, potentially triggered by the presence of weak layers, severe weather events, seismic activity, or disturbances to the upper reservoir. The Polish site also faced slope failure as a high risk, with contributing factors including weak layers, liquefaction, water leakage, prolonged droughts, and the acidification of reservoir waters and aquifers, which could stem from pyrite oxidation in the absence of natural buffering capacities.

Based on these findings, this study recommends the implementation of tailored, region-specific environmental monitoring programs that emphasise slope stability and groundwater protection.

Recommendations

- Implement structured slopes with benches to enhance existing drainage systems. Integrate erosion control measures and apply hydrological and hydraulic modelling techniques to design and construct effective drainage solutions like catch basins or detention ponds. These structures are critical for managing run-off and reducing pressure on embankments to prevent gully erosion.

- Adjust slope angles and incorporate geotextiles along with slope to fortify stability under varying climate conditions. Improve drainage systems to effectively manage increased rainfall and run-off, and control groundwater levels through strategic pumping or recharge tactics to maintain stable water table levels.

- Address the weak layers in slopes by modifying the angle near the water table, flattening the slope, and constructing benches to facilitate controlled drainage. Employ ground improvement like grouting techniques within the weak layers to reinforce them, and consider relocating or removing loads from the slope's top to reduce stress. For weak layers at the Kardia mine and potential liquefaction at the Bełchatów-Szczerców mine, continuously monitor slopes using DInSAR, GPS and pore pressure sensors.

Economic Considerations

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A detailed assessment using advanced models is required to analyse the value of a storage system. Therefore, a mathematical techno-economic model was developed and applied to calculate the overall economic profitability in an HPHS implementation project and to assess the economic risks due to uncertainties in HPHS operation and geology (e.g., *increase in investment and operating costs due to changes in the interest rate* and *unexpectedly high inflation rates during operation, ground surface subsidence, etc.*), as this is a crucial aspect of project evaluation. A sensitivity analysis was carried out to quantify the possible cost bandwidths. Thus, the model was further employed to determine the impact of variation in grid prices, Capital Expenditures (CAPEX), generated energy, interest rates, Operational Expenditures (OPEX) and other operational time-dependent parameters on the overall profitability by means of the net present value (NPV). The analyses carried out were supplemented by an assessment of the socio-economic footprint, which captures the wider context of the changes that may be taking place in coal regions, including in particular the changes that HPHS technology may bring about. Gross Domestic Product (GDP), employment and welfare analyses carried out capture the economic and social benefits of the HPHS.

Model Parametrisation

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Motivation

Detailed site-specific parameters and technical specifications need to be discussed and defined to apply a mathematical techno-economic model for the assessment of economic risks and the calculation of economic prospects. The details of the model depend on the site-specific boundary conditions and also the available data.

Processes

Model parametrisation in the project was discussed in the Workshop on "*Operational management of HPHS systems in both study areas*" with about 30 participants from research and industry and in bi-monthly follow-up online meetings. The resulting HPHS design and operational approaches developed in the project were integrated into the implemented mathematical techno-economic model. Missing parameters that could not be elaborated from the project were estimated based on data from established hydropower installations and available literature.

Investigations

The techno-economic model has been applied to two historical data sets for the Polish and Greek energy markets to calculate the generated energy, profits, and price spreads of the prospective HPHS system implementations in the two study areas. Parameters such as the total capacity of the upper basin, the hydraulic head difference, electricity generation, and the volumetric flow capacities of the pumps and/or turbines were taken into account to determine the economic prospects. The detailed parameters and technical specifications must be defined for the specific site being investigated and were applied in the mathematical techno-economic model implemented within the scope of the ATLANTIS project are listed in Tab. 1.

Tab. 1: System-related parameters and technical specifications that must be defined and that were used in the developed ATLANTIS mathematical technical-economic model.

System	Parameter	Unit
PHS system	Maximum power	(MW)
	Power (average value)	(MW)
	Head difference	(m)
	Frictional head loss	(m)
	Energy storage capacity	(MWh)
	Energy storage capacity charge	(MWh)
	Energy storage capacity discharge	(MWh)
	Number of turbines	(-)
	Max flow rate charge	(m^3/s)
	Max flow rate discharge	(m^3/s)
	Efficiency charge	(%)
	Efficiency discharge	(%)
	Full-load hours pumping	(hours:minutes)
	Full-load hours discharging	(hours:minutes)
	Penstock horizontal length	(m)
	Diameter penstock	(m)
	Friction factor	(-)
	Density of water	(kg/m^3)
Upper reservoir	Volume	(Mm^3)
	Area	(m^2)
Lower reservoir	Volume	(Mm^3)
	Area	(m^2)
	Lake water level variation	(m)

The economic components of a system consist of CAPEX and OPEX, operation and maintenance as well as replacement costs of the individual sub-systems. CAPEX are considered a primary factor for determining the annual costs of HPHS projects, and these should be evaluated thoroughly during the initial stages of any investment decision. The cost-related and economic parameter values for CAPEX and OPEX considered in the model were assumed and calculated based on literature data.

The review indicates that the CAPEX for HPHS plants vary significantly between projects, as shown by Deane at al. (2009), Steffen (2012), Schoenung et al. (2003), Lacala et al. (2014) and Zakery and Syri (2015), emphasising the significance of considering site-specific conditions and long-term lifespan in planning. For example, assuming a *greenfield* HPHS with a generating power capacity of 150 MW, the CAPEX range from 70.5 to 450 M€.

OPEX are often quoted as a percentage of the investment cost per kW per year. Typical values range from 1-6%. The International Energy Agency (IEA) assumes 2.2% for large hydropower and 2.2-3% for smaller projects, with a global average of around 2.5% (IEA, 2010c). IRENA (2012) calculates OPEX as 2% of the CAPEX. Giesecke (2014) estimated the

OPEX based on empirical values from established hydropower plants in a range of 3-5% of the CAPEX per annum, whereby these can be further subdivided into 0.5-1.5% of the investment share related to the construction costs and 2.5-3.5% of the share attributable to the electrical and mechanical equipment costs.

The figures are inversely proportional, i.e. the larger figures apply to smaller systems and vice versa or the percentage share generally decreases with the system size. Approximately a 1% CAPEX share can be additionally accounted for personnel expenditures (Thema and Thema, 2019). These were considered in the techno-economic model and based on historical data sets (2015-2023) for the Polish and Greek energy markets, potential generated energy, profits, and price spreads of the prospective HPHS system implementation in the two study areas were determined.

Recommendations

- The parameters listed in Tab. 1 (e.g., head difference, reservoir volumes, power capacities, efficiencies, length of penstock, full-load pumping and discharging hours, number of turbines) should be elaborated for the parametrisation of a mathematical techno-economic model.
- Apply dynamic model to consider day-ahead energy market data for optimisation of HPHS economic performance as well as site-specific data from RES to quantify energy generation and storage requirements.
- Monitor technological advances (such as battery storage) and variations in energy demand, as these may affect assumptions of models and ultimately impact potential for energy production and profitability.

Energy Availability

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Motivation

A continuous and reliable energy supply is rarely feasible without energy storage. Energy storage can serve as a backup during times of Dunkelflauten and other emergencies as well as rapid changes in the demand (flexibility). The energy storage system ensures that the surplus energy can be stored when the power generation exceeds demand and can be discharged at times of net load, providing a robust, flexible energy reserve for intermittent renewable energy sources. Following the planned phase out of coal mines in many European countries, abandoned open-pit mines can be repurposed and used as energy storage facilities.

Processes

Historical energy data sets of solar and wind power in combination with the current grid price were analysed for the Greek and Polish study areas to calculate potential energy availability and establish an economic assessment of the feasible HPHS energy production. The developed mathematical techno-economic model was applied to these hourly-discretised data sets (Fraunhofer, 2024), representative for the Greek and Polish energy markets from 2015 to 2023. The "Grid price" scenario provides results on whether energy should be stored or generated based on a comparison of the average hourly electricity price (+/- 12-hour time window) with the actual one. In the second scenario "Grid price and residual load", an additional condition applies: the residual load must also be below its average value to initiate energy storage. The residual load represents the load that cannot be covered by renewable generation, and therefore has to be provided by baseload power plants, electricity imports or storage capacities. Hence, this additional condition ensures that a high share of renewable energy is available in the electric grid, which provides the energy to be stored in the upper reservoir.

Investigations

The modelling results for the Greek study area show a steady increase in energy generation from 2015 to 2023, with slight drops in 2018 and 2019 (Fig. 12). The overall trend is positive, indicating a potential for growth and development of storage technologies in Greece, mainly driven by the ongoing build-out of national renewable energy sources. The significant jump in potential profits in 2022 is a result of the war in the Ukraine and the associated energy crisis, in which prices for electricity and gas on the European market have sharply increased. However, an overall increasing trend can be observed, which started in 2018 with the price spread reaching its peak in 2022. This was mainly caused by the increase in renewable energy production and decrease in contributions from fossil-fuelled power plants.

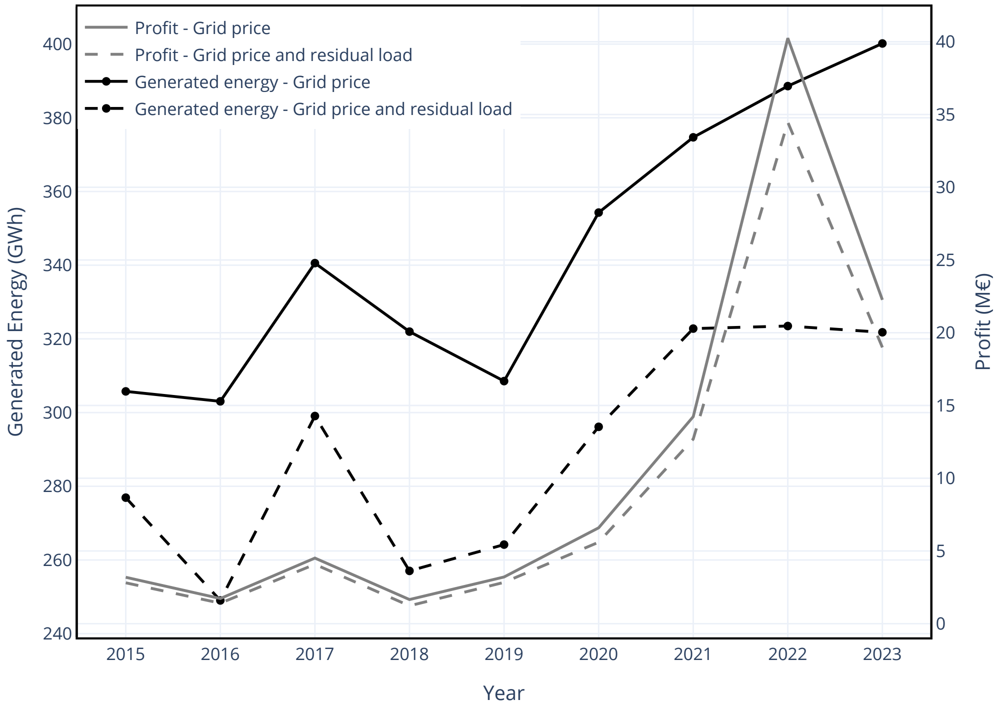

Fig. 12: Comparison of annual generated energy, profit for the Greek energy market from 2015 to 2023 between the two investigated scenarios.

Based on the simulation results of the applied mathematical techno-economic model applied to historical data, an economic HPHS operation is feasible in the Greek and Polish study areas. Even under conservative assumptions of the relevant model parameters, a positive NPV can be attained for both projects. The expansion of renewables will continue to increase, and hence replace conventional energy production, following the generally increasing trend over the years 2015-2023 observed for RES in the EU. As a result, the market is likely to maintain high daily, weather-dependent and seasonal fluctuations in both, the share of renewables in total energy and in grid costs, from which an HPHS system will obviously benefit.

Recommendations

- It is recommended to use site-specific historical data from renewable energy sources in order to estimate the order of magnitude of potentially generated and storable energy to calculate the economic viability.
- In addition, it is recommended to stay informed of technological advances and changes in national energy demand, as these may affect the assumptions of the mathematical techno-economic model and ultimately influence the potential for energy production and profits.
- By constantly monitoring new developments on energy storage, additional costs that may arise due to operational, environmental and changes in legislative frameworks generally market-related can effectively be reduced.

Cost Analysis and Financial Viability

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Motivation

The advantage of HPHS in abandoned open-pit mines is that it makes use of already existing infrastructure, initially reducing the costs the presence of at least one reservoir. Energy storage can extend the capabilities of existing power plants and electric infrastructure by deferring costs of building new ones. Energy can also be stored when it costs less, during off-peak hours, and be discharged when electricity costs are high. The overall costs for HPHS projects and their reliability are highly influenced by the site design, and thus required a preliminary site-specific assessment of the economic viability.

Processes

For the economic assessments undertaken in the ATLANTIS project, a mathematical techno-economic optimisation model was developed for a generic HPHS design and dynamic operation as well as its integration with excess electric energy availability and grid demand. A set of implemented criteria, including country-specific day-ahead electricity grid prices, available storage capacities and residual load must be fulfilled in the model to initiate energy generation or storage. Charging and discharging cycles of an integrated HPHS system can be dynamically determined using historical energy market data (2015-2023). The model used in the ATLANTIS project accounts for losses incurring during the process of charging the upper reservoir when excess energy from renewables and the electric grid is available as well as discharging the upper reservoir for electricity generation when the demand exceeds energy availability (Fig. 13).

The techno-economic model has been applied to two historical data sets for the Polish and Greek energy markets to calculate the generated energy, profits and price spreads of the prospective HPHS system implementations. The model was used to determine the impacts of the variation in grid prices, CAPEX, generated energy, interest rates, OPEX and other operational time-dependent parameters on the overall profitability represented by the Net Present Value (NPV).

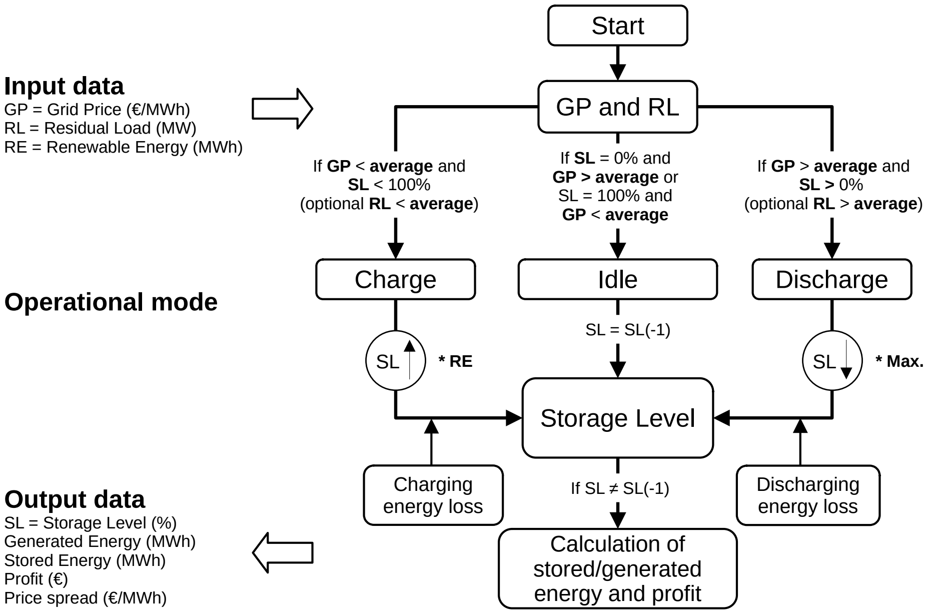

Fig. 13: Flow chart of developed mathematical techno-economic HPHS model used to optimise operational modes based on actual day-ahead grid prices and actual residual load.

Investigations

Evaluating economic key parameters is crucial to determine the economic feasibility of a project. Therefore, a sensitivity analysis was carried out to assess the impact of key parameter changes on the NPV by varying their values by ±50% in ten single steps. Consequently, the risks identified for the ATLANTIS projects sites have been classified into five thematic categories: CAPEX, Generated energy, Interest rate, OPEX and Operational time. This categorisation facilitates a comprehensive examination of the individual impacts of each risk on the overall profitability of HPHS operation in the two study areas by means of the sensitivity analysis. In the site-specific economic modelling assessment, the Kardia site was assigned with CAPEX of € 142 million, while an annual energy generation of 344 GWh was estimated. On the other hand, for the Bełchatów-Szczerców site, CAPEX of € 368 million and an estimated annual energy generation of 837 GWh were applied. Both sites were assumed to operate at an interest rate of 4.5% for 30 years, whereby OPEX were assumed as 3% of the CAPEX.

The sensitivity analysis results are displayed in a spider diagram, showing the outcomes of varying the five identified categories in which the risks are organised (Fig. 14).

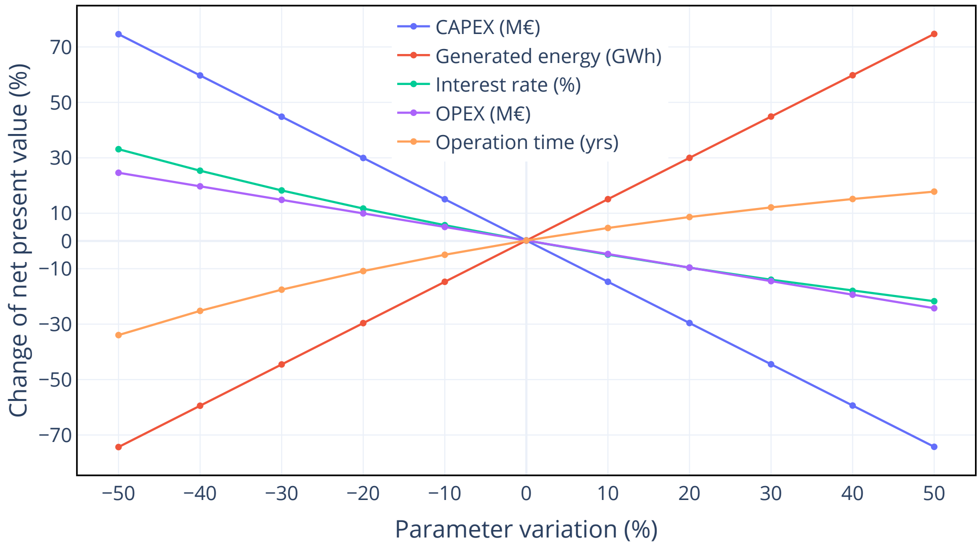

Fig. 14: Sensitivity of the NPV for a variation of ±50% of the key parameters.

The robustness of the system with regard to different key parameters was tested for variations of ±50% in ten single steps. The selected input parameters for the sensitivity analysis can be considered as conservative due to the overall upward trend of the electricity prices. The sensitivity analysis conducted for both projects demonstrates that risks related to higher CAPEX and lower generated energy pose the greatest risk to overall profitability. In addition, an increase in OPEX and interest rates during the 30-year operational period were identified as the second highest risks. However, these risks can be mitigated by extending the operational period. The CAPEX risks are higher for the Polish site, as the larger distance between reservoirs and higher capacity result in an increase by approximately 200 €/kW in the costs per unit of power compared to the Greek site. The findings of the site comparison also reflect the greater profitability potential of the Polish site due to its higher energy storage capacity, which results in a notable increase in the NPV.

In conclusion, the proposed ATLANTIS HPHS approach is a viable option for both the Greek and Polish study areas, with the potential for significant Return Of Investment (ROI). However, further analysis of the investment costs are required at the final design stage for the successful implementation of both projects. The ATLANTIS project has improved the state-of-the-art by demonstrating that HPHS in open-pit mines is a feasible and economically viable option for storing excess renewable and grid energy.

Recommendations

- The long-term financial viability and potential benefits of the technology has to be demonstrated to attract investors and secure funding for HPHS expansions.
- Cost-benefit-analyses for specific region should be undertaken as the costs are site specific. The analyses must align with regional and national legislative frameworks.
- For a successful and economic HPHS implementation, it is recommended to further analyse the investment costs in the final planning phase.

Economical Risks and Resulting Possible Cost Bandwidths

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Motivation

Pumped hydropower storage is considered the most mature and cycle-efficient technology with the lowest annual operation and maintenance costs compared to other energy storage technologies (Xu, et al., 2020). However, for the technology to be implemented effectively, also considering the integration of renewable energy sources, it is required to identify and manage risks as early as possible in a project, so that appropriate prevention measures can be timely implemented, and consequently to circumvent the costs for mitigating the consequences. Uncertainties such as market structure and grid price variability, variable renewable energy integration, governmental incentives in the form of subsidies, and legislative regulations can pose a challenge for proposed pumped hydropower storage projects. Therefore, a better understanding and quantification of these risks is needed to determine the economic effects of HPHS implementations at regional-scale and to quantify possible cost bandwidths based on region-specific geological, operational and economic uncertainties, simultaneously improving the efficiency of the project investment.

Processes

There are many approaches that can be used to assess risks in a project. The assessment can be applied to either the entire project for an overview of all risks or to specific project activities. The ATLANTIS project adopted and modified the NASA guidelines for risk management (NASA, 2022) to undertake a comprehensive risk assessment, which was executed in iterative steps (Fig. 15). The exchange of information between the individual process steps was regularly communicated, integrated, and fed back.

The risk assessment adopted consists of four steps: identification, estimation, prioritisation and mitigation (Fig. 15). A detailed description of these steps can be found in NASA (2022).

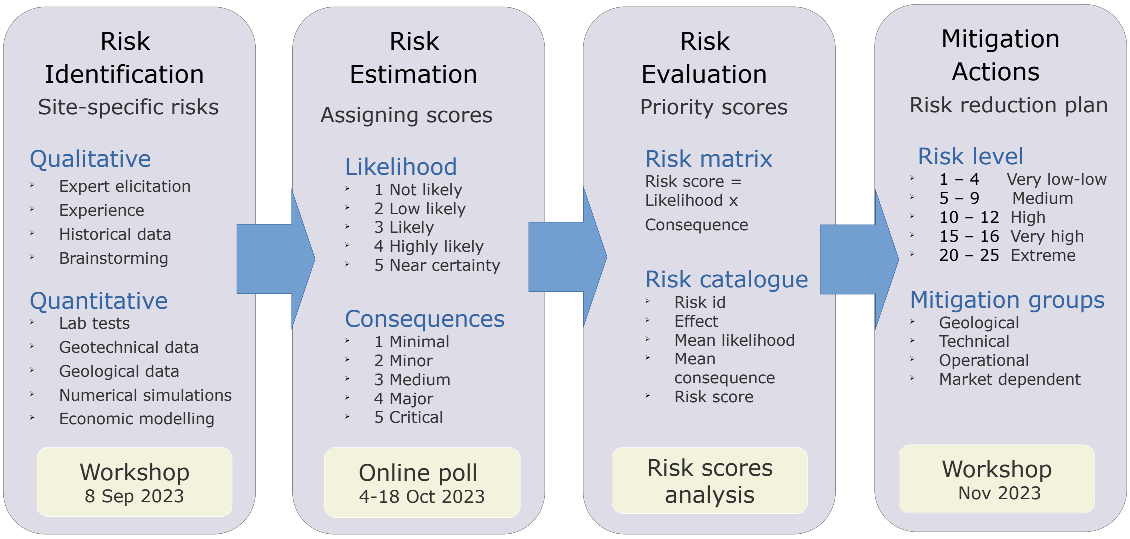

Fig. 15: Comprehensive risk assessment workflow adopted from NASA (2022) and implemented in the ATLANTIS project.

Investigations

The aim of the study was to assess the potential economic risks arising from the environmental, technical and operational uncertainties in view of the overall HPHS system profitability for the study areas of the ATLANTIS project. A semi-quantitative risk assessment (NASA, 2022) was adapted to meet the project's requirements and used for the identification of potential risks, estimation and evaluation of their likelihoods and consequences, to determine suitable mitigation actions to reduce their overall severity. Qualitative and quantitative methods were used to assess the site-specific risks for the regional-scale HPHS implementation at two prospective sites investigated in the project. Site-specific risks with priority scores ≥8 were further analysed and suitable mitigation actions determined. In spite of the low environmental concerns posed by the identified risks with score rankings below 8, it was decided to limit mitigation actions to close monitoring of these, only, so that timely actions can be taken if negative impacts occur. Scenarios were developed and grouped into the categories as depicted in Fig. 14.

Based on these, sensitivity analyses on the prospective HPHS projects were conducted to assess the impacts of economic key parameters on the NPV in both study areas. Thence, resulting cost bandwidths were determined, allowing for a cost-efficient HPHS implementation.

Recommendations

- Challenges related to the implementation of HPHS projects can be overcome by thoroughly assessing site-specific risks in advance. The use of current site data as a basis for the risk assessment is essential and highly recommended, since it allows for more accurate predictions of the required mitigation and monitoring actions.
- Intensive communication and coordination among project partners and stakeholders is recommended throughout the project duration to comprehensively

address environmental, technical and operational risks. Regular exchange ensures that relevant site-specific information from the experts is included in the risk assessment and can be reliably addressed when minimising risks.

- The use of multiple risk analysis tools and the consideration of different criteria and approaches is recommended to enhance the overall risk assessment reliability. The threshold for extreme risks or risk unacceptability is always site- and project-dependent. To assign appropriate threshold rankings to the identified risks in the project, it is crucial to discuss these aspects with the relevant experts.

Socio-Economic Footprint

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Motivation

The transition of coal regions into sustainable energy landscapes is a pivotal chapter in the European Union's energy strategy, highlighting a shift towards sustainability with significant socio-economic implications (European Commission, 2014). This transformation is exemplified by the integration of HPHS systems into former coal mines, which transcends mere repurposing of these sites to become epicentres of socio-economic revitalisation. These initiatives not only leverage the existing infrastructure and potential for renewable energy integration but also significantly enhance regional development. A comprehensive evaluation of the socio-economic footprint is central to these projects, quantifying benefits like economic growth, job creation, and improved community well-being, thus offering a progressive model for global sustainable development. The broad analysis of economic, demographic and market data provides deep insights into the sustainable potential of repurposed mining landscapes, serving as a guide for stakeholders from local to international levels in scaling sustainable energy solutions.

Processes

A socio-economic footprint refers to the comprehensive measure of the impact that activities, especially in sectors like energy, have on society and the economy. This concept aims to quantify how such activities affect employment, income distribution, economic growth, and social welfare (Jie et al., 2023). It encompasses the broader implications of transitions or changes within specific sectors on the overall social fabric and economic structures. There is no specific and universal method for calculating the socio-economic footprint. For the ATLANTIS project, the adopted approach presented by The International Renewable Energy Agency (IRENA; Garcia-Casals, 2019) was used, which was adapted to take into account the availability of data for the local level, i.e. the study areas (Fig. 16).

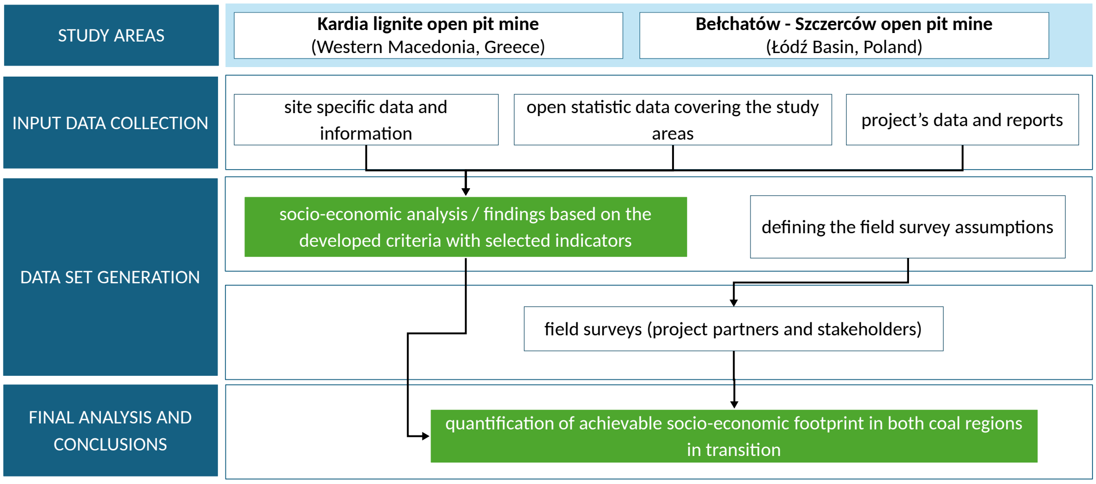

Fig. 16: Approach to socio-economic footprint analysis and calculation of the ATLANTIS RFCS project.

The process of calculating the socio-economic footprint in the ATLANTIS project involves three main stages:

- Input data collection, which reviews the project's findings and calculations to date, collects available statistical data and reviews local and regional policies relating to the study areas, with a particular focus on transition issues.
- Data set generation. At this stage, the information collected was systematised, some of it was processed into questions for a survey to gain a better understanding of the public perception of HPHS technology development in relation to the ongoing transition process. The remaining quantitative data were used to estimate changes in the dimensions of the socio-economic footprint.
- Final analysis and conclusions, is the stage in which the estimation and analysis of the carbon footprint for the study areas is carried out. In addition, the calculations undertaken are supplemented with the results from the survey.

The main limitation of the calculations carried out is the lack of detailed, location-specific data. Hence, it was necessary to adopt estimates; another limitation is the lack of investment decisions, which affects the accuracy of the calculations. Difficulties in obtaining responses to the undertaken surveys due to the lack of public awareness of the transition cannot be either overlooked.

Investigations

The approach for calculating the socio-economic footprint for the implementation of the HPHS technology started with the identification of metrics used to describe the three main dimensions of the footprint, i.e. (1) economic growth, which is expressed as GDP (Pollitt, 2014), but for the purpose of the project municipal revenues were used, (2) employment, which is measured in terms of the proportion of the working population compared to the total population, and (3) well-being, which is described in terms of the estimated mortality costs of carbon (Bressler, 2021) and social costs of carbon. The required data from 2021 were then collected for both study areas, and an estimation of changes in indicator values was carried out using available statistical data and experts' analyses, which determined the possible influence of HPHS technology related factors on the development of socioeconomic footprint indicators. Based on this, projections of the development of the socio-economic footprint up to 2050 were made. Fig. 17 presents the results obtained for one of the study areas at the time of writing this report.

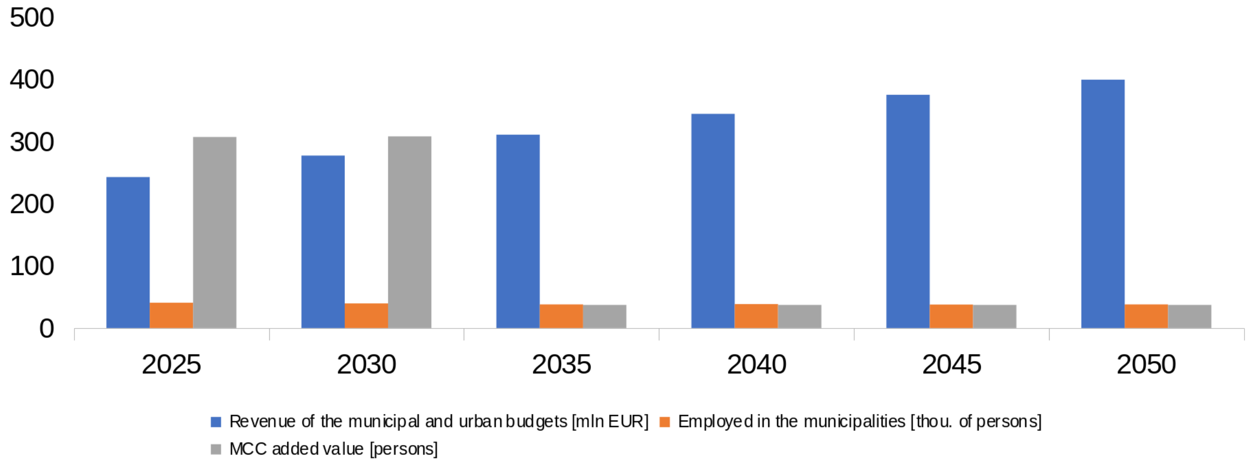

Fig. 17: Tesults of socio-economic footprint assessment for one of the study areas at the time of writing the present report.

The analysis indicates that the projected socio-economic footprint in terms of economic growth and employment will remain relatively constant (if the transformation plan is implemented as foreseen, assuming of course that this is the case). Major changes can be seen in relation to well-being, where the social costs associated with CO_2 emissions are significantly reduced due to, for example, improvements in the health of the population or the adaptation of land for recreational and tourism purposes. With the implementation of HPHS technologies, additional (greater than estimated) effects are expected according to experts: economic growth and employment.

Recommendations

- The implementation of HPHS systems in former coal mines can play a pivotal role in revitalising local economies. By repurposing existing infrastructure for renewable energy storage, HPHS technology stimulates economic growth, attracts new investments, and creates employment opportunities, thereby fostering a sustainable transition away from coal dependency.

- The conversion of open-pit coal mines into HPHS facilities contributes significantly to socio-economic development. This transformation leads to job creation, not only during the construction and operational phases but also in ancillary services and industries. It positively impacts local communities by improving overall living standards and providing new avenues for economic activity, thus reducing the socio-economic gap in transitioning regions.

- The successful implementation of HPHS systems requires active engagement and collaboration among policymakers, energy sector stakeholders, and local communities. It underscores the importance of adopting inclusive policies that address the needs and concerns of affected communities, ensuring that the transition to a sustainable energy future is equitable and inclusive.

Conclusions

The ATLANTIS project explored the potential of utilising abandoned open-pit coal mines as HPHS facilities. The findings from technical, economic and environmental studies were applied to design and evaluate commercially-viable HPHS sites that comply with EU environmental directives. The approach involves comprehensive site identification and assessment for HPHS suitability, including systematic mapping and evaluation of open-pit coal mines. The methodology emphasises the long construction times, high investment requirements, and the necessity for robust and transparent market regulations and authorisation procedures to mitigate risks and uncertainties. Regarding the role of HPHS as an energy storage resource, the project elaborated on associated challenges and opportunities, key factors influencing storage operations, and the regulatory framework. The main findings and recommendations regarding the current status of HPHS can be summarised as follows:

- Economic, environmental, and social factors are crucial in evaluating hydropower potential, requiring a comprehensive and standardised quantification at global and continental scales (IHA, 2023).
- Long construction times and high investments pose risks for new PHS projects, particularly large ones. The EU should implement robust market regulations and transparent authorisation procedures to reduce legislative delays and uncertainties (IHA, 2023).
- The EU should leverage its strengths in research, innovation, and market development to enhance hydropower stability and technology. Policymakers need to create mechanisms that reward system flexibility to increase hydropower capacity (IHA, 2023).
- Comprehensive site identification and systematic mapping of potential HPHS sites are recommended to support sustainable infrastructure and improve energy policy decisions.
- The integration of intermittent renewable energy sources with PHS plants should be significantly increased. Accelerating renewable energy expansion through faster authorisations will aid this process.
- Given the limited potential for hydropower expansion, modernising infrastructure and exploring unconventional sites like decommissioned open-pit mines are recommended to overcome capacity and topographical limitations.
- Screening former open-pit mines for HPHS potential is necessary due to the significant capacity available from closed coal mining sites. This should include assessing nearby renewable energy installations and infrastructure.

- HPHS projects in open-pit mines may impact groundwater through mineral oxidation and release. Thorough hydrogeological and hydrochemical assessments supported by numerical modelling are recommended to understand these impacts.
- To utilise abandoned open-pit mines for HPHS, governments must create financial and market incentives, streamline permitting processes, and embed sustainable practices in regulations (Quaranta et al., 2023).
- At EU level, a detailed and clear legal framework should be established for both PHS and the different types of HPHS (solar, wind, etc.) to facilitate the construction of new installations in the member states through appropriate directives.

The successful transformation of open-pit coal mines into HPHS facilities depends on careful design. Several significant parameters must be considered during the design process. One crucial factor is the required head difference between the upper and lower reservoirs. Additionally, geotechnical evaluation of slope stability and remote sensing monitoring before construction and during operation are essential. Effective HPHS operational management, efficiency optimisation, and power grid integration are also critical components of the design. The main findings and recommendations can be summarised as follows:

- Open pits can store significant amounts of water, providing large reservoirs and substantial energy storage capacities due to the head elevation difference between upper and lower reservoirs. Pit lakes can thus be transformed into energy storage units.
- Transforming abandoned open pits into HPHS facilities supports effective post-mining land use and aligns with European climate neutrality objectives for 2050.
- The investigations in ATLANTIS confirm the feasibility of using decommissioned open-pits for renewable energy storage, providing a plan for energy transition. Further research and development, including comprehensive technical and economic feasibility studies as well as geotechnical and surface deformation monitoring, are recommended.
- The Kardia mine in Greece and the Bełchatów-Szczerców mine in Poland are suitable for HPHS facilities. However, the applied optimisation models need enhancement to account for dynamic real-time conditions and load predictions.
- In the event that the HPHS supports an Ultra High Voltage Center (UHVC), there is a significant advantage in terms of energy storage capacity if support is provided exclusively for RES generation.
- The HPHS facility at Kardia mine supports only 270 MW_p capacity. To accommodate additional capacity, such as 1180 MW_p from PV parks in Ptolemais, further evaluation of additional HPHS facilities at Mavropigi and South Field Mines is necessary.

Several factors must be considered to identify potential risks to human health, the environment, and infrastructure prior to any HPHS operation, and to minimise these risks through appropriate measures before and during implementation. One crucial environmental issue associated with open-pit coal mines is slope instability and surficial damage. Additionally, hydrochemical alterations of pit lakes, ground uplift, induced seismicity, and contamination of surface and adjacent aquifers due to the possible reactivation of pre-existing geological features, such as fault zones, are significant concerns. The main findings and recommendations are as follows:

- The hydrochemical system of flooded open-pit lignite mines is influenced by local geochemical conditions. Comprehensive hydrochemical investigations and numerical modelling are recommended to assess potential site-specific groundwater impacts before HPHS operations.
- The hydrochemical impact of HPHS operations on adjacent water bodies depends on water oscillation between the reservoir and sediments. While simulations show minimal water quality impact, a detailed assessment of mineral composition and water penetration is necessary.
- Limiting oxygen availability in pyrite-bearing sediments can reduce oxidation impacts. Sealing sediments and liming discharge areas are recommended to manage leachate pH without affecting sulfate concentration.
- Slope stability and erosion can be managed through proper design and additional measures. Constructing foot protection dams or placing additional weight at the slope's toe at Kardia is recommended to counteract underwater erosion forces and instability. At Bełchatów-Szczerców, compacting internal dump materials is essential to minimise void spaces, enhance erosion resistance, and ensure long-term slope consolidation.
- Adjust slope angles and incorporate stabilising measures to enhance slope stability. Improve drainage systems to manage rainfall and run-off, and control groundwater levels through strategic pumping or recharge.
- Modify slope angles, flatten slopes, and structure slopes with benches to enhance stability and drainage situation. Use, e.g., grouting or geotextiles to reinforce weak layers and remove loads from the slope top to reduce stress. Integrate erosion control measures and use hydrological and hydraulic modelling to design effective drainage solutions like catch basins and detention ponds.
- Implement comprehensive drainage systems using deep well pumping and horizontal drains to manage groundwater and mitigate hydrostatic pressure. Modulate lake water levels at Kardia and Bełchatów-Szczerców to enhance slope stability and prevent erosion. Design erosion-safe outlets using concrete, boulders, gravel, and geotextile reinforcements for high flow rates. Regularly monitor slopes, especially at Kardia, to address erosion due to lake level fluctuations and coordinate with powerhouse and lower basin outlet designs.

The transformation of open-pit coal mines into hybrid pumped hydropower storage (HPHS) facilities offers significant potential for renewable energy storage and regional economic revitalisation. To achieve this, it is crucial to implement regular workshops and meetings to integrate project findings and develop a comprehensive mathematical techno-economic modelling framework. Utilising site-specific historical data and the consideration of technological advances will enhance the accuracy of economic viability assessments. Active engagement and collaboration among stakeholders are essential to ensure the success and sustainability of HPHS projects, fostering an equitable transition to renewable energy. The main findings and recommendations are as follows:

- Implement a mathematical techno-economic modelling framework tailored to the specific requirements of HPHS development for storing excess energy from renewable sources.
- Use site-specific historical data from renewable energy sources to estimate the potential generated and storable energy, aiding in economic viability calculations.
- Keep informed about technological advancements and changes in national energy demand, as these can influence the assumptions and outcomes of the techno-economic model.
- Continuously monitor new developments in energy storage to reduce additional costs related to operational, environmental, and legislative changes. Ensure active communication and collaboration among project partners, policymakers, energy sector stakeholders, and local communities to address environmental, technical, and operational risks effectively.

References

Australian National University (2024). Accessed: 18/03/2024. URL: https://re100.anu.edu.au/#share=g-86017342a9043e28d084d3f46ca2734a.

Breeze, P. (2019). Chapter 10 - Power System Energy Storage Technologies, Editor(s): Paul Breeze, Power Generation Technologies (3rd Edition), Newnes, p. 219-249, doi: 10.1016/B978-0-08-102631-1.00010-9.

Bressler, R.D. (2021). The mortality cost of carbon. Nature Communications 12, 4467. https://doi.org/10.1038/s41467-021-24487-w

Commission Recommendation of 14 March 2023 on Energy Storage (2023). Underpinning a decarbonised and secure EU energy system 2023/C 103/01. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023H0320%2801%29

Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31992L0043

Deane J.P., Ò'Gallachóir, B., McKeogh, E.J. (2010). Techno-economic review of existing and new pumped hydro energy storage plant. Renewable and Sustainable Energy Reviews 14: 1293-1302.

Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

Directive (EC) 2000/60 of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Available online: https://eur-lex.europa.eu/eli/dir/2000/60/oj

Directive (EC) 2009/147 of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (Codified version). Available online: https://eur-lex.europa.eu/eli/dir/2009/147/oj

Directive (EU) 2011/92 of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0092.

Directive EU 2014/52 of the European Parliament and of the Council of 16 April 204 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0052

Energy storage website (2023). Accessed: 19/03/2024. URL: https://energy.at-site.be/storage/.

EU (2018). Guidance on The requirements for hydropower in relation to EU Nature legislation Luxembourg: Publications Office of the European Union, 2018.

European Commission (2014). IMPACT ASSESSMENT, a policy framework for climate and energy in the period from 2020 up to 2030, {COM(2014) 15 Final} {SWD(2014) 16 Final}, in European Commission Report (2014).

European Commission (2020). Commission staff working document impact assessment part 2/2: Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people, {COM(2020) 562 Final. - {SEC(2020) 301 Final. - {SWD(2020) 177 Final. - {SWD(2020) 178 Final., vol. 5, no. 2, pp. 40–51, 2020. https://eur-lex.europa.eu/resource.html?uri=cellar:749e04bb-f8c5-11ea991b01aa75ed71a1.0001.02/DOC_2&format=PDF

European Commission (2023). Commission staff working document: Energy Storage- Underpinning a decarbonised and secure EU energy syytem. SWD(2023) 57 Final. https://energy.ec.europa.eu/document/download/12624902-59aa-483f-ade8-d5861181fdd3_enfilename=SWD_2023_57_1_EN_document_travail_service_part1_v6.pdf

Fraunhofer (2024). https://energy-charts.info.

Garcia-Casals, X., Ferroukhi, R. & Parajuli, B. (2019). Measuring the socio-economic footprint of the energy transition. Energy Transition 3, 105-118. https://doi.org/10.1007/s41825-019-00018-6

Giesecke, J., Stephan Heimerl, S., Mosonyi, E. (2014). Wasserkraftanlagen: Planung, Bau und Betrieb, 6. Auflage.

Hunt, J. D.; Zakeri, B.; Lopes, R.; Barbosa, P. S. F.; Nascimento, A.; Castro, N. J. d.; Brandão, R.; Schneider, P. S.; Wada, Y. (2020). Existing and new arrangements of pumped-hydro storage plants. Renewable and Sustainable Energy Reviews, 129:109914.

IEA – International Energy Agency (2010). Energy Technology Perspectives 2010, OECD/IEA, Paris.

— (2023). ETP Clean Energy technology Guide – Data tools. Accessed: 25/03/2024. URL: https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.

— (2021). Innovative Pumped Storage Hydropower Configurations and Uses – Capabilities, Costs & Innovation Working Group. World Hydropower Congress 09/2021.

— (2022). Hydropower Status Report Sector trends and insights, IHA Central Office, United Kingdom.

— (2022a). World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

— (2022b). Pumped Storage Tracking Tool; online: https://www.hydropower.org/hydropower-pumped-storage-tool; IHA: Paris, France, 2022.

IHA – International Hydropower Association (2023). World Hydropower Outlook. Opportunities to advance net zero; International Hydropower Association, London, United Kingdom, 2023.

International Renewable Energy Agency (IRENA) (2012). Renewable energy technologies: Cost analysis series. Volume 1: Power Sector, Issue 3/5, June 2012.

Javed, M. S.; Ma, T.; Jurasz, J.; Amin, M. Y. (2020). Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. Renewable Energy, 148:176-192.

Jiang, D., Shao, C., Wenhao, L., Yiwei, R., Pengyv, G., Zongze, L. (2021). Underground Hydro-Pumped Energy Storage Using Coal Mine Goafs: System Performance Analysis and a Case Study for China, Frontiers in Earth Science 9, doi: 10.3389/feart.2021.760464.

Jie, H., Khan I., Alharthi, M., Zafar, M.W. & Saeed, A. (2023). Sustainable energy policy, socio-economic development, and ecological footprint: The economic significance of natural resources, population growth, and industrial development. Utilities Policy 81, 101490. https://doi.org/10.1016/j.jup.2023.101490.

Jinyang, F.; Heping, X.; Jie, C.; Deyi, J.; Cunbao, L.; Tiedeu, W. N.; Ambre, J. (2020). Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs. Applied Energy, 258:114007.

Kitsikoudis, V.; Archambeau, P.; Dewals, B.; Pujades, E.; Orban, P.; Dassargues, A.; Pirotton, M.; Erpicum, S. (2020). Underground Pumped-Storage Hydropower (UPSH) at the Martelange Mine (Belgium): Underground Reservoir Hydraulics. Energies, 13, 3512. doi: 10.3390/en13143512.

Krassakis, P.; Karavias, A.; Zygouri, E.; Roumpos, C.; Louloudis, G.; Pyrgaki, K.; Koukouzas, N.; Kempka, T.; Karapanos, D. (2023). GIS-Based Assessment of Hybrid Pumped Hydro Storage as a Potential Solution for the Clean Energy Transition: The Case of the Kardia Lignite Mine, Western Greece. Sensors 2023, 23, 593, doi:10.3390/s23020593.

Menéndez, J., Loredo, J. (2019). Use of closured open pit and underground coal mines for energy generation: Application to the Asturias Central Coal Basin (Spain). E3S Web of Conferences 80, 2018 International Conference on Renewable Energy and Environment Engineering (REEE 2018), doi: 10.1051/e3sconf/20198001005.

Mongird, K.; Fotedar, V.; Viswanathan, V.; Koritarov, V.; Balducci, P.; Hadjerioua, B.; Alam, J. (2019). Energy Storage Technology and Cost Characterization Report; U.S. Department of Energy's Water Power Technologies Office by Pacific Northwest National Laboratory: Washington, DC, USA.

NASA (2022). S3001: Guidelines for Risk Management. Version: I, online: https://www.nasa.gov/wp-content/uploads/2023/08/ivv-s3001-guidelines-for-risk-management-ver-i-05-31-2022.pdf?emrc=eb880a

Nikolaos, P.C.; Marios, F.; Dimitris, K. (2023). A Review of Pumped Hydro Storage Systems. Energies 2023, 16, 4516. https://doi.org/10.3390/en16114516.

Papadakis, N., Fafalakis, M & Katsaprakakis, D. (2023). A review of pumped hydro storage systems. Energies, 16(11), 4516.

Pollitt, H., et al. (2014). An economic and environmental assessment of future electricity generation mixes in Japan—an assessment using the E3MG macro-econometric model. Energy Policy 67, 243–254.

Pujades, E., Willems, T., Bodeux, S., Orban, P., Dassargues, A. (2016). Underground pumped storage hydroelectricity using abandoned works (deep mines or open pits) and the impact on groundwater flow. Hydrogeology Journal (2016) 24:1531–1546. doi: 10.1007/s10040-016-1413-z.

Pujades, E.; Orban, P.; Bodeux, S.; Archambeau, P.; Erpicum, S.; Dassargues, A. (2017). Underground pumped storage hydropower plants using open pit mines: How do groundwater exchanges influence the efficiency? Appl. Energy, 190, 135–146.

Quaranta, E., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Grabowska, M., Gea Bermudez, J. and Tattini, J. (2023). Clean Energy Technology Observatory: Hydropower and Pumped Hydropower Storage in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023. doi:10.2760/841176, JRC134918.

Ramli, M.A.M.; Bouchekara, H.R.E.H.; Alghamdi, A.S. (2018). Optimal sizing of PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm. Renew. Energy 2018, 121, 400–411, doi:10.1016/j.renene.2018.01.058.

Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC Available online: http://data.europa.eu/eli/reg/2019/941/oj.

Rehmann, S.; Al-Hadhrami, L.M.; Mahbub Alam, Md. (2015). Pumped hydro energy storage system: A technological review, Renewable and Sustainable Energy Reviews, 44, 2015, 586-598, doi:10.1016/j.rser.2014.12.040.

Sawle, Y.; Gupta, S.; Bohre, A.K. (2018). Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system. Renew. Sustain. Energy Rev. 2018, 81, 2217–2235, doi:10.1016/J.RSER.2017.06.033.

Schoenung, Susan M; Hassenzahl William V. (2003). Long- vs. Short-term energy storage technologies analysis – a life cycle cost study. Sandia National Laboratories.

Simão, M.; Ramos, H. M. (2020). Hybrid Pumped Hydro Storage Energy Solutions towards Wind and PV Integration: Improvement on Flexibility, Reliability and Energy Costs. Water. 2020, 12, 2457; doi:10.3390/w12092457.

Voith (2024). Accessed: 18/06/2024. URL: https://voith.com/corp-en/industry-solutions/hydropower/pumped-storage-plants.html.

Wessel, M.; Madlener, R.; Hilgers, C. (2020). Economic Feasibility of Semi-Underground Pumped Storage Hydropower Plants in Open-Pit Mines. Energies, *13*, 4178. https://doi.org/10.3390/en13164178.

Whittingham, M.S. (2012). History, Evolution, and Future Status of Energy Storage. Proc. IEEE 2012, 100, 1518–1534, doi:10.1109/JPROC.2012.2190170.

Xu, X., Hu, W., Cao, D., Huang, Q., Chen, C., Chen, Z. (2020). Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system, Renewable Energy, Volume 147, Part 1, Pages 1418-1431, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2019.09.099.

Zakeri, B., Syri, S. (2015). Electrical energy storage systems: A comparative life cycle cost analysis, Renewable and Sustainable Energy Reviews, Volume 42, Pages 569-596, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2014.10.011.

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