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Opportunities for the future development of energy infrastructure after production closure in the KGHM shaft, by the example of the creation of an underground pumped – storage hydropower plant

The article touches on the technical and technological aspects in the field of the possibility of creating energy infrastructure after the end of production in a selected shaft of "KGHM Polska Miedź S.A." A cascade system of placing turbines in the shaft was proposed and the possibility of its creation was evaluated, respecting the dimensions of the turbines and the shaft. During the analysis, the relevant turbine capacities, flows, infrastructure dimensions, and possible solutions to overcome the limitations of developing an Underground Peak and Pumped Storage Power Plant (UPSH) in a post-mining facility were examined.

Key words: *energy storage, hydroelectric power plant, reclamation, underground pumped storage hydropower, post-mining facilities*

1. INTRODUCTION

The presented analysis is a proposal for the development and further exploration of design opportunities in the creation of post-mining infrastructure for energy storage and production. Its main purpose is to analyse the possibility of using mining locations, e.g. shafts and underground infrastructure for energy storage and production to secure the needs of power generation in the Legnica-Glogów Copper Belt. The article is based on calculations and analyses performed in the Master's thesis entitled: "Opportunities for future development of an energy infrastructure after production closure in "KGHM Polska Miedź S.A." shaft, by the example of an underground pumped – storage hydropower creation. For a more in-depth discussion of the topic, as well as the processes and analyses carried out, the authors encourage readers to seek out the original thesis [1].

2. PROPOSAL OF ENERGY INFRASTRUCTURE DEVELOPMENT IN THE SHAFT OF "KGHM POLSKA MIEDŹ S.A." AFTER THE END OF COPPER PRODUCTION

In an era of increasing environmental awareness, many companies are expanding their climate-neutral business operations in line with EU recommendations. Such a tendency is also evident in mining, for example through the use of electric cars, the establishment of photovoltaic and wind farms on reclaimed post-mining land [2]. "KGHM Polska Miedź S.A." in its policy does not differ from the general international pro-environmental trend. The company's plan is to generate 50% of its electricity from the company's own environmentally friendly sources by 2030 [3]. Once mining ceases, mine shafts will be decommissioned in accordance with the Polish Mining and Geological Law. An important part of decommissioning mining facilities is their efficient use in the future [4]. The location of an electrical power generation facility in the shaft for the production of electricity is one such proposal. In the literature, a few examples have been proposed as to how to use post-mining infrastructure for the establishment of an energy-producing system, but none has been commercialized so far [5]. Typically, it is possible to find proposals in the literature for converting potential energy into kinetic energy using the natural gradient in a mine shaft, or using energy stored in water, or even by gravity. As for the solution using water, such an idea has been called Underground Pumped-Storage Hydropower (UPSH). The presented solution can be combined with the company's already existing power facilities and efficiently use surplus energy by storing it in the hydropower plant, and during times of increased energy consumption, the previously stored potential energy can be converted into electricity. The energy generated in this manner can be used to make nearby cities in the copper basin energy independent, and will also give an opportunity for a new development impulse in the region after KGHM's copper ore exploitation ends.

3. BASIC PRINCIPLES OF PUMPED STORAGE HYDROPOWER

According to the KOMAG Institute of Mining Technology in "Review of Energy Storage Solutions" (2021) pumped storage power plants are the most cost-effective energy storage facilities at this point (compared to other energy market proposals) [6]. In Poland, these power plants are well-known, as there are as many as six such facilities in operation in the country, and several are still in the design phase. The main operating principle of such a power plant is to use the surplus energy produced by nearby electric power facilities, including RES. During periods when this energy is not used, it can be stored, while when there is a high demand for energy, the stored energy can be exploited. This is done relatively quickly (in a few hours or so), responding to market needs accordingly.

The power infrastructure of such power plants includes turbines, pumps, a generator together with an engine and, outside the shaft, an upper and lower reservoir in which water is stored. Often the role of water reservoirs for PSH is played by lakes, ponds, or artificial reservoirs. The pump can be a separate device, but so-called pump-turbines and Francis turbines are also known and quite often used, which can act as turbines as well as pumps, depending on the system in which they operate [6].

4. CHALLENGES IN THE DEVELOPMENT OF UPSH INFRASTRUCTURE IN THE SELECTED SHAFT OF KGHM POLSKA MIEDŹ S.A.

4.1. Limitations of UPSH system

In the literature, it is possible to find information on ongoing research regarding the development of UPSH systems in underground mines, for example in "The FCN Working Paper Series" or in "Energies" [7, 8]. In Poland, preliminary studies on the implementation of UPSH were conducted at Jastrzębska Spółka Węglowa (JSW S.A.) and the KOMAG Institute of Mining Technology. In Europe, such studies were conducted in Germany, Spain, and the Czech Republic, where a prototype of such a system was established in the Jeremenko coal mine. This was based on a Pelton turbine and with the use of the already existing mine drainage system [9]. Analysing the possibilities of designing a UPSH system at KGHM, it is easy to conclude that a major challenge will be properly designed lower reservoir. In the Copper Basin, mining is carried out by the chamber-pillar method, with ceiling collapse, and with the use of a hydraulic filling. Such a system already imposes very high design constraints at the outset. The lower reservoir cannot serve as a reservoir in the strict sense of this term, as there is no adequate space in the excavations. The possibility of simply flooding the tunnels, preceded by sealing them, was also considered, but such a solution would carry too many risks. This is due to the need of maintaining permanent access to the mine workings, which makes flooding impossible. The second issue is the potential risk of water leakage. The German research and development centre E.ON has proposed an alternative solution involving the construction of new tunnels to act as a lower reservoir. While this is a promising idea, it could be very costly to implement due to the high cost of conducting mining operations [8].

4.2. Project assumptions

After a careful analysis of the possibilities, it was decided to build a network of pipes underground.

Part of the excavations will be used to store water, which will be accumulated in pipes. The other part will be a designated access road to carry out operations: safety work, etc. With such a proposal, it would also be necessary to think about appropriate venting so that the flow in the lower reservoir can be controlled efficiently. In Figure 1, a cutout with a typical KGHM mine pit of averaged size, with a network of pipes installed is visible. With such a system, it is also necessary to take into account potential additional costs associated with the design of the network and the indispensable mining work required for its construction. It was calculated that it would be possible to use pipes with an outside diameter of 3 to 3.5 m.

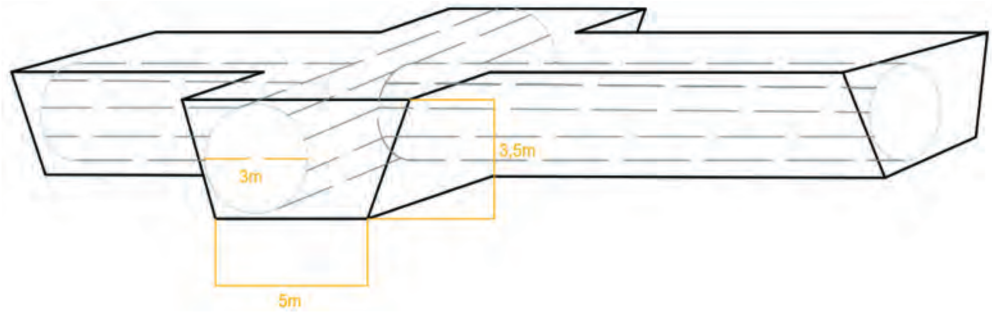

Fig. 1. A cutout of KGHM tunnels with installed network pipeline (lower reservoir)

Calculations carried out on the proposed pipe dimensions show that underground workings, preferably transport workings (collapses and galleries) ranging from 73 km to as much as 100 km in length, would be used for this purpose.

The upper reservoir should not be on a par with the lower one in terms of problems but rather in terms of the technical design.

Conceptually, this would be a standard water reservoir, with the most favourable solution being the use of an existing nearby reservoir. If this is not possible, it is proposed to build one with appropriate sealing. Depending on whether underground water (from mine dewatering) will be used in the UPSH or not, the reservoir will need to be properly protected against possible leakage and environmental contamination.

The SW-3 shaft, a ventilation shaft which is 950 m long, is located near the city of Polkowice and was selected for the design analysis (Fig. 2). It also has a shaft tower with a hoist that can be appropriately converted, which was confirmed during a conversation with an employee of KGHM Cuprum – CBR Sp. z o.o. The main idea is to appropriately develop and use the diameter of the shaft to build PESP infrastructure in a cascade system. Francis turbines would be installed together with the engine and generator in the shaft. This would be a competitive solution to that of the power plant at the Czech coal mine “Jeremenko”, as it will not require as much in terms of mining operations. It would also not be necessary to conduct additional mining in the areas of the shaft, which is rather inadvisable due to the possible violation of the stability of the infrastructure and the shaft itself. For such a solution, it will be necessary to make appropriate calculations of the size of the turbines so that, respecting the diameter, they can fit into the shaft.

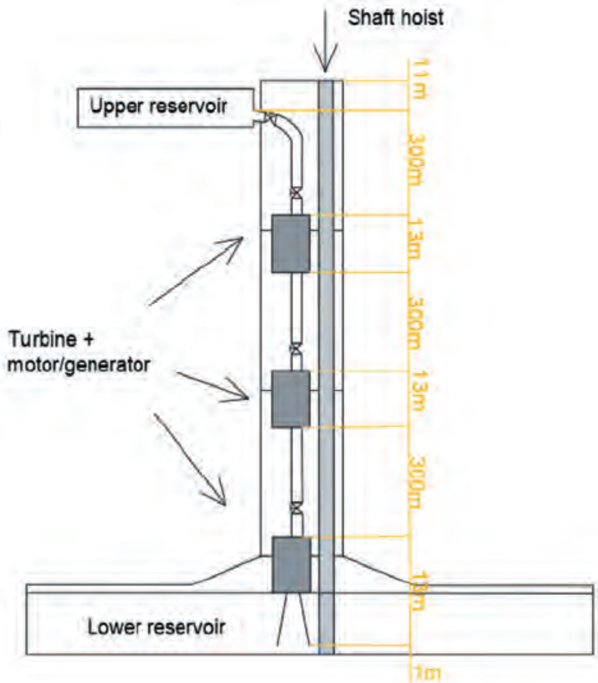

Fig. 2. UPSH infrastructure setup within the SW-3 shaft

A horizontal projection on the shaft can show the idea of infrastructure layout in a mine shaft in an easier way. The dimensioned parts of the infrastructure in Figure 3 are:

- inlet to the spiral casing – 1.38 m;
- diameter of the spiral casing of the selected Francis Turbine – 4.79 m;
- space for the “rebuilt shaft” – 2.5 m (this is not a binding dimension, but rather a proposal);
- diameter of the SW-3 shaft – 7.5 m.

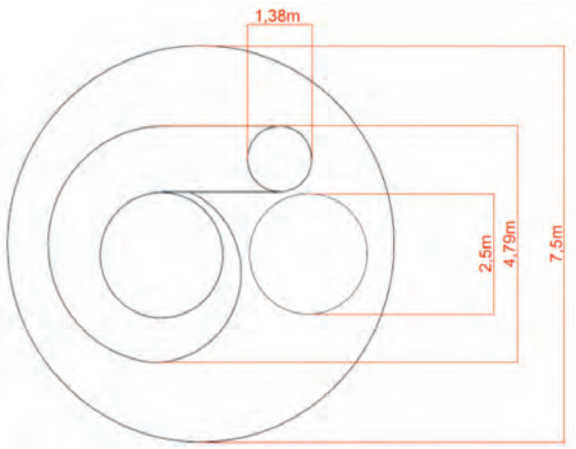

Fig. 3. Possible infrastructure setup within the SW-3 shaft – top view

5. CALCULATIONS

5.1. Basics of Francis Turbine operations

During the performed analysis, appropriate design assumptions were used which made it possible for the correct calculations to be made. The capacity (volumetric flow rate) was calculated and a turbine casing diagram was developed (Fig. 4), and from it the volume of water that can be pumped out over a typical head of the system, which equals 300 m. The result made it possible to determine the appropriate capacity for further calculations. This is a value that can be controlled anyway by appropriate adjustment of the blades of the turbine itself. Q_p = 12.24 m^3/s, and Q_g = 15.12 m^3/s [8].

Pumping:

$$Q_p = \frac{P_p \cdot \eta_p}{g \cdot \rho \cdot h} \tag{1}$$

Generating:

$$Q_g = \frac{P_g}{g \cdot \rho \cdot h \cdot \eta_g} \tag{2}$$

where:
- Q_p – volume flow rate [m^3/s],
- P_p – power [W],
- η_p – efficiency [–],
- g – gravitational acceleration [m/s^2],
- ρ – water density [1000 kg/m^3],
- h – head [m].

The results of the computations indicated that the water reservoir will have a volume of min 0.69 Gl of water. For the purpose of mathematical analyses, the efficiencies during pumping and generation η = 90% were assumed, while these numbers final may change due to the specifics of the system.

5.2. Francis Turbine dimensions analysis

Further calculations required the iterative analysis of turbine dimensions with respect to the diameter of the shaft – 7.5 m. After careful analysis, it was concluded that the most reasonable choice would be a turbine with a power of about 40 MW. It will be possible to install such a unit in the shaft without any major problems. The designs proposed by F. de Siervo & F. de Leva were used for this [10].

$$A = \left(1.2 - \frac{19.56}{N_s}\right) \cdot D_r \tag{3}$$

$$B = \left(1.1 + \frac{54.8}{N_s}\right) \cdot D_r \tag{4}$$

$$C = \left(1.32 + \frac{49.25}{N_s}\right) \cdot D_r \tag{5}$$

$$D = \left(1.5 + \frac{48.8}{N_s}\right) \cdot D_r \tag{6}$$

$$E = \left(0.98 + \frac{63.6}{N_s}\right) \cdot D_r \tag{7}$$

where:
- D_r – diameter at the outlet of the rotor [m],
- N_s – speed [–].

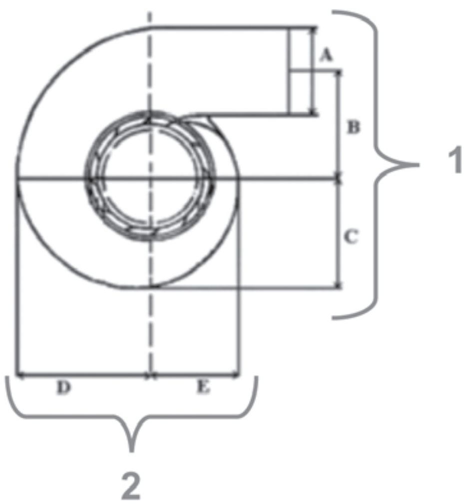

Fig. 4. Francis turbine spiral casing (own elaboration based on F. de Siervo & F. de Leva [10]) 1 = D + E, 2 = 1/2A + B + C

Based on these values for each turbine power, it was possible to iteratively check the values of the longest side 1 and 2.

5.3. Operation of the system during the pumping cycle

Further testing consisted of checking the water pressure height loss, or so-called hydraulic loss, during pumping in the cascade system proposed in Figure 2. Table 1 presents the parameter values during water pumping.

$$H_{total} = H_s + H_d \tag{8}$$

where:
- H_s – static head [m],
- H_d – dynamic head [m].

$$H_d = \frac{Kv^2}{2g} \tag{9}$$

where:
- K – losses [–],
- v – velocity [m/s],
- g – gravitational acceleration [m/s^2].

Table 1

Operating conditions and parameter values during water pumping

Parameter	Value	Unit
I Turbine		
Head	306.3253	[m]
Power	40 885 053	[W]
Power (buffer)	42	[MW]
II Turbine		
Head	305.3812	[m]
Power	40 771 506	[W]
Power (buffer)	42	[MW]
III Turbine		
Head	305.3812	[m]
Power	40 759 041	[W]
Power (buffer)	42	[MW]

The results of the turbines' cooperation in the proposed cascade system showed that it would be worth adopting an appropriate safety buffer for the turbine power. It needs less than 41 MW of power, but it is reasonable to overestimate this value. The dimensions for the 42 MW Francis turbine have already been plotted in Figure 3. These are the dimensions that meet the design assumptions and such a turbine can be installed in mine shaft SW-3.

5.4. Operation of the system during the power generation cycle

For the initial analysis of the working system, it was decided to use the basic equation in fluid mechanics, the Bernoulli equation. However, it assumes a number of simplifications, including the assumption that the flow is not turbulent, but laminar, which is false. Laminar flow occurs very rarely in nature, yet it offers room for promising analysis. By using Bernoulli's equation, which is suitably extended, very reliable results can be obtained for academic consideration [9].

$$\begin{aligned} P_1 + 0.5\rho v_1^2 + \rho g h_1 + P_p &= P_2 + \\ &+ 0.5\rho v_2^2 + \rho g h_2 + f_R \rho g + P_T \end{aligned} \tag{10}$$

where:
- P_i – pressure [Pa],
- ρ_i – water density [1000 kg/m^3],
- v_i – water velocity [m/s],
- h_i – head [m],
- P_p – pumping power [W],
- f_R – friction factor [–],
- P_T – generating power [W],
- g – gravitational acceleration [9.81 m/s^2].

Table 2

Operating conditions and parameter values during power generation

Turbine	Power [MW]	Efficiency [%]
I Turbine	36.86	87.76
II Turbine	35.22	83.85
III Turbine	35.20	83.82

The results presented in Table 2 are very satisfactory therefore it indicates that the design assumptions and power selection were correct. Most PSH systems have a capacity within 0.81 (0.9 × 0.9). The results of the present analysis, for pumping and generating, were also similar: I Turbine – 78.99%, II Turbine – 75.46%, III Turbine – 75.44%. Overall Efficiency of the proposed system: 76.63%.

Table 3
The total amount of energy in different cycles of operation

Cycle	Amount of Energy [MWh]	Time [h]
Generating	1173.12	11
Pumping	1652.61	13.5

It therefore follows that the operational time required to pump water to the surface will be 13.5 hours, according to the assumptions, while it will be possible to generate power for almost 11 hours.

6. SUMMARY

The energy capacity of the system is remarkably close to those power plants operating in the energy market today. The capacity of the aforementioned system analysed is 107.28 MW. In comparison, PSH Żydowo has 156 MW and the height difference is 80 m. It can operate for about 5h. Due to the higher water drop, and flow regulation, the proposed Underground Peak-Pumped Power Plant has a chance to be as important a unit in maintaining energy stability as the smallest PSH in Poland – "Żydowo".

A series of calculations showed that a preliminary analysis for the proposed cascade system demonstrates the potential design possibilities for the concept under consideration. The proposed UPSH is feasible to build in the shaft after mining operations are complete. Of course, additional, more detailed analyses would need to be performed including:

– A detailed study of the feasibility of designing the underground pipe network as a lower reservoir with appropriate venting. The focus should not only be on the appropriate choice of levelling, but also on protecting the infrastructure from potential leakages. One would also have to consider the possibility of supplying additional water, in case the pipe network leaks.
– The cooperation of Francis turbines and losses in the proposed system would have to be carefully analysed using CFD, or other experimental calculations,
– Financial analysis of the project, based on the studied technical capabilities of the shaft and the cascade system of Francis turbine operation, taking into account the specifics of the underground power plant.

It would be necessary to keep in mind that during construction, and during the continued operation of the Underground Pumped Storage Hydropower (UPSH), it will be necessary to assume that the operating system will be similar to the one that existed during the operation of the mining plant. It will be important to maintain mine supervision, the excavations, tunnels (repair work, revisions, etc.) and properly ventilate the mine, so there may be a need to include an additional shaft in the overall system. Of course, this will involve additional maintenance costs for the entire PESP infrastructure. It is likely that additional supervision of the entire project will also be the responsibility of the Higher Mining Authority.

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