CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (4): 0212-0227
DOI: 10.59440/ceer/214169
Original Research Article

DECOMMISSIONING OF A LIGNITE MINE COMBINED WITH THE DEVELOPMENT OF A PUMPED-STORAGE POWER PLANT: A PRELIMINARY FEASIBILITY ASSESSMENT

Wojciech NAWORYTA[1], Mateusz SIKORA
Faculty of Civil Engineering and Resource Management, AGH University of Krakow, Krakow, Poland

Abstract

This publication addresses the potential construction of a pumped-storage power plant (PSP) in post-lignite mining areas.The Turów mine, located in the Bogatynia commune in southwestern Poland, was selected as a case study. Several design variants for the upper reservoir, situated on the former external mine dump, were analyzed. Several design variants for the upper reservoir, situated on the former external mine dump, were analyzed. Based on data from existing Polish PSP facilities, the potential capacity of the Turów PSP was estimated depending on the selected reservoir configuration. The study highlights the advantages of coordinating the construction of the PSP with the mine closure process. The use of mining machines withdrawn from the mine was recommended. Earth masses from the dump should be used in the process of preparing the final excavation to serve as a reservoir. Combining the construction of the PSPP with the liquidation of the mine will accelerate both processes and reduce costs. The presented project is of a future nature. According to the concession, the end of mining will take place no later than 2044. Preparing the excavation to serve as a reservoir and filling the reservoir with water may take up to 4 decades. Due to the limited availability of water, it is difficult to accelerate this process. As a result, electricity from the PSP may flow at the earliest in the 80s of the 21st century. A general conclusion drawn from this study is that former lignite mining sites—featuring excavations that can serve as reservoirs and adjacent external dumps—offer significant potential for the development of pumped-storage power plants. The article also identifies additional locations with similar suitability for future PSP development.

Keywords: lignite mine, mine decommissioning, pumped-storage power plant, energy storage, external dump, renewable energy

[1] Corresponding author: Wojciech Naworyta, Faculty of Civil Engineering and Resource Management, AGH University of Krakow, Al. Mickiewicza 30, 30-059 Krakow, e-mail: naworyta@agh.edu.pl, telephone: 12 617 2940

1. INTRODUCTION

Energy transformation involves switching from fossil fuel-based energy to renewable energy. The technology of generating electricity using wind or solar power has been well-mastered. However, it is known that renewable energy production depends on weather conditions, wind power, and solar radiation, and these of course cannot be planned. The main problem of modern energy lies not so much in energy production, but in its storage. If the sources produce more electricity than the demand, this surplus is most often dispersed and wasted. Effective methods of storing surplus energy have not yet been invented. Energy storage facilities have limited capacity, their efficiency changes over time, their production is resource- and energy-intensive, which makes it expensive and, above all, not very ecological (Naworyta 2025). Excess unconsumed energy from renewable sources can lead to deregulation of the country's energy system, even causing a blackout. The risk of a blackout had been predicted earlier (Carreras et al. 2021) and the events in Spain and Portugal in April 2025 painfully confirmed these predictions (Latona 2025).

A mastered way of storing energy is pumped-storage power plants (PSP). Such an installation is based on two water reservoirs located at different elevations. The power of water falling from the upper to the lower reservoir is used to produce energy. When there is a surplus of energy in the system, it is used to fill the upper reservoir, and during increased demand, energy is generated by the force of the water fall. The energy balance of such a power plant is, naturally, negative, as more energy is consumed during pumping than is generated during electricity production. However, pumped-storage power plants should be treated not as production units, but as energy storage installation. The idea of a pumped-storage power plant has been known for years; they were built much earlier, before renewable energy facilities and the resulting energy surpluses appeared in energy systems. There are 6 pumped-storage power plants in Poland so far (Table 1).

Table 1. Pumped-storage power plants in Poland

Pumped-storage plant	River/Lake	Year of commissioning	Installed capacity [MW]
PSP Dychów	Bóbr River	1936	87.9
PSP Solina	Solińskie Lake	1968	198.6
PSP Żydowo	Kamienne and Kwiecko Lakes	1971	167
PSP Porąbka-Żar	Soła River	1979	540
PSP Żarnowiec	Żarnowieckie Lake	1982	716
PSP Niedzica	Czorsztyńskie Lake	1997	92.7

The largest facility of this type in Poland is the Żarnowiec PSP, with a gross capacity of 716 MW. Originally, in the 1980s, it was intended to serve as an energy storage system for the first Polish nuclear power plant, which was then under construction. Although the nuclear power plant project was eventually abandoned, the pumped-storage power plant was completed and remains in operation. In the Sudety region, the construction of the Młoty PSP was planned as early as the 1970s; however, the project has yet to be realized. In recent years, efforts to revive the initiative have resumed (Kowalski 2008, Kulpa et al. 2024).

Table 2 presents the main parameters of three Polish pumped-storage plants constructed with the use of artificial, non-flowing upper reservoirs.

Table 2. Selected parameters of pumped-storage power plants in Poland

	PSP Żar	PSP Żarnowiec	PSP Żydowo
Gross power [MW]	540	716	167
Upper reservoir capacity [million m^3]	2,3	13,8	3
Upper reservoir area [ha]	14	135	100
Height difference [m]	440	125	82,7
Derivation langth [m]	500	1100	467

2. POST-LIGNITE MINING AREAS AS POTENTIAL SITES FOR PUMPED-STORAGE POWER PLANT DEVELOPMENT

The potential for constructing new pumped-storage power plants in mountainous regions is highly limited. A significant portion of Poland's mountainous areas is under legal protection due to their natural and scenic value. These regions are also important tourist destinations. The development of upper reservoirs and associated power plant infrastructure entails substantial environmental disruption and leaves a lasting negative impact on the mountain landscape. Moreover, the construction of hydrotechnical facilities in such terrain is technically challenging and often requires the demolition of residential buildings and farms, as well as modifications to existing infrastructure. These interventions typically provoke strong public opposition and social discontent.

In Poland, however, there remains significant potential for the development of new, large-scale pumped-storage power (PSP) installations. This potential lies primarily in current and future post-lignite mining areas. In the near future, due to the depletion of lignite reserves, the country's two largest lignite mines—Bełchatów and Turów—are expected to undergo decommissioning.

The concept of utilizing post-mining areas for energy production or storage is not new, although most existing approaches focus on the use of underground mine workings (Alvarez et al. 2021, Jardon et al. 2020, Jinyang et al. 2020, Menendez et al. 2020). The installation of photovoltaic systems in post-mining areas has also gained popularity in recent years (Bodis et al. 2019, Antoniadis et al. 2021).

The exploitation of lignite deposits significantly transforms the landscape, creating large, deep open pits and adjacent external overburden dumps. In the initial phase of mining, the overburden is deposited on external dumps, forming massive earth structures that can reach volumes exceeding 1 billion m^3 and heights of up to 200 meters above ground level. During active mining, open pits are subject to intensive dewatering. Once exploitation ceases and the dewatering systems are deactivated, the excavations gradually fill with water. In Poland, several artificial reservoirs have formed in decommissioned lignite open pits as a result of this process. Some of these reservoirs, due to their proximity to former overburden dumps, already exhibit favorable conditions for the development of pumped-storage power plants. Table 3 provides a summary of reservoirs created in former lignite pits following mine closure.

Table 3. Artificial reservoirs in former lignite mining pits (Wachowiak and Wachowiak 2005, Bajcar et al. 2021, Kaliński 2023, Nowak et al. 2023)

No.	Water reservoir	Volume [Mm^3]	Area [ha]	Characteristics
1	Morzysław	0.1	2.5	Existing
2	Niesłusz	11.1	18.5	Existing
3	Gosławice	48.75	32.5	Existing
4	Pątnów	79.58	346	Existing
5	Kazimierz South	3.25	65	Existing
6	Kazimierz North	143	522	Existing
7	Lubstów	137	480	Existing
8	Jóźwin II B	250	740	In preparation
9	Drzewce	35.2	157	In preparation
10	Tomisławice	69.2	290	After the end of operation
11	Bogdałów	0.6	9.5	Existing
12	Przykona	4.9	123.4	Existing
13	Janiszew	4	75	Existing
14	Koźmin	7.57	121	Existing
15	Pośredni Adamów	22	105	During flooding
16	Głowy	20.1	94.4	During flooding
17	Końcowy Koźmin	35.4	131	Existing
18	Władysławów	23.3	109	Existing
19	Końcowy Adamów	90.8	309	During flooding
20	Bełchatów i Szczerców	3 075	3 891	After the end of operation
21	Turów	1 680	1 966	After the end of operation

The reservoirs formed in post-mining excavations listed in Table 3 serve, or are intended to serve, various functions, including water retention, ecological, and recreational uses. Some of them, due to the size of the basin and the proximity of external overburden dumps, are suitable for the construction of pumped-storage power plants. In the vicinity of the Konin lignite mine, the Lubstów and Tomisławice open pits are of particular interest. Adjacent to the Lubstów pit, there is an external overburden dump covering approximately 130 hectares. The straight-line distance between the dump and the excavation is about 1.2 kilometers. The Tomisławice opencast mine is currently in its final phase of operation. An external dump is located near the active excavation, and the plateau surface covers approximately 100 hectares.

Taking into account the terrain configuration—specifically the size and elevation of overburden dumps, as well as the surface area and volume of final excavations—the greatest potential for the construction of pumped-storage power plants (PSPs) is offered by three open pits at active lignite mines: Bełchatów, Szczerców, and Turów (Sawicki 2009). Lignite extraction at the Bełchatów mine has already been completed, while operations at the Szczerców pit are expected to end by 2038, and at the Turów mine by 2044. These dates correspond to the expiration of concessions for lignite extraction. Following the cessation of mining operations, the open pits are to be repurposed as water reservoirs, with a subsequent flooding phase planned. The mine closure process will be prolonged, due both to the extensive preparatory work required and the projected duration of pit flooding. As a result, the potential development of PSPs in these areas must be deferred. Nevertheless, it is worthwhile to initiate a public and technical discussion on the feasibility of PSP construction, along with the planning of works that could be implemented in parallel with mine decommissioning.

An important advantage of post-mining areas is the absence of residential and infrastructural development. Utilizing these areas for PSP construction would not necessitate population displacement. This contrasts with similar projects in built-up regions, which often provoke social opposition and public protest.

3. PUMPED-STORAGE POWER PLANT IN THE FUTURE POST-MINING AREA OF THE TURÓW LIGNITE MINE: A CASE STUDY

Among both current and future lignite mining sites, the Turów lignite mine area, located in the Bogatynia commune in southwestern Poland, is considered by the authors to be the most suitable location for the construction of a pumped-storage power plant (PSP). Several arguments support this assessment, the most significant being the favorable terrain configuration and the presence of existing energy infrastructure associated with the Turów lignite power plant.

Following the cessation of lignite extraction, the mining excavation and the adjacent external overburden dump can be repurposed for the construction of a pumped-storage power plant (PSP). The external dump, after reclamation, is under the administration of the State Forests Authority (Wójcik and Krzaklewski 2019). Regardless of other factors, an artificial reservoir will be formed in the final excavation (see Table 3). Due to its substantial surface area and depth, the reservoir will be suitable for multiple applications, including serving as the lower reservoir for a PSP.

The capacity of the upper reservoir will ultimately determine the plant's generating power. Figure 1 illustrates the proposed location of the upper reservoir on the dump, along with the layout of the derivation pipelines for one of the analyzed PSP design variants.

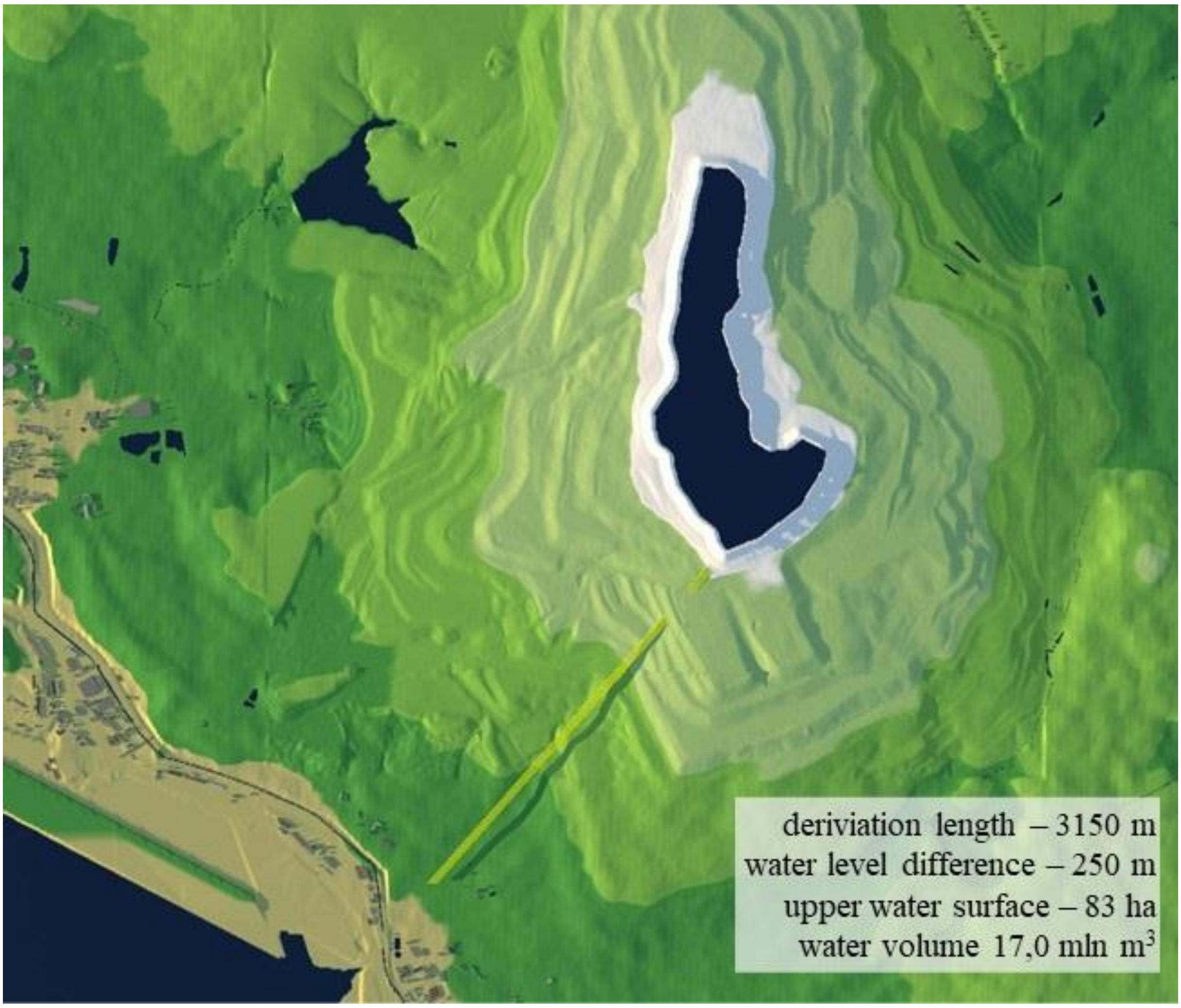

Fig. 1. One of the PSP construction variants in the post-lignite mining area of the Turów Mine

The upper reservoir can be located on the top section of the external overburden dump, from which water would be conveyed to the lower reservoir—situated in the former open pit—via derivation pipelines (see Fig. 1). Depending on the design variant, the elevation difference between the upper and lower water surfaces ranges from approximately 195 to 225 meters, while the straight-line distance between the reservoirs exceeds 3 kilometers.

At the outlet of the pipelines into the lower reservoir, facilities housing the PSP's turbines and pumps should be constructed. This location is approximately 2 kilometers from the existing Turów power plant. Although the lignite-fired power plant (with a capacity of around 2,000 MW) will cease operation following the closure of the mine, the existing energy distribution infrastructure can potentially be repurposed for future PSP electricity transmission. Table 4 presents the key characteristics of the Turów mine's open pit and former external dump that are relevant to the development of a pumped-storage power plant.

Table 4. Key characteristics of the former external dump and open pit of the Turów Mine relevant to pumped-storage power plant construction

External dump	
Area	2175 ha
Overburden volume	1,470 billion m^3
Elevation	475 m above sea level
Altitude	245 m above terrain level
Completion of dumping	year 2006
Excavation (Pit)	
The area of water table	2100 ha
Elevation of the water table	225 m above see level
Volume	1,5 billion m^3
Depth	135 m
End of operation	by year 2044

The construction of the upper reservoir must be preceded by detailed geotechnical investigations to rule out the risk of future landslides. This is particularly important, as the load on the upper reservoir will be dynamic during PSP operation. At present, the dump is considered stable. Since dumping activities ceased in 2006, no landslides have been recorded, and the overburden material has undergone natural compaction. For safety reasons, the upper reservoir should not impose additional vertical loads on the dump. The external dump has a hill-like morphology with a distinct peak, which necessitates the removal of a significant volume of material to create a stable platform for reservoir construction.

4. DESIGN PARAMETERS OF THE UPPER RESERVOIR INTEGRATED INTO THE EXTERNAL DUMP

The storage potential and power output of the pumped-storage power plant (PSP) depend primarily on the size of the upper reservoir. Its capacity should be maximized while minimizing the volume of earth that needs to be removed. It is assumed that the material excavated from the external dump will be reused for the construction of the reservoir's embankments, while any surplus will be utilized to shape the final excavation pit.

To determine the parameters of the potential PSP installation, several design variants for the upper reservoir were analyzed, based on the following assumptions:

- The top of the external dump will be leveled to create a plateau suitable for the construction of the upper reservoir;
- The crest of the upper reservoir will be constructed with a 15-meter-wide safety buffer from the edge of the plateau;
- The slopes of the reservoir embankments will have an inclination of 1:2;
- The width of the embankment crest will be 5 meters;
- The height of the embankments will be 30 meters;
- The total depth of the upper reservoir will be 24 meters.

Based on the digital terrain model (DTM) of the Turów lignite mine's external dump, volume calculations were conducted to estimate the amount of earth to be removed for the construction of the upper reservoir. Nine design variants were analyzed, assuming reservoir bottom elevations ranging from

455 meters above sea level (a.s.l.) down to 415 meters a.s.l., in 5-meter increments. Figure 2 presents selected examples of reservoir configurations, while Table 5 summarizes their key technical parameters.

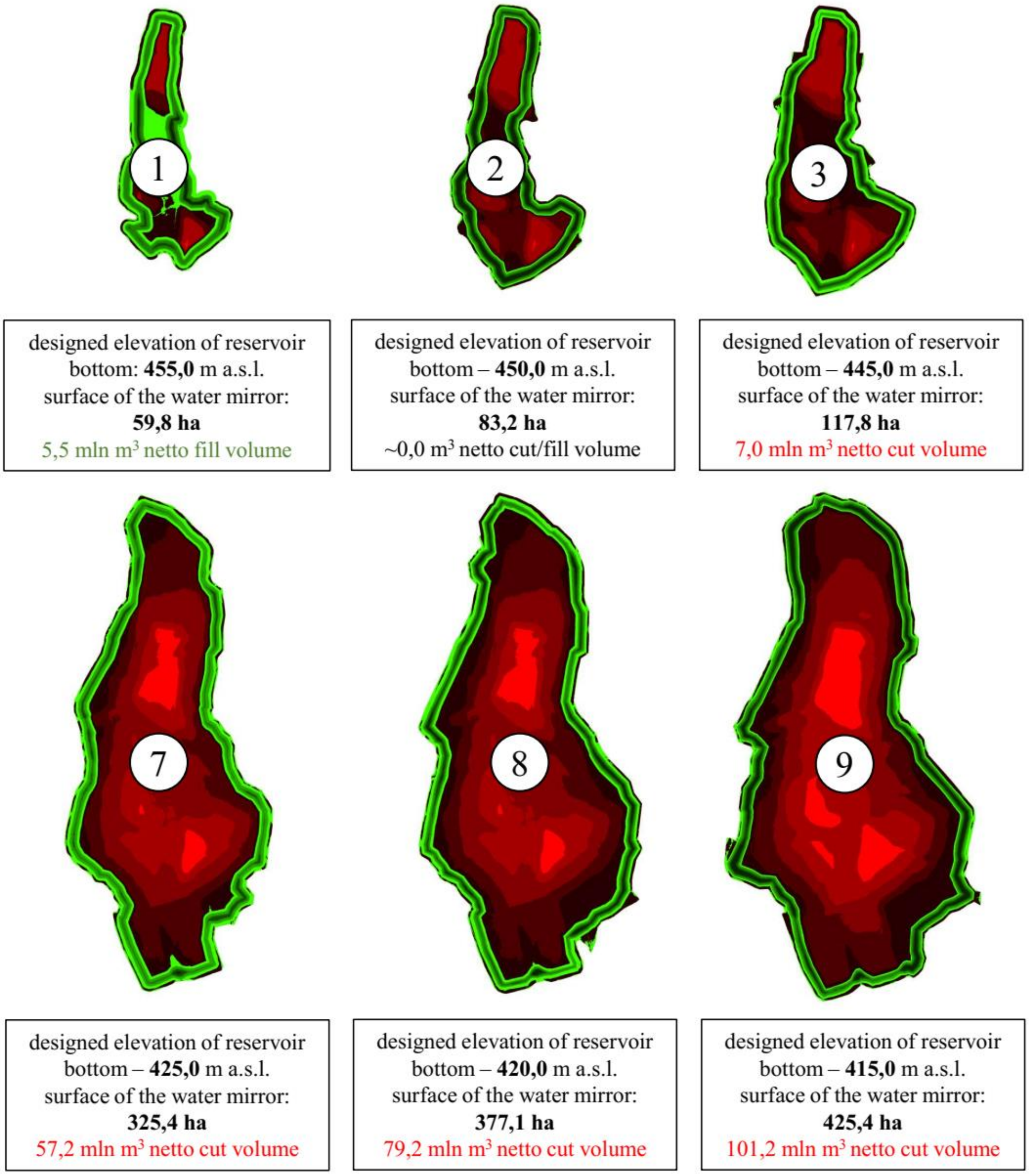

Fig. 2. Selected shapes of the designed upper reservoir depending on bottom elevation

Table 5. Key parameters of the upper reservoir and earthwork volumes depending on the designed bottom elevation

Variant No.	designed elevation of reservoir bottom	designed elevation of water level	total depth of water	water reservoir surface	water reservoir volume	earthworks volumes		
						cut volume	fill volume	earthworks net volume
	[m a.s.l.]	[m a.s.l.]	[m]	[ha]	[M m^3]	[M m^3]	[M m^3]	[M m^3]
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
1	455,0	479,0	24,0	59,8	15,3	2,0	7,5	-5,5
2	450,0	474,0		83,2	17,0	6,5	6,5	0,0
3	445,0	469,0		117,8	25,2	13,4	6,4	7,0
4	440,0	464,0		168,5	36,7	23,5	8,1	15,4
5	435,0	459,0		219,5	48,1	35,5	9,9	25,6
6	430,0	454,0		270,5	59,8	50,0	10,6	39,4
7	425,0	449,0		325,4	72,8	68,5	11,3	57,2
8	420,0	444,0		377,1	85,1	89,2	11,0	78,2
9	415,0	439,0		425,4	96,4	112,3	11,0	101,3

The reservoir shapes presented in Figure 2 are irregular and not intended to represent realistic design solutions. The primary objective of the analysis was to determine the maximum potential capacity of the upper reservoir within the selected elevation range and to estimate the maximum volume of earthworks required. The quantitative analysis and the resulting conclusions serve as a basis for selecting the most favorable variant, which will form the foundation for subsequent detailed design work.

Figure 3 presents a graph illustrating how the following values vary with changes in the designed bottom elevation of the reservoir on the dump: the volume of earth to be excavated (red), the volume of material required for constructing the embankments (green), and the total volume of the upper reservoir (blue).

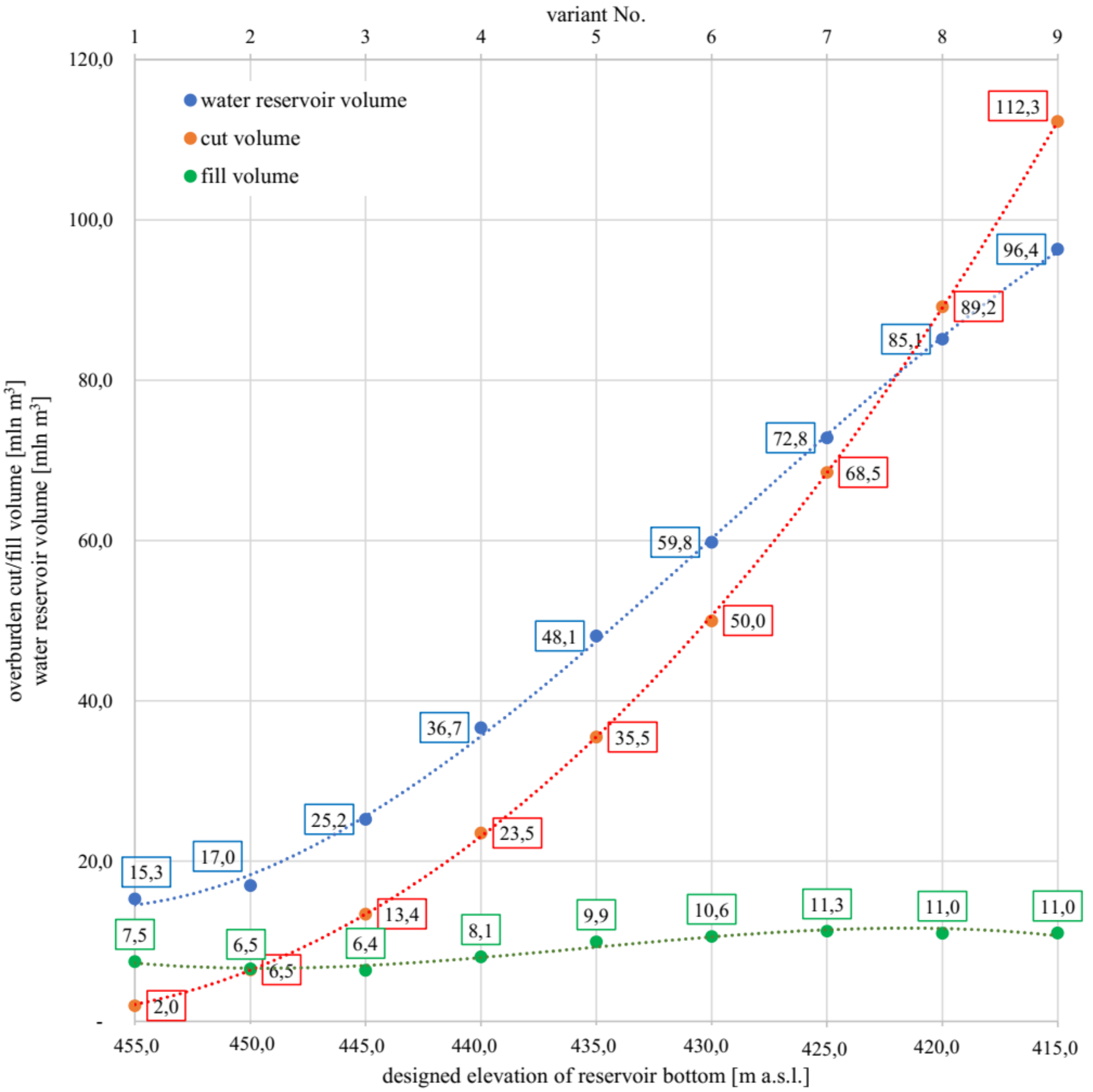

Fig. 3. Diagram of upper reservoir volume and earthwork volumes as a function of designed bottom elevation

The graph presented in Figure 3 allows for several noteworthy conclusions. Variant 1 represents a minimalist design, resulting in the smallest reservoir volume—15.3 million cubic meters (M m³). In this case, the volume of earth required to construct the reservoir embankments exceeds the amount of material excavated from the tank base. In other words, an additional 5.5 M m³ of material would need to be sourced externally to complete the embankments. This variant does not comply with the geotechnical safety assumptions of the project, which prohibit additional loading of the dump during PSP construction.

A similar issue arises with Variant 2. Here, the excavation and embankment curves intersect, indicating that the volume of excavated material would be equal to the volume needed for embankment construction. While favorable from the perspective of mass balance, this variant would result in an upper reservoir filled with approximately 17 M m³ of water during operation—thus imposing an unpermitted load on the dump, which is geotechnically unacceptable.

As shown in Figure 3, lowering the elevation of the reservoir base increases the volume of excavated material, as expected, while also increasing the reservoir's storage capacity. However, the rate of change of these parameters is not uniform. At an elevation of approximately 422 meters above sea level (between Variants 7 and 8), the curves intersect—indicating that the excavated volume equals the theoretical volume of the reservoir. Beyond this point, further lowering of the base elevation yields only marginal increases in reservoir volume, making such changes economically inefficient.

It is worth noting that even the smallest variant analyzed, with a capacity of 15.3 M m³, would exceed the volume of the upper reservoir at Żarnowiec PSP—the largest currently operating pumped-storage facility in Poland—which has a capacity of 13.8 M m³.

5. ESTIMATION OF PSP CAPACITY IN THE FUTURE POST-MINING AREA OF THE TURÓW LIGNITE MINE

The gross power output of a pumped-storage plant (PSP) depends primarily on the volume of water stored in the upper reservoir and the elevation difference between the water levels in the upper and lower reservoirs. It is also influenced by additional factors such as generator capacity, pump efficiency, and the number and characteristics of the derivation pipelines.

For the purposes of this study, the estimated power output of the proposed PSP Turów was determined based on the parameters of the upper reservoir. The analysis utilized reference data from three existing Polish pumped-storage plants with non-flow upper reservoirs: PSP Żarnowiec, PSP Żar, and PSP Żydowo. The relationship between installed power and three key parameters was examined: the volume of the upper reservoir, the height difference between the two water levels, and the length of the derivation pipelines. It was assumed that the reservoir volume and elevation difference both have a direct positive influence on power output, whereas the pipeline length has an inversely proportional effect. Specifically, longer pipelines typically result in a smaller inclination angle, thereby reducing the effective hydraulic head and the potential energy available for electricity generation.

Figure 4 presents a graph illustrating the relationship between PSP power output and a composite parameter, based on the following theoretical dependency:

$$W = F(V \text{x} \frac{\Delta h}{L}) \quad (5.1.)$$

where:

F – function,
V – volume of the upper reservoir [M m^3],
Δh – height difference between the water tables of the upper and lower reservoirs [m],
L – length of the derivation pipeline route [m].

The data points representing the existing power plants were approximated using a logarithmic function. Based on this fitted function, the theoretical power output was calculated for four different design variants of the proposed PSP Turów. In Variant 2, the estimated power output is approximately 700 MW, which is comparable to that of PSP Żarnowiec. For the remaining variants, the estimated power ranges from approximately 1,050 MW (Variant 4) to over 1,400 MW (Variant 8).

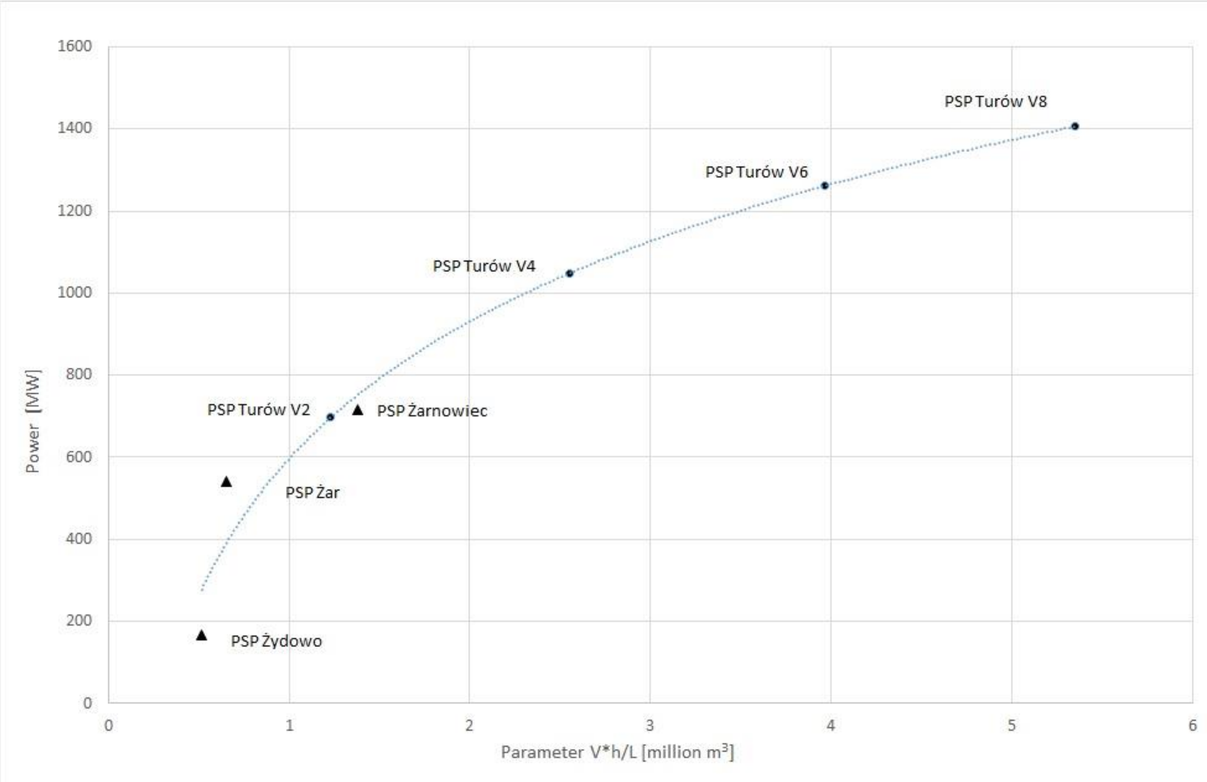

Fig. 4. Forecast of the potential power output of PSP Turów based on equation (1)

6. TIMEFRAME AND FORMAL CONSTRAINTS FOR PSP CONSTRUCTION IN POST-LIGNITE MINING AREAS

Before the flooding of the final excavation can begin, the slopes must be prepared for their new function. To ensure the long-term stability of the slopes and edge zones, structural support using earth masses is required. It is planned that the necessary material will be sourced from the internal dump. Additionally, the future reservoir shoreline must be reprofiled and abrasion zones reinforced to protect against wave-induced erosion. These preparatory works are estimated to take approximately 15 years. Only upon their completion can the flooding process commence (Naworyta 2014).

Water for filling the excavation will be drawn from the border river Nysa Łużycka. However, available water resources will be limited due to the requirement to maintain minimum ecological flow in the river. It is estimated that the complete filling of the excavation will take between 20 and 25 years. As a result, the total flooding process is expected to take 35 to 40 years following the end of mining. If lignite extraction ceases in 2044, the resulting reservoir would be fully formed between 2079 and 2084. This timeline cannot be accelerated; thus, time remains the primary constraint in the implementation of the PSP project in the post-mining area of the Turów mine. Similar limitations are expected for the other two prospective locations in the Bełchatów and Szczerców lignite mines.

The construction of the upper reservoir will require large-scale earthworks on the external dump. Depending on the selected variant (see Table 4), between 7 and 101.3 million cubic meters (M m^3) of earth material will need to be relocated to the excavation. This will necessitate the occupation of approximately 85 to 430 hectares of forested area for the upper reservoir alone. Additional space will be required for derivation pipelines, access roads, and PSP facilities. The mass relocation process must be coordinated with the earthworks required for preparing the final excavation.

Currently, the dump is covered with forest stands of varying ages, ranging from 15 to 60 years. The youngest stands are located on the upper part of the dump, where the upper reservoir is planned. By 2044, when mining is expected to cease, these trees will be at least 38 years old. In accordance with Polish regulations, obtaining the necessary permits for deforestation of the former external dump will be a prerequisite for construction of the upper reservoir.

7. COORDINATION OF PSP CONSTRUCTION WITH THE MINE DECOMMISSIONING PROCESS: BENEFITS AND CHALLENGES

The construction of a pumped-storage power plant (PSP) in the future post-mining area of the Turów lignite mine is inherently a long-term undertaking, primarily due to the ongoing mining operations. While approximately two decades remain until the end of exploitation under the current concession, certain preparatory actions can be initiated well in advance. Early implementation of selected tasks would not only reduce the overall cost of PSP construction but also accelerate the mine decommissioning process.

A key aspect of the PSP development is the need to relocate large volumes of material from the top of the external dump—ranging from 7 to 101.3 million cubic meters (M m^3), depending on the design variant. The excavated material can be effectively used to stabilize the slopes of the final excavation. Earthworks on the dump can be carried out using existing mining machinery such as excavators and spreaders, connected by belt conveyor systems. These machines, scheduled for gradual withdrawal at the end of lignite exploitation, can be redeployed to the top of the dump via the existing ramp system. Additionally, former transport routes on the dump—used prior to 2006 to move material from the pit to the dump—can be repurposed for locating conveyor lines.

Carrying out these operations in parallel with the mine decommissioning will expedite PSP construction and significantly reduce costs. By contrast, using standard construction equipment such as single-bucket excavators, trucks, and haulers would be more expensive and time-consuming. A major advantage of combining excavation closure with PSP construction lies in the reuse of earth masses from the PSP site to shape the final excavation into a reservoir.

Another logistical benefit is the downward direction of earth transport—from the top of the dump to the pit—which greatly reduces transport costs. From a financial perspective, it is also important to highlight that the most expensive component of a PSP—a large lower reservoir—will already be constructed as part of the mine reclamation process. This reservoir will be developed regardless of the decision to implement a PSP, thus significantly lowering the marginal cost of PSP development.

8. POTENTIAL ENVIRONMENTAL AND SOCIAL CONFLICTS DURING THE CONSTRUCTION OF A PUMPED-STORAGE POWER PLANT ON THE SITE OF A DECOMMISSIONED LIGNITE MINE

The construction of a pumped-storage power plant in the area of the decommissioned Turów mining and energy complex raises no significant concerns regarding social or environmental impacts. As part of the post-mining land reclamation process, the excavated pit will be filled with water regardless of whether the pumped-storage facility is built. Prior to inundation, the steep slopes of the future reservoir must be reshaped using approximately 100 million cubic metres of earth materials to reduce their inclination. The process of filling the pit with water is also independent of the decision to construct the pumped-storage power plant. There is no alternative method for reclaiming such a large and deep final excavation other than filling it with water.

Potential environmental issues may arise only in connection with the construction of the upper reservoir on the plateau of the external overburden dump, which has already been successfully afforested as part of the reclamation process. Before authorisation for the construction of the upper reservoir within the PSP project can be granted, an Environmental Impact Assessment (EIA) procedure must be conducted, along with an amendment to the spatial development plan of the Bogatynia municipality. Polish law requires public participation in both of these procedures.

In the course of constructing the pumped-storage power plant, the key environmental impacts will occur during the implementation phase rather than during the operational phase of the facility. The environmental nuisance associated with the operation of a pumped-storage power plant is essentially negligible. Implementing a similar project in a natural, mountainous area unaltered by mining activities would encounter considerable difficulties, primarily due to the interference with the natural landscape. Most mountainous regions in Poland are legally protected owing to their high natural and landscape value. Furthermore, mountain areas are, to some extent, inhabited and developed, which would likely lead to social conflicts associated with reservoir construction.

The utilisation of post-mining areas, such as the site of the former Turów lignite deposit, for the construction of a pumped-storage power plant allows such environmental and social conflicts to be effectively avoided.

9. SUMMARY AND CONCLUSIONS

The presented case study supports the conclusion that post-lignite mining areas offer viable conditions for the construction of a pumped-storage power plant (PSP). In such settings, the final excavation can serve as the lower reservoir, while the elevation difference between the water table and the top of the external overburden dump provides the necessary head. An upper reservoir with a capacity ranging from approximately 15 to 96 million cubic meters (M m^3) can be constructed on the dump, providing the technical basis for a PSP with an estimated capacity of 700 to 1,400 MW.

The proposed location for a PSP within the Turów lignite mine area is particularly advantageous due to its proximity to existing power grid infrastructure. The current transmission lines, used by the Turów power plant for lignite-based electricity generation, could be adapted for PSP operation, facilitating both power intake and output.

The construction of the upper reservoir will be a costly undertaking, primarily due to the need to relocate a large volume of overburden material from the external dump to the Turów lignite mine excavation. However, integrating the construction of the upper reservoir with the reinforcement of excavation slopes prior to flooding may significantly reduce the overall cost of both processes. Additionally, utilizing decommissioned mining equipment for earthworks on the dump can further lower investment expenditures, as well as reduce the costs associated with excavation and material transport.
The beginning of operations at the Turów pumped-storage power plant (PSP), planned for the future post-mining areas of the Turów lignite mine, primarily depends on the mine's decommissioning timeline—particularly the process of flooding the final excavation. Preparing the excavation to serve as a reservoir and subsequently filling it with water is expected to take nearly four decades following the end of mining activities. Integrating the mine closure process with the construction of the upper reservoir for PSP Turów could yield multiple benefits for both projects, including cost and time efficiencies.

Moreover, the development of PSP infrastructure on former lignite mine sites would contribute significantly to national energy security by providing flexible, large-scale energy storage.

The presented case study illustrates the potential that lies within post-lignite mining areas. In addition to the analyzed location, other former opencast mines—such as Bełchatów, Szczerców, Tomisławice, and Lubstów—also exhibit favorable conditions for similar development. An important factor supporting the construction of pumped-storage power plants (PSPs), beyond terrain configuration, is the absence of residential and infrastructural development in these areas. As a result, the development of PSPs in post-mining sites is unlikely to trigger social opposition and protests that often accompany such projects in densely populated or urbanized regions.

This research was funded by AGH University of Krakow, Faculty of Civil Engineering and Resource Management; subsidy number: 16.16.100.215.

REFERENCES

1. Álvarez, H, Domínguez, G, Ordóñez, A, Menéndez, J, Álvarez, R and Loredo, J 2021. Mine water for the generation and storage of renewable energy: A hybrid hydro–wind system. *International Journal of Environmental Research and Public Health*, 18, 6758. doi:10.3390/ijerph18136758
2. Antoniadis, A, Roumpos, C, Anagnostopoulos, P and Paraskevis, N 2021. Planning RES projects in exhausted surface lignite mines—Challenges and solutions. *Materials Proceedings* **5**, 93. doi:10.3390/materproc2021005093
3. Bajcar, A, Szczepiński, J and Rogosz, B 2021. Bathymetry surveys of post-mining pit lakes formed after exploitation of lignite. *Materials Proceedings* **5**, 117. doi:10.3390/materproc2021005117
4. Bódis, K, Kougias, I, Taylor, N and Jäger-Waldau, A 2019. Solar photovoltaic electricity generation: A lifeline for the European coal regions in transition. *Sustainability* **11**, 3703. doi:10.3390/su11133703
5. Carreras, BA, Colet, P, Reynolds-Barredo, JM and Gomila, D 2021. Assessing blackout risk with high penetration of variable renewable energies. *IEEE Access* **9**. doi:10.1109/ACCESS.2021.3114121
6. Jardón, S, Ordóñez, A, Álvarez, R, Cienfuegos, P and Loredo, J 2013. Mine water for energy and water supply in the Central Coal Basin of Asturias (Spain). *Mine Water and the Environment* **32(2)**. doi:10.1007/s10230-013-0224-x
7. Fan, J, Xie, H, Chen, J, Jiang, D, Li, C, Ngaha Tiedeu, W and Ambre J 2020. Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs. *Applied Energy* **258**, 114007. doi:10.1016/j.apenergy.2019.114007
8. Kaliński, J 2016. Zagłębia węgla brunatnego w Polsce po 1945 r. [Lignite basins in Poland after 1945]. W: Jarosz-Nojszewska, A, Morawski, W (red.), *Problemy energetyczne Polski*. *Część I: Surowce*. Warszawa: OW SGH. (In Polish)
9. Kałuza, T, Hämmerling, M, Zawadzki, P, Czekała, W, Kasperek, R, Sojka, M, Mokwa, M, Ptak, M, Szkudlarek, A, Czechlowski, M, et al. 2022. The hydropower sector in Poland: Barriers and the outlook for the future. *Renewable and Sustainable Energy Reviews* **163**, 112500.
10. Kowalski, E, Rotkegel, M and Stałęga, S 2008. Uwarunkowania geologiczno-inżynierskie wznowienia budowy Elektrowni Szczytowo-Pompowej „Młoty" koło Bystrzycy Kłodzkiej [Geological and engineering conditions for the resumption of construction of the Pumped-Storage Power Plant "Młoty" near Bystrzyca Kłodzka]. *Górnictwo i Geoinżynieria* **32**, 213–226. (In Polish)

11. Krupa, K, Nieradko, Ł, Haraziński, A 2018. Prospects for energy storage in the world and in Poland in the 2030 horizon. *Polityka Energetyczna – Energy Policy Journal* **21(2)**, 19–34. doi:10.24425/122770
12. Kulpa, J, Kopacz, M, Stecuła, K and Olczak, P 2024. Pumped storage hydropower as a part of energy storage systems in Poland—Młoty case study. *Energies* **17(8)**, 1830. doi:10.3390/en17081830
13. Latona, D, Pinedo, E and Lombardi, P 2025. How warning signs hinted at Spain's unprecedented power outage. Reuters. Access: Mai 2025. https://www.reuters.com/business/energy/spain-suffered-multiple-power-incidents-build-up-full-blackout
14. Menéndez, J, Fernández-Oro, JM, Galdo, M and Loredo, J 2020. Efficiency analysis of underground pumped storage hydropower plants. *Journal of Energy Storage* **28**, 101234. doi:10.1016/j.est.2020.101234
15. Menéndez, J, Ordóñez, A, Álvarez, R and Loredo, J 2019. Energy from closed mines: Underground energy storage and geothermal applications. *Renewable and Sustainable Energy Reviews* **108**, 498–512. doi:10.1016/j.rser.2019.04.007
16. Naworyta, W 2014. Discussion on the future development of the post-mining areas of LM Turów, taking into account the possibilities and limitations. *Węgiel Brunatny* **2(87)**, 22–26. (In Polish)
17. Naworyta, W 2025. Assessment of the possibility of balancing energy consumption in a household using a PV installation and energy storage. *Zeszyty Naukowe IGSMiE PAN*, 1(113), 17–33. doi:10.33223/zN/2025/02 (In Polish, abstract in English)
18. Nowak, B, Szadek, P, Szymański, K and Lawniczak-Malińska, A 2023. Concept and implementation of solutions improving water relations in the area of the flooded opencast lignite mine Kazimierz Północ in the East Wielkopolska Region (Central-West Poland). *Water* **15(4)**, 706. doi:10.3390/w15040706
19. Rzętała, M, Jagus, A and Rzętała, M 2013. Water storage in anthropogenic lakes in southern Poland during high and low water stages. *Chemistry-Didactics-Ecology-Metrology* **18**, 77–88. doi:10.2478/cdem-2013-0020
20. Sawicki, J 2009. Analiza technicznych możliwości budowy elektrowni szczytowo-pompowej w odkrywkach KWB Bełchatów [Analysis of the technical possibilities of building a pumped-storage power plant in the open-pit mines of the Bełchatów Lignite Mine]. *Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej*, 128. (In Polish, abstract in English)
21. Wachowiak, M and Wachowiak, A 2005. Zbiornik w wyrobisku końcowym odkrywki „Pątnów" Kopalni Węgla Brunatnego „Konin" i jego bilans wodny za okres 2003–2004 [The reservoir in the final excavation of the "Pątnów" open pit of the "Konin" Lignite Mine and its water balance for the period 2003–2004]. Badania Fizjograficzne nad Polską Zachodnią. Seria A, *Geografia Fizyczna*, 56, 157–176. (In Polish)
22. Wójcik, J and Krzaklewski, W 2019. Afforestation as a method of reclamation of soilless land in brown coal mining in Poland. *Ecological Engineering & Environmental Technology* **20(1)**, 24–37. doi:10.12912/23920629/106204