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Hybrid energy storage system using post-mining infrastructure (HESS)



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Guidelines on the adaptation and use of inactive shafts possible to energy storage

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PART 1

Guidelines on the adaptation of shafts for a pumped storage power plant (PSH)

Table of contents

1. Introduction	7
2. Identification of mine shafts in Poland	7
2.1 Shafts of JSW hard coal mines	9
2.2 Shafts of PGG hard coal mines	11
2.3 Shafts of PKW S.A. hard coal mines	14
2.4 Shafts of private hard coal mines	15
2.5 WĘGLOKOKS hard coal mine shafts	16
2.6 Shafts of SRK hard coal mines liquidated and under liquidation	16
2.7 Shafts of liquidated SRK ore mines	17
2.8 Shafts of BOGDANKA hard coal mines	17
2.9 Shafts of KGHM copper mines	18
2.10 Shafts of the KŁODAWA Salt Mine	21
3. Characteristics of mine shafts	22
3.1 JSW S.A. shafts	22
3.1.1 Shaft "1-Bzie" – KWK Borynia-Zofiówka-Bzie mine, Ruch „Bzie”	23
3.1.2 Shaft VI – KWK Budryk mine	23
3.1.3 Shaft V – KWK Pniówek mine	24
3.2 PGG S.A. shafts	25
3.2.1 Shaft III – KWK Ruda mine, division Ruch Bielszowice	26
3.2.2 Shaft VII – "Staszic-Wujek Coal Mine ", Ruch "Murcki-Staszic"	28
3.3 Shaft of Południowt Koncern Węglowy S.A.	29
3.3.1 Shaft Grzegorz – ZG Sobieski mining plant	29
3.4 Shafts Węglokoks Kraj S.A.	31
3.4.1 Józef" shaft – Ruch "Bobrek"	31
3.5 Shafts of PG Silesia sp. z o.o.	32

3.5.1	Shaft No. 5 - KWK Silesia coal mine	32
3.6	Shafts from ZG Siltech sp. z o.o.	34
3.6.1	"Mikołaj" shaft - ZG "Siltech"	34
3.7	EKO-PLUS shafts	35
3.7.1	"Kopernik" shaft - ZG "Eko-Plus"	35
3.8	SRK shafts	37
3.8.1	"Paweł" shaft - CZOK, Ruch I, PG "Saturn"	37
3.8.2	Gigant Shaft – CZOK, Division II, PS „Pstrowski”	39
3.9	BOGDANKA shafts	41
3.9.1	Shaft 1.5 – „Nadrybie” area	41
3.10	Summary review of the mine shafts in Poland	43
4.	Identification and characteristic of mine shafts in Czech Republic	44
4.1	Coal Mine ČSM	44
4.2	Coal Mine ČSA	46
4.3	Coal Mine Darkov	48
5.	Identification and characteristic of mine shafts in Slovenia	49
5.1	General outline and mine access system	49
5.2	History of mine shaft construction	50
5.3	Modern era shafts	51
5.3.1	Ventilation shaft Pesje (1973)	51
5.3.2	Ventilation shaft Šoštanj I (1980)	52
5.3.3	Transport shaft Nove Preloge – NOP (1984/1987)	53
5.3.4	Intake shaft Šoštanj II (1993)	54
5.3.5	Ventilation shaft Nove Preloge II – NOP II (2017)	55
6.	Multicriteria system for assessment of mine shafts and underground workings	56
6.1	Shaft evaluation criteria	56
6.1.1	Shaft depth	56

6.1.2	Surface area for upper water reservoir	57
6.1.3	Shaft configuration	57
6.1.4	Hoisting devices	57
6.1.5	Methane content in mine workings	57
6.1.6	Shaft dewatering	58
6.2	Scoring for each criterion	58
6.2.1	Shaft depth	58
6.2.2	Surface area for upper water reservoir	59
6.2.3	Shaft configuration	60
6.2.4	Hoisting devices	60
6.2.5	Methane content in mine workings	61
6.2.6	Dewatering of mine workings	61
6.3	Importance of each criterion	61
6.4	Summary of multicriterial system for shafts assessment	62
7.	Selecting the shafts suitable for PSH implementation	63
7.1	Shafts with PSH implementation with a bottom water reservoir in Poland	63
7.1.1	Shaft II of KWK Budryk mine	64
7.1.2	Shaft II of KWK Budryk mine	65
7.1.3	Shaft 2.1 – "Stefanów" Region	66
7.1.4	Shaft 2.2 – "Stefanów" Region	67
7.1.5	Shaft "Grunwald III" – KWK "Ruda", "Halemba" Section	68
7.1.6	Shaft V – KWK "Ruda", "Bielszowice" Section	70
7.2	Shafts with PSH implementation with a bottom water reservoir in the Czech Republic	72
7.3	Shafts with PSH implementation with a bottom water reservoir in Slovenia	72
7.4	Further actions	73
8.	Literature	74

1. Introduction

This task determined the possibility of using the mine shafts for energy storage. Mine underground infrastructure, its equipment, dimensions and depth, and the distance from the nearest mine working as well as adopted hydroelectric power plant concept, its requirements from the point of view of hydrogeology and geoengineering were determined. These requirements will additionally help in designing the proper place for installation, so that the potential of HESS is used to the maximum and at the same time does not cause damage. An interdisciplinary system for comprehensive assessment and classification of shaft workings was developed. KOMAG, SUT and ITPE recognized Polish mines, VSB-TUO and PV recognized Czech and Slovenian mines, respectively.

2. Identification of mine shafts in Poland

During the work realization, mining infrastructure was identified, in particular the shafts. Since the shafts of closed mines are subject to backfilling in accordance with applicable law, all shafts of active mines that will be closed in the future were analysed.

Mine shafts have been divided according to the companies they belong to. Data were collected from mining companies, mining authorities and through personal communication. The list of all existing mine shafts, excluding museums and the "Barbara" Experimental Mine is updated at the beginning of 2024. Data regarding the shafts was collected from the following companies:

- Jastrzębska Spółka Węglowa S.A. (JSW)
- Polska Grupa Górnicza S.A. (PGG)
- Południowy Koncern Węglowy S.A. (PKW)
- Spółka Restrukturyzacji Kopalń S.A. (SRK)
- Węglokoks Kraj Sp. z o.o. (WĘGLOKOKS)
- Przedsiębiorstwo Górnicze „SILESIA” Sp. z o.o. (SILESIA)
- Zakład Górniczy EKO-PLUS Sp. z o.o. (EKO-PLUS)
- Zakład Górniczy SILTECH Sp. z o.o. (SILTECH)
- Lubelski Węgiel BOGDANKA S.A. (BOGDANKA)
- KGHM Polska Miedź S.A. (KGHM)
- Kopalnia Soli „KŁODAWA” S.A. (KŁODAWA)

Mine shafts of each company were assigned to the mines in which they are located, and then to the internal departments of these mines.

The list shows the number of shafts owned by each mine. The description of each shaft includes the following:

- name of the mine shaft,
- shaft function,
- shaft diameter,
- shaft depth,
- change in diameter with depth,
- height of the clearing,
- other information and comments such as: shaft lining type, different shaft cross-section, levels connected to the shaft, equipment, etc.

- information about the shafts under construction, flooded and withdrawn from operation.

This list enabled collecting the information on all 200 shafts located in Poland. Three of them are scheduled for liquidation by backfilling in the near future. This summary allows for the development of a system for selecting the shafts for energy storage and constitutes the basis for estimating the energy storage capacity in this type of installations in Poland. With this in mind, it should be emphasized that these data are partially sensitive data due to the strategic importance of the mining sector for the Polish economy.

The main results of the created list are the ability to determine the total number of shafts in Poland which, due to their size, can be adapted for energy storage.

The comparison will also allow estimating the total energy storage capacity in kWh.

In order to transfer the project results to a European scale, it was decided to create a comprehensive assessment tool enabling a preliminary assessment of the energy storage capacity of the shafts.

The location of the identified shafts is shown on maps based on Google maps [29].

Most of the mine shafts are located in the Upper Silesian Coal Basin (GZW). Of these, 162 shafts are related to hard coal mining, and one is ore mining. The remaining 6 coal shafts are in the Lublin Coal Basin (LZW). 28 copper ore shafts are located in the Legnica-Głogów Copper District (LGOM), and 3 salt shafts in the Polish Lowlands. There are currently no mine shafts in the Lower Silesian Coal Basin (DZW), and the newly constructed coal mine "Heddi II" in Ścinawka Średnia, owned by Nexano Minerals Sp. z o. o., intends to make the deposit available. In the GZW area, hard coal is extracted through mine shafts by deep mines belonging to the following companies: JSW, PGG, PKW, WĘGŁOKOKS, SILESIA, EKO-PLUS and SILTECH. Shafts of closed mines and those in the process of liquidation are managed by SRK (Fig. 1). Some of them are transformed into pumping stations protecting the workings of active mines against flooding, some of them serve as ventilation shafts, and three shafts are intended for liquidation by backfilling.

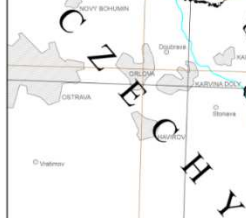


Fig. 1 Map of hard coal mining concessions in the GZW area (as of January 31, 2024) [4]

2.1 Shafts of JSW hard coal mines

Four JSW mining plants, organized in seven departments, extracting the coking coal, using 32 mine shafts. They are grouped in two areas: northern and southern. There are 16 shafts in the northern area: Shaft I, Shaft II, Shaft III, Shaft V and Shaft VI, belonging to the Budryk coal mine, as well as Ruch "Knurów" shaft "Jan" (III) belonging to the Knurów-Szczygłowiec coal mine (III), the "Paweł" Shaft, the "Foch I" Shaft, the "Foch II" Shaft, the "Aniołki" Shaft and the Shaft VI (fig. 2).

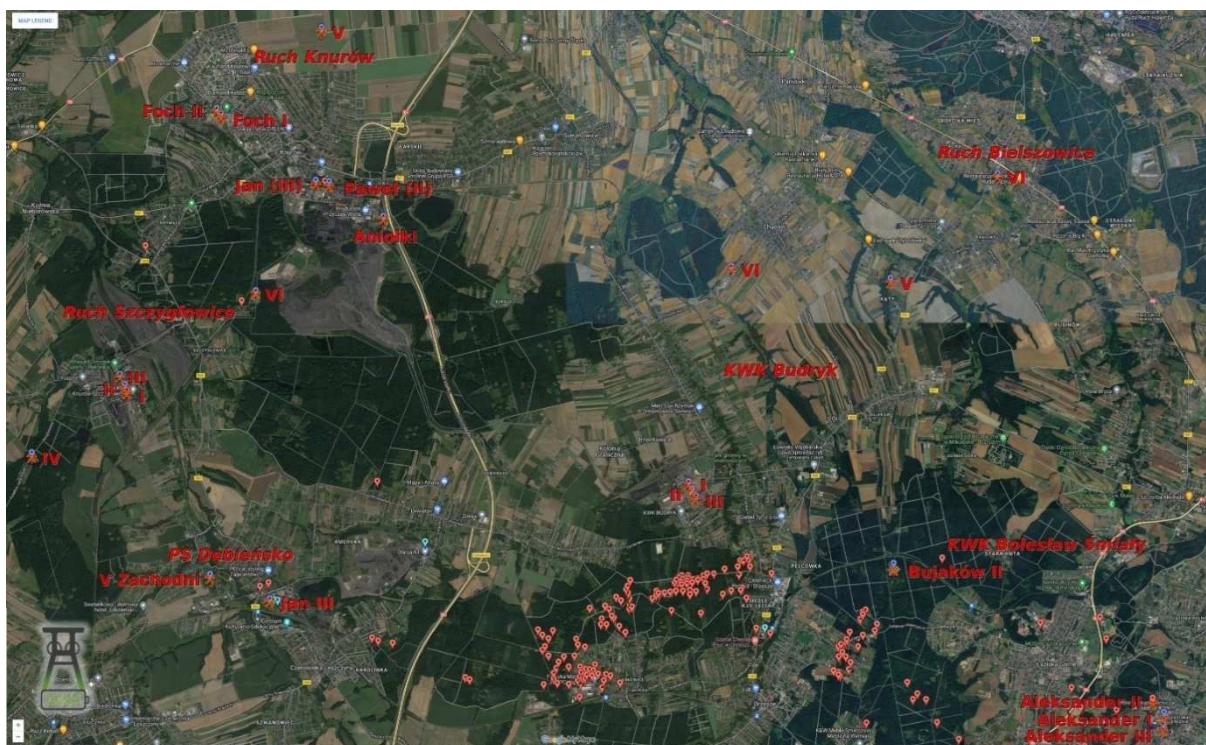


Fig. 2 Map of JSW – Obszar N and KWK “Bolesław Śmiały” (PGG) coal mines shafts localization

The remaining 16 mine shafts are located in the southern area. The "Pniówek" coal mine includes Shaft Ludwik, Shaft II, Shaft III, Shaft IV and Shaft V. The "Borynia-Zofiówka-Bzie" Division "Borynia" coal mine includes: Shaft I, Shaft II, Shaft III, Shaft V and Shaft VI, the "Zofiówka" Division includes: Shaft Iz, Shaft IIz, Shaft IIIz, Shaft IVz and Shaft Vz, and the "Bzie" Division includes the "Jan Paweł" Shaft (1-Bzie) (fig. 3).



Fig. 3 Map of JSW – Obszar S and Ruch „Jastrzębie III” (SRK) coal mines shafts localization

2.2 Shafts of PGG hard coal mines

In the GZW area, there are seven mining plants belonging to PGG (Fig. 4), with 72 mine shafts.

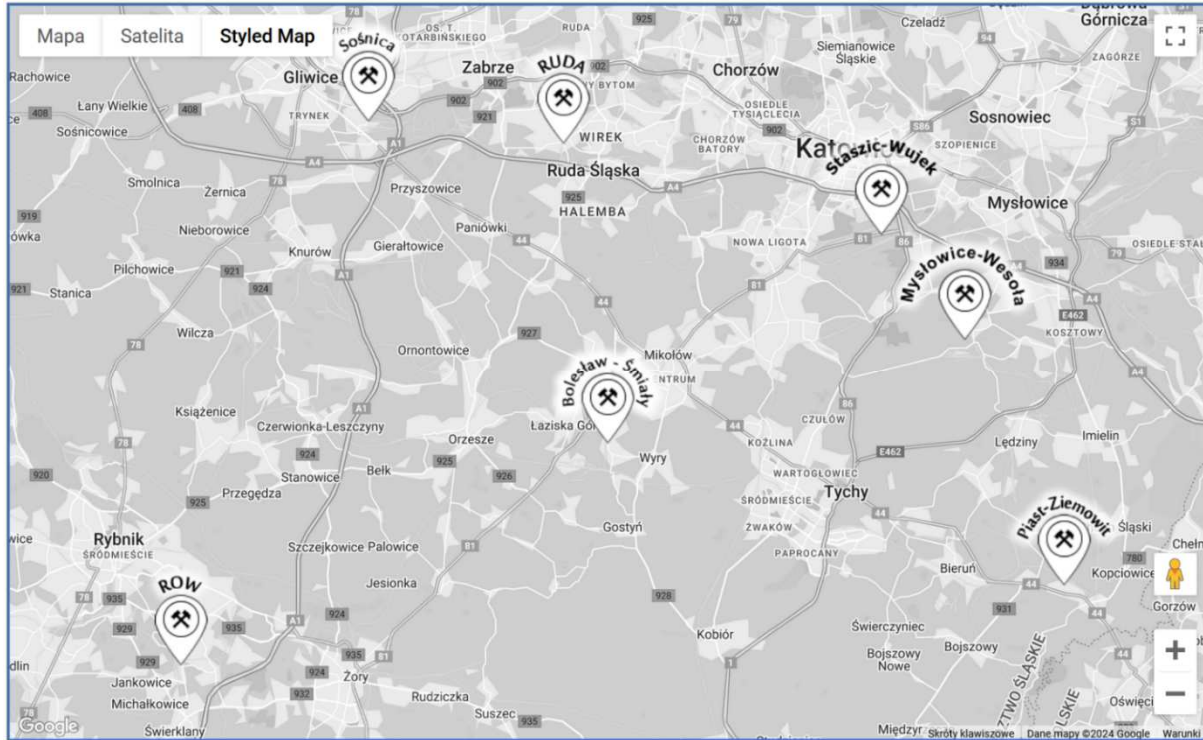


Fig. 4 Map of the location of PGG mining plants in the GZW area [5]

Among the PGG mines in the southwestern part of the GZW, coal is mined by KWK "ROW", which has 21 shafts. Mining is carried out in 4 moves. The "Chwałowice" Movement includes Shaft I, Shaft II, Shaft V, Shaft VII and Shaft VIII. The "Jankowice" Movement operates Shaft 2, Shaft 4, Shaft 3 ("Poniatowski"), Shaft 4, Shaft 7 and Shaft 8. The two-field "Marcel" Movement uses Shaft III ("Julia"), Shaft IV ("Bartek"), the "Wiktor" Shaft, the "Antoni" Shaft and the "Marklowice I" Shaft, the "Marklowice II" Shaft and the "Underground" Shaft. The "Ruch Rydułtowy" operates the "Leon II" Shaft, the "Leon IV" Shaft, the "Erbreich" Shaft ("Air I") and the "Agnieszka" Shaft ("Air V") (Fig. 5).

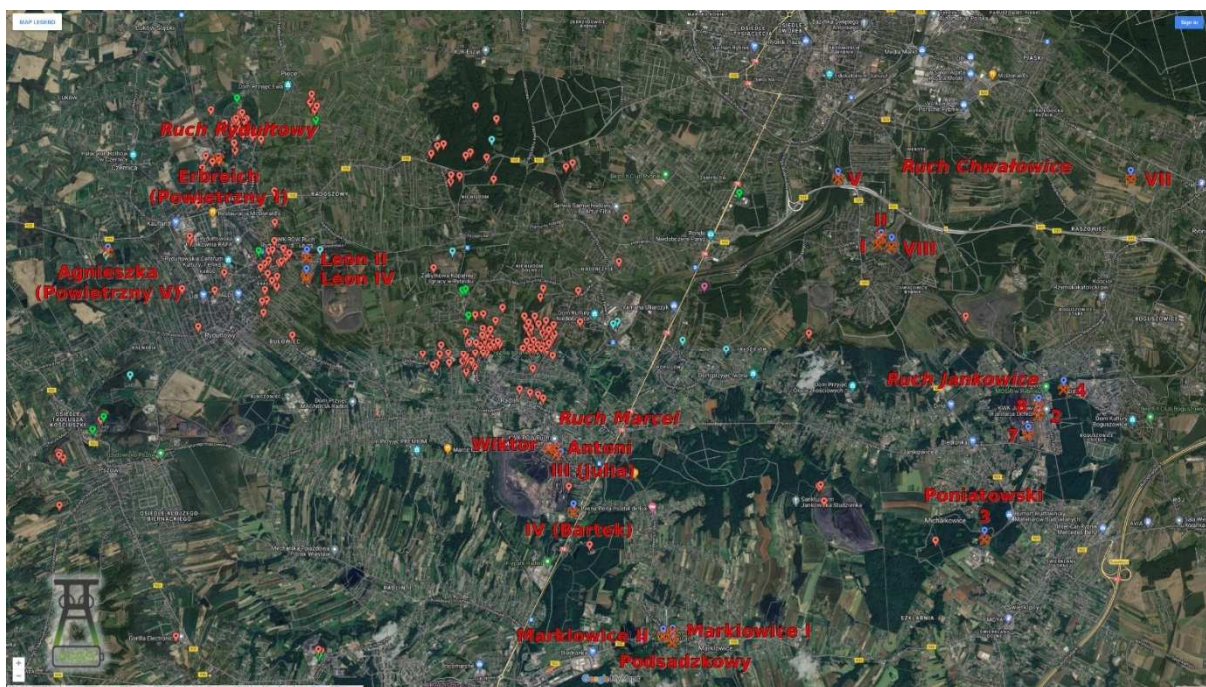


Fig. 5 Map of the location of mine shafts of KWK "ROW" (PGG) - GZW, SW part

In the western part of the GZW, hard coal is extracted by two PGG mining plants: the KWK "Sośnica", which has 7 shafts: Shaft III, Shaft IV, Shaft V, Shaft VI, Shaft VII, Shaft "Bojków" and "Backfilling" Shaft and two-field coal mine "Ruda", in which Ruch "Bielszowice" has 8 shafts: Shaft I, Shaft II, Shaft III, Shaft IV, Shaft V, Shaft VI, Shaft "Pawłów Górny I" and Shaft "Pawłów Górny II", and Ruch "Halemba" has 6 shafts: the "Grunwald II" Shaft, the "Grunwald III" Shaft, the "Grunwald IV" Shaft, the "Northern I" Shaft, the "Northern II" Shaft and the "Eastern" Shaft. (Fig. 6).

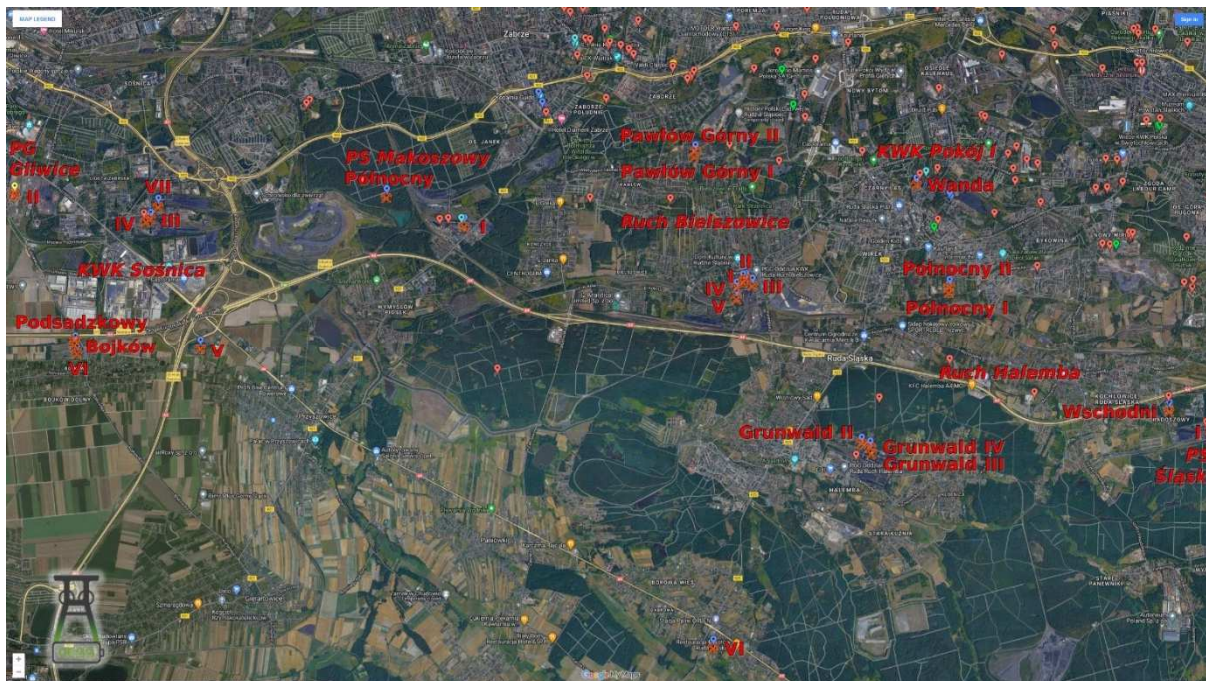


Fig. 6 Map of the location of the PGG and SRK mine shafts – GZW W part

To the south of the "Ruda" coal mine, there is the "Bolesław Śmiały" coal mine, in which there are four shafts: the "Aleksander I" shaft, the "Aleksander II" shaft, the "Aleksander III" shaft and the "Bujaków II" shaft (Fig. 2).

There are two mines operating in the central part of the GZW. The first is the two-motion coal mine "Staszic-Wujek", where on the "Wujek" movement there are 4 shafts: the "Lechia" shaft, the "Krakus" shaft, the "Ventilation I" shaft and the "Ventilation II" shaft, and on the "Murcki-Staszic" shaft another 6 shafts: Szyb I, Szyb II, Szyb IV, Szyb V, Szyb VII and Szyb "Zygmunt". The second one is the "Mysłowice-Wesoła" coal mine with one "Wesoła" mine, with 5 shafts: the "Bronisław" shaft, the "Piotr" shaft, the "Karol" shaft, the "Wacław" shaft and the "Ventilation II" shaft (Fig. 7).



Fig. 7 Map of the location of the PGG and SRK mine shafts - GZW, middle part

In the south-eastern part of GZW, PGG mines hard coal in the two-stage mining plant of KWK "Piast-Ziemowit", using 11 mine shafts (Fig. 8). There are 6 shafts in the "Ziemowit" Movement: Szyb I, Szyb II, Szyb III, Szyb "Szewczyk", Szyb "W-I" ("Wiatrok") and Szyb "W-II". Ruch "Piast" has 4 shafts: Szyb I, Szyb II, Szyb III and Szyb IV. The eleventh "K-1" shaft is used by the "Wola" Pumping Station, which is the retention and dosing reservoir of saline waters of the "Piast" and "Ziemowit" mines.



Fig. 8 Map of the location of PGG and PKW mine shafts - GZW part SE

2.3 Shafts of PKW S.A. hard coal mines

In the extreme eastern and south-eastern mining areas of GZW, three PKW mining plants operate. In total, they use 17 mine shafts. 6 of them operate in the east as part of the "Sobieski" Mine i.e. Shaft "Kazimierz", Shaft "Traugutt", Shaft "Sobieski III", Shaft "Karolina", Shaft "Helena" and Shaft "Leopold". The seventh shaft of this mine is under development - the "Grzegorz" Shaft (Fig. 9).

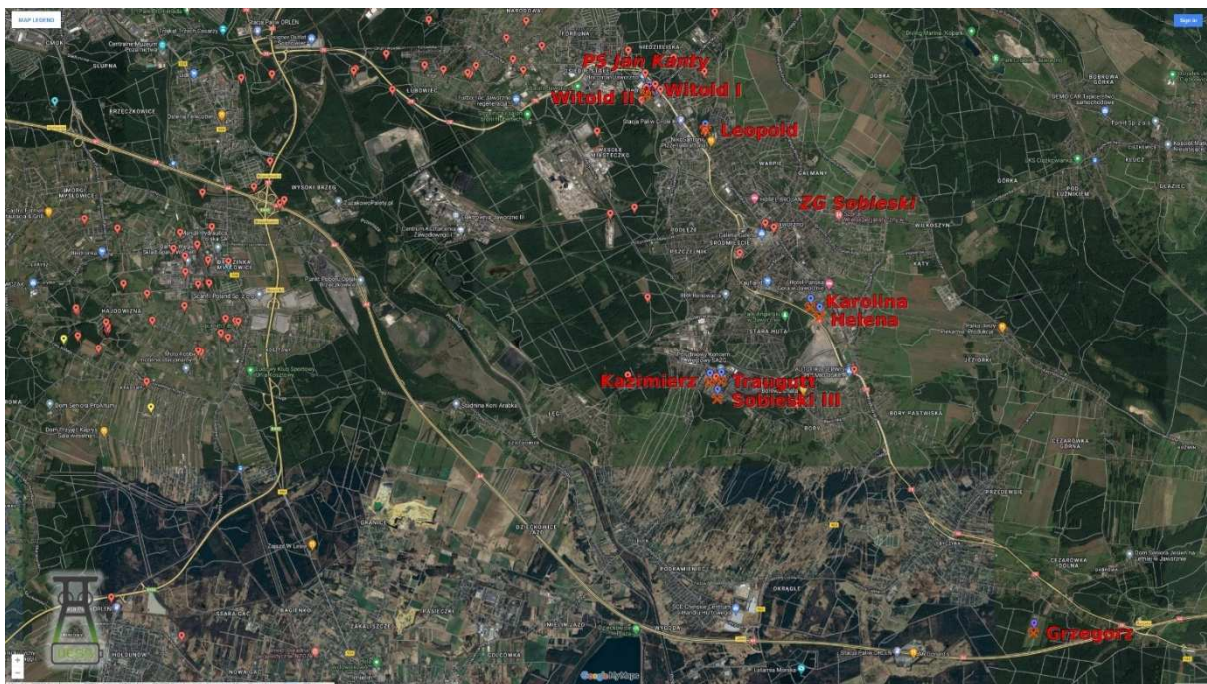


Fig. 9 Map of the location of PKW and SRK mine shafts - GZW, part E

The "Janina" Mining Plant extracts steam coal in the south-east of GZW, using 5 shafts: the "Janina I" shaft, the "Janina III" shaft, the "Janina IV" shaft, the "Janina VI" shaft and the "Zachodni" shaft (Fig. 8).

The third PKW plant, located in the south of the "Brzeszcze" Mine, has another 5 shafts: the "Andrzej I" Shaft, the "Andrzej II" Shaft, the "Andrzej V" Shaft, the "Andrzej VIII" Shaft and the "Andrzej IX" Shaft (Fig. 10).

2.4 Shafts of private hard coal mines

To the south-west Private PG "Silesia" Sp. operates from the "Brzeszcze" mine. z o. o. with one KWK "Silesia" mine. This mine has 4 shafts: Shaft "No. 1", Shaft "No. 2", Shaft "No. 3" and Shaft "No. 5".



Fig. 10 Map of the location of the PKW and SILESIA mine shafts - GZW part S

The remaining two private mining plants are located in the northern part of the GZW (Fig. 11). The EKO-PLUS mine operates 1 shaft: the "Kopernik" shaft. Similarly, 1 shaft operates in the SILTECH mine: the "Mikołaj" shaft.

there is Shaft "Witold I" and Shaft "Witold II" (Fig. 9). At the "Pstrowski" pumping station, Shaft "Gigant" and Shaft "Staszic" are operational. At the "Szombierki" pumping station, there is Shaft "Ewa." At the "Siemianowice" pumping station, Shaft "Zygmunt August," Shaft "Railway I," Shaft "Siemianowice III," and Shaft "Bańgów" are operational. At the "Centrum" pumping station, there is Shaft "Budryk" and Shaft "Staszic" (Fig. 11).

Of the remaining SRK shafts, the "Ventilation and Backfilling Shaft" of the former "Powstańców Śląskich" Pumping Station serves as a ventilation and emergency-inspection function for the private EKO-PLUS mine (Fig. 11), and two shafts of the Jastrzębie III Coal Mine: the "Jas I" Shaft and The "Jas IV" shafts (Fig. 3) are being liquidated by complete backfilling, in accordance with the requirements of the Geological and Mining Law - implementing regulations (Journal of Laws 2017, item 1118, §88), Warsaw, June 2017.

2.7 Shafts of liquidated SRK ore mines

The last of the CZOK stationary pumping stations is PS "Bolko", which removes water from the goaf of copper ore mines. The pumping station is located in the "Bolko" Shaft (Fig. 11).

2.8 Shafts of BOGDANKA hard coal mines

Lubelski Węgiel Bogdanka S.A. Mine is located in the Central Coal District (CRW) located in the north-eastern part of the Lublin Coal Basin (LZW). The mining areas of the mine are divided into three mining fields - the Bogdanka field, the Stefanów field and the Nadrybie field. In each of the fields there is a pair of shafts: ventilation and material transport shafts. In the Bogdanka District these are Shaft "1.2" and Shaft "1.3", in the Nadrybie District - Shaft "1.4" and Shaft "1.5", and in the Stefanów District - Shaft "2.1" and Shaft "2.2" (Fig. 12).



Fig. 12 Map of location of LW "Bogdanka" mine shafts - CRW area

2.9 Shafts of KGHM copper mines

There are three deep copper mines operated by KGHM in the LGOM area. In total, there are 28 mine shafts, providing access to copper ore deposits in eight mining areas (Fig. 13).

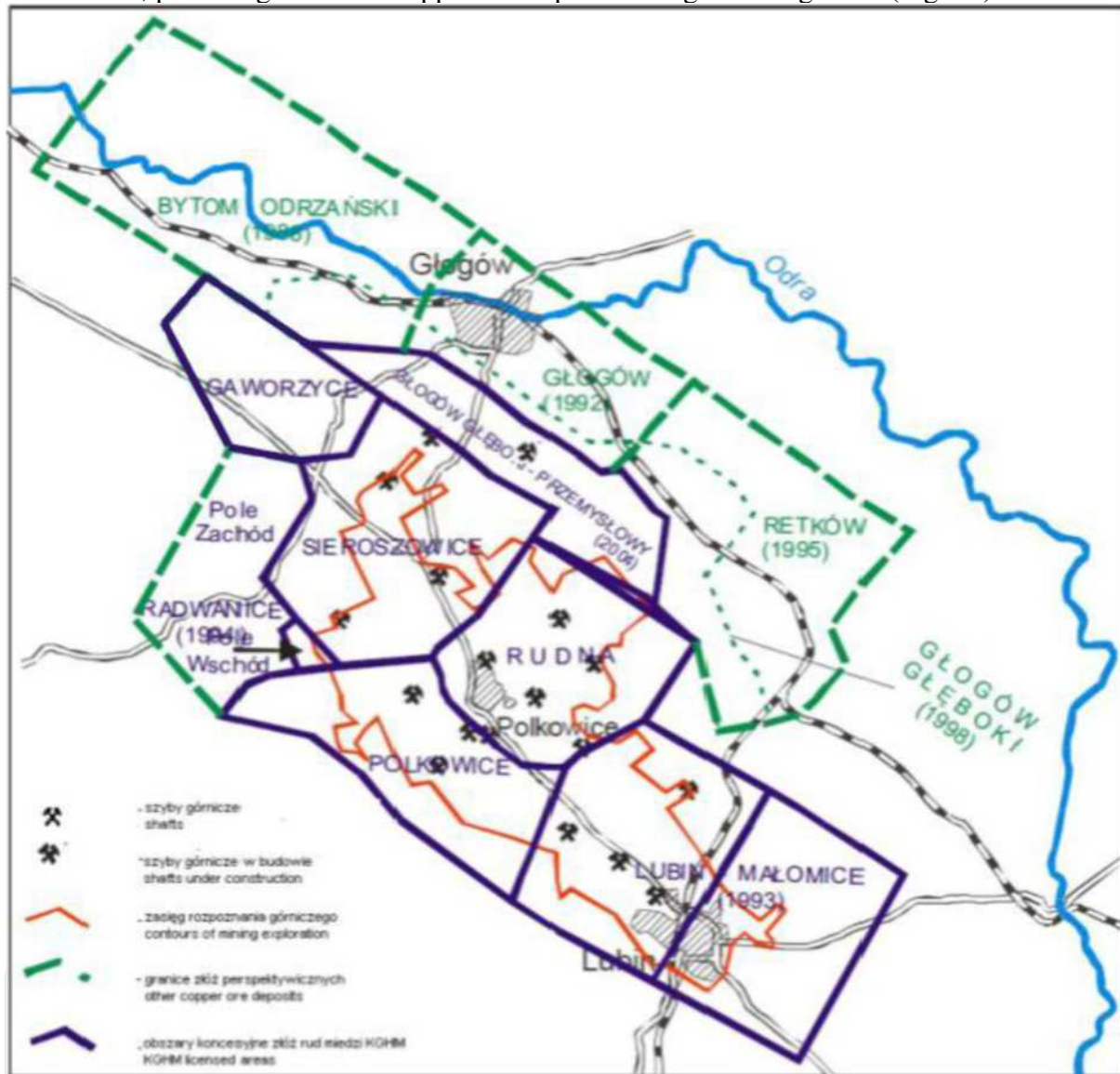


Fig. 13 Map of KGHM mining plants on the LGOM area [3]

In the southern part of the LGOM, north-west of the city limits of Lubin, there are 7 shafts of the "Lubin" Mining Plant, exploiting the copper ore deposit in the "Lubin-Małomice" mining area at a depth of 550 to 1006 m. There is a shaft in the Lubin Główny area. "L-I" and Szyb "L-II", in the Lubin Wschodni area - "L-III" Shaft and "L-VII" Shaft, in the West Lubin area - "L-IV" Shaft and "L-V" Shaft, and in Rynarce - "L-VI" shaft (Fig. 14).

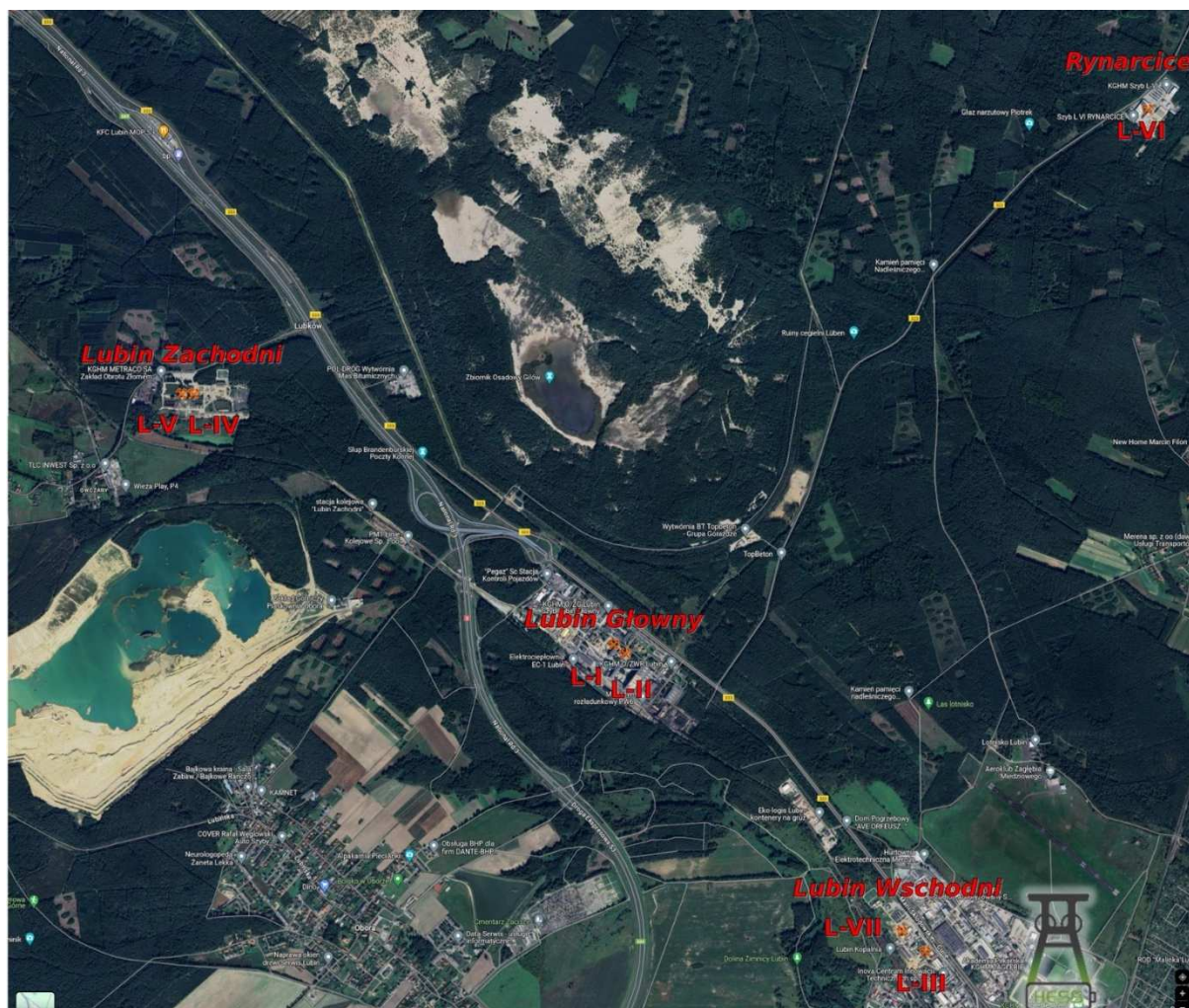


Fig. 14 Map of location of KGHM - ZG Lubin - LGOM mine shafts, part S

"Polkowice-Sieroszowice" mining plants have 11 mine shafts located in the western (Fig. 15) and north-western (Fig. 16) parts of LGOM, west and north-west of the city border of Polkowice. The "Polkowice-Sieroszowice" mine conducts its basic mining activities in four mining areas: "Polkowice", "Radwanice Wschód", "Sieroszowice" and "Gaworzyce", and in the mining area "Głogów Wiedzy - Przemysłowy", where an investment project related to making this deposit available for exploitation. In the "Polkowice" mining area, in the "Polkowice Główny" area, there are the "P-I" Shaft and the "P-II" Shaft, in the "Polkowice Zachodnie" area - the "P-IV" Shaft and the "P-V" Shaft, and in Sobin there is the "P-V" Shaft. P-VII. In the "Sieroszowice" mining field, in Kaźmierzów there is the "SW-1" Shaft ("Jan Wyżykowski"), in Sieroszowice - the "SW-3" Shaft (Fig. 15), and in Jerzmanowa, "Sieroszowice Główny" has the "SG-1" Shaft ("Saint James") and Shaft "SG-2". The "SW-4" ("Tadeusza Zastawniaka") shaft is located in Łagoszów Mały, right next to the border of the "Sieroszowice" copper ore deposit area with the "Głogów Wiedzy - Przemysłowy" copper ore deposit area located to the north. In the area of the latter deposit, the deepest shaft in Poland, "GG-1" ("Józef Zwierzyckiego"), operates in Kwielice, which was transferred to the "Rudna" mine (Fig. 16).



Fig. 15 Map of KGHM mines shafts – ZG Polkowice-Sieroszowice – LGOM part W



Fig. 16 Map of KGHM mines shafts – ZG Polkowice-Sieroszowice – LGOM part N

"Rudna" exploiting copper ore deposits mainly in the "Rudna" mining area. In the central part of LGOM, east and north-east of the city of Polkowice, there are 10 shafts. In the "Rudna Główna" area there are the "R-I" Shaft, "R-II" Shaft and "R-V" Shaft, in the "Rudna Zachodnia" area there is the "R-I" Shaft. "R-III", Shaft "R-IV" and Shaft "R-X", in the area of "Rudna Północna" there is Shaft "R-VII", near Pieszkowice there is Shaft "R-VIII", near Komorniki there is Shaft "R- IX", and near Grodowiec - Shaft "R-XI" (Fig. 17).



Fig. 17 Map of the location of KGHM mine shafts - ZG Rudna - LGOM, central part

2.10 Shafts of the KŁODAWA Salt Mine

The last three mine shafts are located in the central part of the Polish Lowland, in the Kłodawa area. These are the shafts of the "Kłodawa" Salt Mine: the "Michał" Shaft, the "Barbara" Shaft and the "Chrobry" Shaft (Fig. 18).



Fig. 18 Map of the location of KS "Kłodawa" mine shafts - the central part of the Polish Lowlands

3. Characteristics of mine shafts

Mine shafts have been systematized and discussed in separate groups for each managing company. Due to the assumptions in the project application, only shafts of hard coal mines were subjected to multi-criteria analysis.

Illustrations showing the location of the shafts based on the map of the Polish Geological Institute - National Research Institute [25], and the infrastructure and development of the area were based on the Geoportal orthophoto map [22]. The study used data published and obtained from managing mines, as well as from the "Drilling holes" database of the Polish Geological Institute [25]. The photos were taken from the "Explorers" forum [13], mining press [2, 24], websites [12, 14, 15, 16, 17, 18, 19, 20, 21, 23, 26, 27, 28, 30, 31], and some of them were performed during the task implementation [1].

The data collected during the project realization included in this study are partially sensitive data due to the strategic importance of the mining sector for the Polish economy.

This report contains selected examples of the developed shaft characteristics.

3.1 JSW S.A. shafts

Characteristics of 32 hard coal mine shafts belonging to four JSW S.A> mining plants were developed, organized in 7 divisions

1. KWK „Borynia-Zofiówka-Bzie”
 - 1.1. Ruch „Borynia”
 - 1.2. Ruch „Zofiówka”
 - 1.3. Ruch „Bzie”
2. KWK „Budryk”
3. KWK „Knurów-Szczygłowiec”
 - 3.1. Ruch „Knurów”
 - 3.2. Ruch „Szczygłowiec”
4. KWK „Pniówek”

3.1.1 Shaft “1-Bzie” – KWK Borynia-Zofiówka-Bzie mine, Ruch „Bzie”

The 1 Bzie shaft, named Jan-Paweł, is an intake shaft that provides access to the Bzie-Dębina 1-Zachód and Bzie-Dębina 2-Zachód deposits in Bzie near Jastrzębie-Zdrój (Fig. 19). The shaft is connected to the workings of the Ruch Zofiówka at a level of 1,110 m. The shaft was deepened in the years 2010 ÷ 2016. The shaft bottom is located at an altitude of 269 m above sea level. Its depth is 1,164.00 m, diameter is 8.0 m. It has a level of 1,110 m. It is equipped with a shaft tower 34 m high.

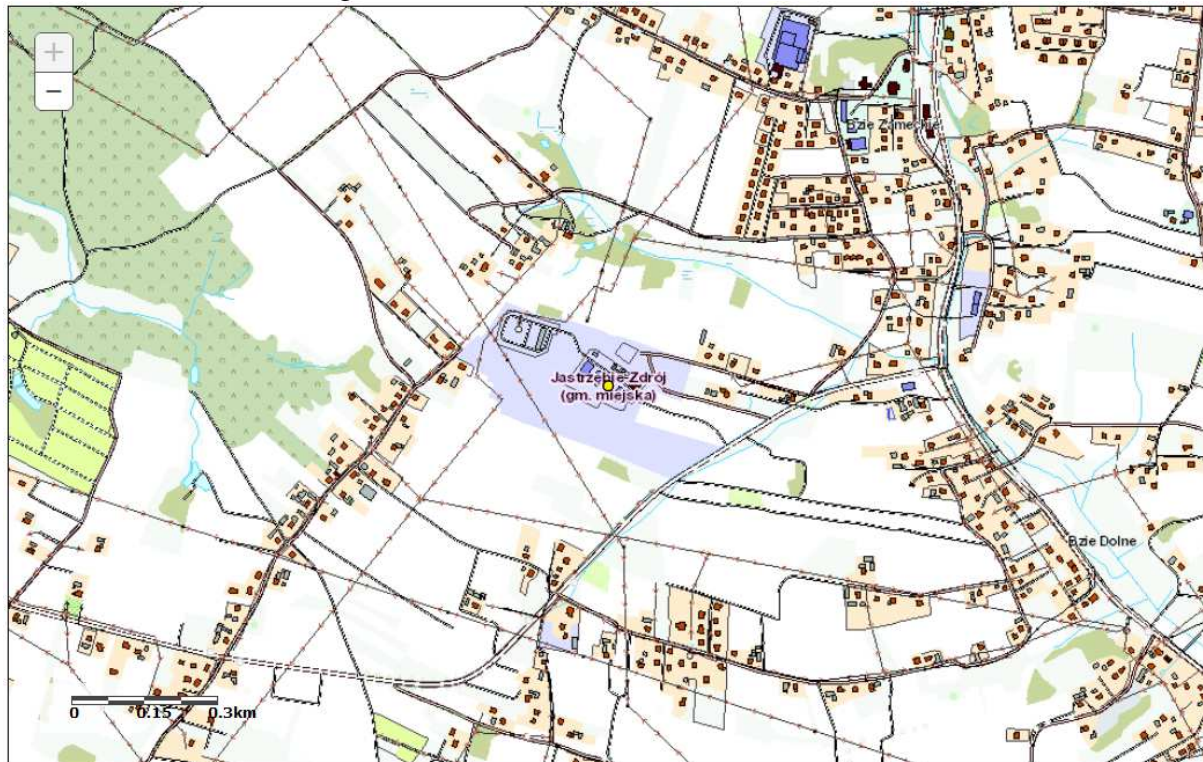


Fig. 19 Ruch „Bzie” – location of „Bzie-1” (Jan-Paweł) Shaft

3.1.2 Shaft VI – KWK Budryk mine

Shaft VI is an intake shaft for transportation of people and materials, located peripherally in Chudów (Fig. 20). The deepening of the shaft was completed in 2015. The shaft bottom is located at an altitude of 253.70 m above sea level. Its depth is 1,319.60 m, diameter is 9.0 m and it is the deepest coal shaft in Poland. It offers levels of 900m, 1050m and 1290m.

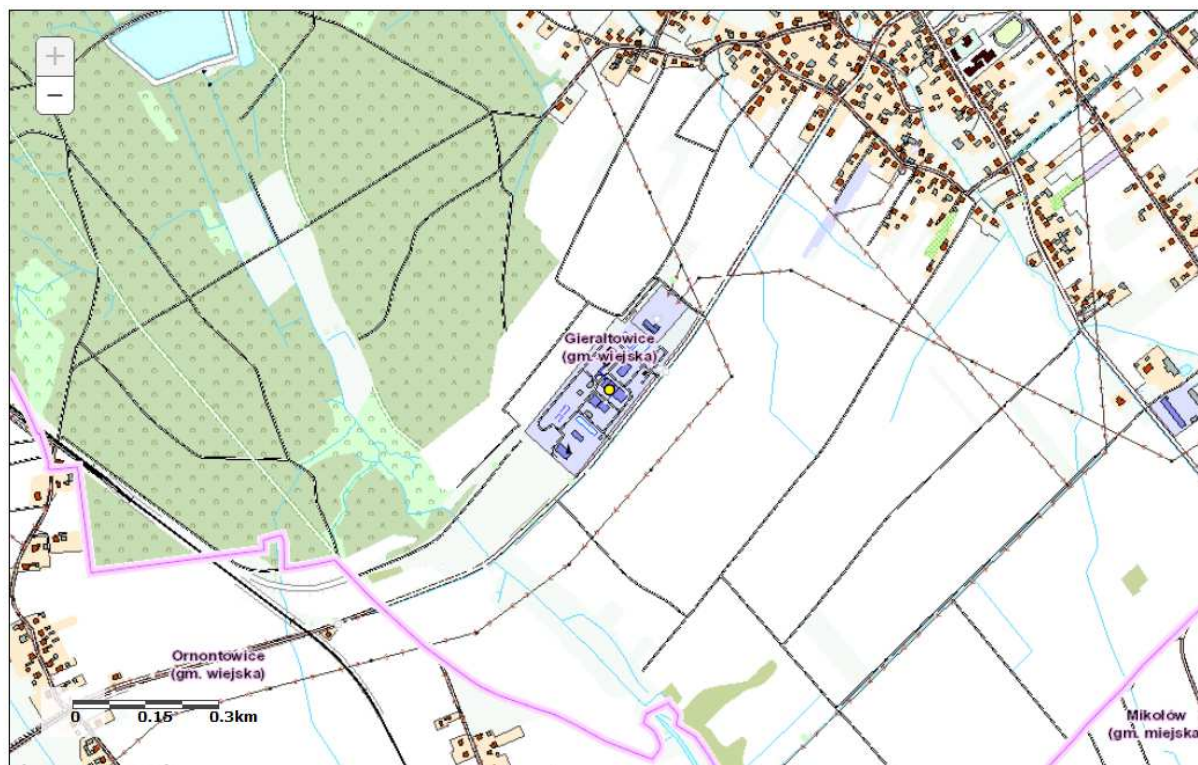


Fig. 20 KWK "Budryk" - location of the peripheral Shaft VI in Chudów

3.1.3 Shaft V – KWK Pniówek mine

Shaft V is a peripheral ventilation shaft located in Pawłowice Koźle (Fig. 21). It was developed from November 1, 1974 to January 1, 1977. The shaft bottom is located at an altitude of 264.79 m above sea level. Its depth is 1,017.5 m and its diameter is 7.5 m. On average, 14,500 m³/min of air from VAM flows through it.



Fig. 21 "Pniówek" Coal Mine - location of Shaft V and the main fan station

Shaft V is connected to the main fan station by two main supply channels, laid on the ground surface, of which Channel N is used, and Channel S is a reserve channel (Fig. 22). The main fan station at shaft IV has an average capacity of 10,800 m³/min. Shaft V ventilates parts P and W of the "Pniówek" deposit and parts PW, PN and PE of the "Pawłowice 1" deposit. The average methane concentration in ventilation air was 0.33% in 2023 at an air flow of 13,492 m³/min. Forecasts regarding the coal mining plans envisage maintaining high methane concentration in Shaft V, which will range from 0.15% to 0.42% in the coming years.



Fig. 22 Pniówek Coal Mine - Shaft V, Channel S and main fan station with diffusers [1]

At Shaft V, as part of the REM project, the world's first innovative installation is being implemented to reduce methane emissions into the atmosphere from the abandoned areas of an operating mine. Methane obtained from post-mining goaf will be used to produce electricity in specially designed gas motors connected to power generators.

3.2 PGG S.A. shafts

Characteristics of 72 hard coal mine shafts belonging to 7 PGG mining plants, organized in the following 13 divisions, was developed:

1. KWK ROW mine:
 - 1.1. Ruch Chwałowice
 - 1.2. Ruch Jankowice
 - 1.3. Ruch Marcel
 - 1.4. Ruch Rydułtowy
2. KWK "Ruda" mine:
 - 2.1. Ruch Bielszowice
 - 2.2. Ruch Halemba
3. KWK Piast-Ziemowit mine:
 - 3.1. Ruch Piast
 - 3.2. Ruch Ziemowit
4. KWK Bolesław Śmiały mine
5. KWK Sośnica mine
6. KWK Staszic-Wujek mine
 - 6.1. Ruch Wujek

- 6.2. Ruch Murcki-Staszic
- 7. KWK Mysłowice-Wesoła
- 8. KWK „Bolesław Śmiały”

3.2.1 Shaft III – KWK Ruda mine, division Ruch Bielszowice

Shaft III is an intake shaft transporting people and run-of-mine located on the area of the main plant of Ruch Bielszowice Division in Ruda Śląska Bielszowice (Fig. 23).



Fig. 23 Ruch Bielszowice division - location of the Shaft III on the area of the main plant

Construction of Shaft III was planned before 1939, but was completed after the war. The current depth is 1055.19 m, diameter 7.2 m. It offers levels: 160m, 260m, 320m, 642m, 840m, 900m and 1000m. The shaft bottom is located at an altitude of 255.69 m above sea level. It has a tower (Fig. 24). In the eastern section there are two 6-story cages.



Fig. 24 Ruch Bielszowice division - Shaft III tower, as of 2023 [14]

3.2.2 Shaft VII – "Staszic-Wujek Coal Mine ", Ruch "Murcki-Staszic"

Shaft VII is an intake ventilation shaft located on the area of the main plant of Ruch "Murcki-Staszic" division in Katowice Giszowiec (Fig. 25).

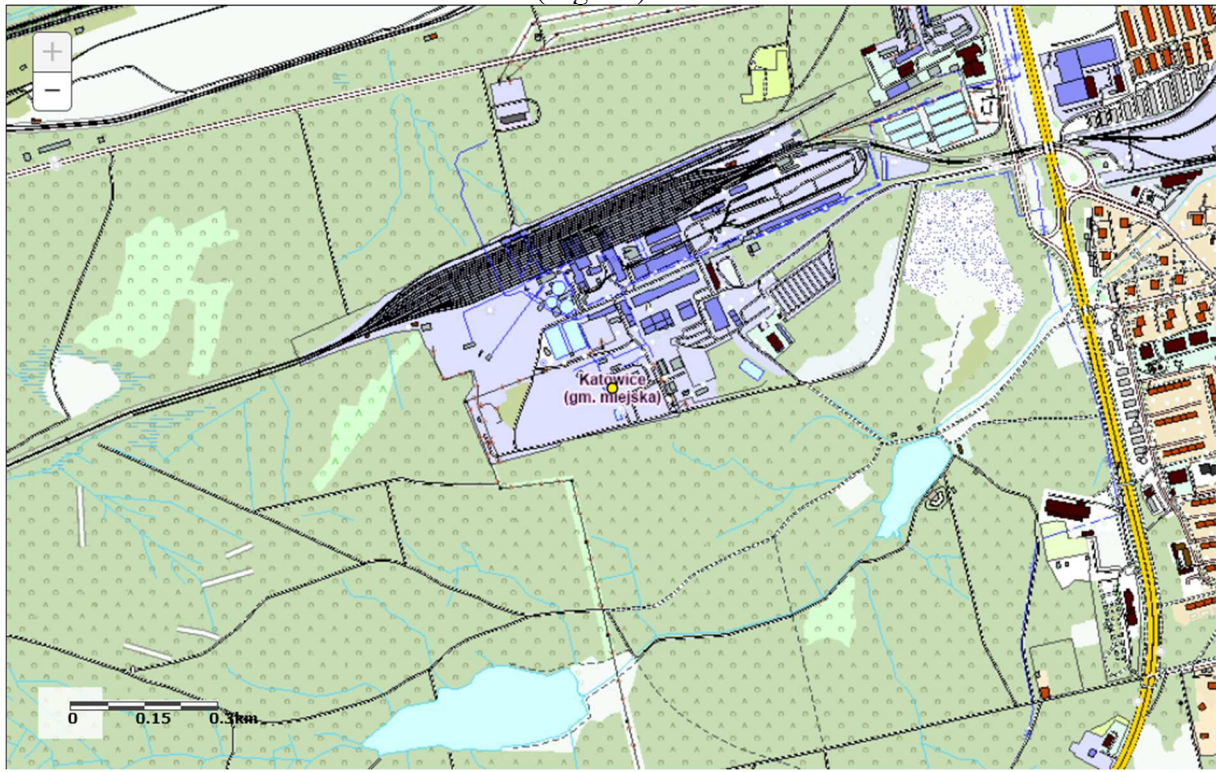


Fig. 25 Ruch Murcki-Staszic division - location of Shaft VII on the area of the main plant

The shaft VII was deepened in the years 1987 ÷ 1990. The shaft reached a depth of 1126.00 m with a diameter of 9.0 m. The shaft provides levels of 720 m, 830 m and 900 m, below which it is flooded with water. The shaft bottom is located at an altitude of 294.60 m above sea level. The shaft is not finished, has no tower and reinforcement (Fig. 26).



Fig. 26 Ruch Murcki-Staszic division - unarmed Shaft VII, 2013 [24]

3.3 Shaft of Południowy Koncern Węglowy S.A.

Out of three mines of Południowy Koncern Górniczy S.A. - the Brzeszcze Mining Plant extracts steam coal in methane seams is carried out by. Coal is mined through three shafts and ventilation is realized through two ventilation shafts.

The characteristics of 17 hard coal mine shafts belonging to the following three PKW mining plants were developed:

1. ZG Brzeszcze
2. ZG "Janina"
3. ZG "Sobieski"

3.3.1 Shaft Grzegorz – ZG Sobieski mining plant

The "Grzegorz" shaft is an intake ventilation shaft under construction, and in the longer term also a material and transport shaft, located peripherally to the "Sobieski" mine in Byczyna - a district of Jaworzno (Fig. 27).



Fig. 27 Sobieski Mine - location of the peripheral Grzegorz Shaft

Development of the Grzegorz shaft started in September 2017. In January 2024, it was 353.0 m deep with a diameter of 7.5 m. At the first stage of shaft development, a depth of 591.20 m is to be reached by 2027. The target depth of the "Grzegorz" shaft is 870 m. The shaft will provide access to the Dąb deposit. The shaft bottom is located at an altitude of 258.00 m above sea level. It is equipped with a trestle tower with 2 compartments (Fig. 28).



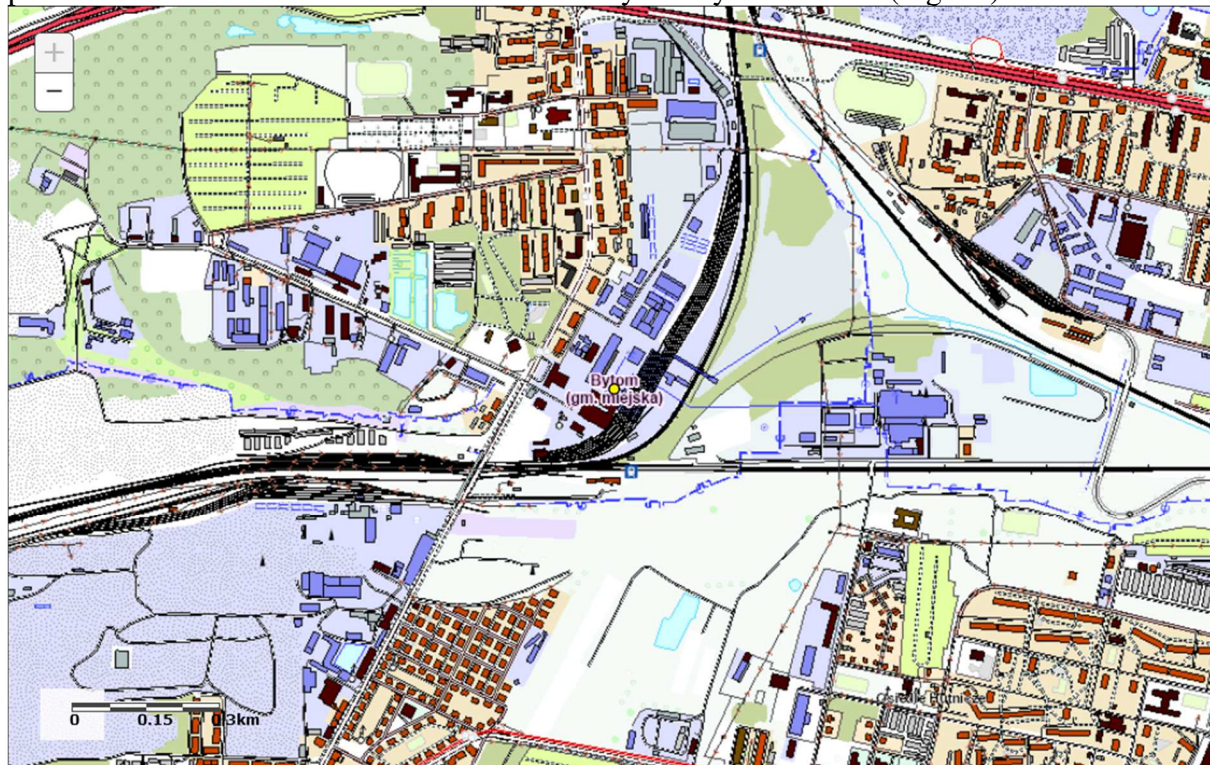
Fig. 28 ZG Sobieski mining plant - trestle tower of the deepened peripheral shaft "Grzegorz", 2024 [6]

3.4 Shafts Węłokoks Kraj S.A.

Węłokoks Kraj S.A. has one two-shift coal mine Bobrek-Piekary. Ruch Bobrek operates in Bytom, and Ruch "Piekary" in Piekary Śląskie is in liquidation. The characteristics of 4 hard coal mine shafts belonging to the company was developed.

3.4.1 Józef" shaft – Ruch "Bobrek"

The "Józef" shaft is an intake, material transporting and exit shaft located on area of the main plant of Ruch "Bobrek" - KWK "Bobrek-Piekary" in Bytom Bobrek (Fig. 29).



Rys. 29 Ruch „Bobrek” division – location of Józef Shaft on the area of the main mining plant in Bytom Bobrek

The sinking of the "Józef" ("Gräfin Johanna") shaft began in 1907 ÷ 1910. Initially, the shaft was 105 m deep and 5.8 m in diameter. It was deepened to a depth of 871.21 m. Below the depth of 96 m, it has a diameter of 6.4 m. The shaft provides levels of 540m, 726m and 840m. The shaft core is located at an altitude of 285.04 m above sea level. It is equipped with a strut tower (fig. 30).



Fig. 30 Ruch Bobrek division - strut tower of the Józef shaft on the area of the main plant, 2011 [13]

3.5 Shafts of PG Silesia sp. z o.o.

Przedsiębiorstwo Górnicze "Silesia" sp. z o.o. owns one coal mine "Silesia" in Czechowice-Dziedzice. The "Silesia" hard coal deposit contains significant amounts of methane, occurring both physically and chemically bound to the coal as the so-called sorbed methane, as well as filling the pores and cracks in the coal and waste rocks as the so-called free methane. A significant part of the sorbed methane is released in ventilation air directly to the atmosphere. Methane drainage uses a surface methane drainage station and a network of underground methane pipelines. The mine is ventilated through two ventilation shafts.

3.5.1 Shaft No. 5 - KWK Silesia coal mine

Shaft No. 5 is an exhaust ventilation shaft, located peripherally in Rudółtowice, in the "Czechowice II" mining area. (fig. 31).



Fig. 31 KWK Silesia mine – location of the peripheral Shaft V in Rydułtów

Shaft No. 5 was built in 1966 in a concrete casing. After deepening in 1983, it reached a final depth of 291.68 meters with a diameter of 6.50 meters. The undershaft is on level I (288 m) and entry to level 0 (205.35 m above sea level). The shaft core is located at an altitude of 252.66 m above sea level. The shaft is unreinforced and has no extraction devices. The only equipment is a ladder compartment (Fig. 32).



Fig. 32 KWK "Silesia" - Shaft V and main fan station in Rydułtów, 2013 [13]
The new fan station from 2019 is equipped with two main fans.

3.6 Shafts from ZG Siltech sp. z o.o.

Zakład Górniczy "Siltech" sp. z o. o. owns one coal mine in Zabrze Rokitnica. There is no methane hazard in the mine and it is extremely dry - the water flow to the workings is below 1 m³/min. Coal mining is carried out on a decline basis. The peripheral ventilation shaft "Mikołaj" is used to ventilate the workings.

3.6.1 "Mikołaj" shaft - ZG "Siltech"

The "Mikołaj" shaft is an exhaust ventilation and inspection shaft, located peripherally in Zabrze Rokitnica (Fig. 33).



Fig. 33 ZG Siltech mining plant - location of the peripheral "Mikołaj" shaft in Zabrze Rokitnica

Deepening of the "Mikołaj" shaft was carried out in 1904. The shaft has a depth of 429.30 m, a diameter of 4.0 m. The shaft has levels of 250 m and 380 m. The shaft bottom is located at an altitude of 266.26 m above sea level. It is equipped with a steel trestle tower and an inspection hoist (Fig. 34).



Fig. 34 ZG "Siltech" - peripheral shaft "Mikołaj" and the main fan station in Rokitnica, 2018 [15]

The main fan station is equipped with two axial fans for main ventilation.

3.7 EKO-PLUS shafts

Zakład Górniczy "Eko-Plus" sp. z o. o. owns one coal mine in Bytom. There is no methane hazard in the mine and it is extremely dry - the water flow to the workings is below 1 m³/min. ZG "Eko-Plus" uses one shaft. The peripheral "Ventilation and Backfilling" shaft belonging to SRK is used to ventilate the workings.

3.7.1 "Kopernik" shaft - ZG "Eko-Plus"

The "Kopernik" shaft is an intake shaft transporting run-of-mine, materials and people, located on the area of the "Eko-Plus" plant in Bytom (Fig. 35).

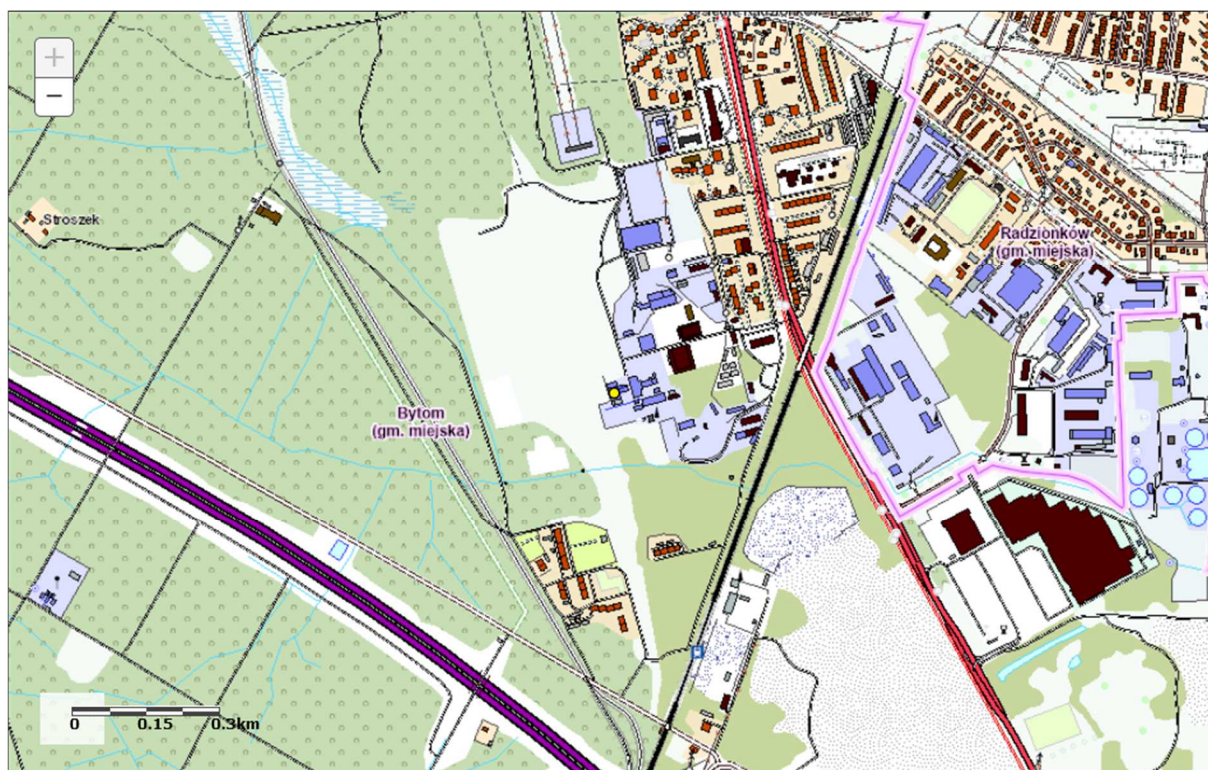


Fig. 35 ZG „Eko-Plus” – location of the Kopernik shaft on the main mining plant. Deepening of the "Kopernik" (formerly "Glück Auf") shaft was carried out in 1923 ÷ 1926. The shaft is 676.10 m deep and has a diameter of 6.6 m. The shaft has a level of 650 m. The shaft bottom is located at an altitude of 288.65 m above sea level. It is equipped with a strut tower and 2 compartments: the eastern one is closed, the western one is a cage-skip compartment (Fig. 36).



Fig. 36 ZG "Eko-Plus" - strut tower of the "Kopernik" shaft on the premises of the main plant, 2013 [12]

3.8 SRK shafts

Currently, SRK is under liquidation by filling two shafts of the Jastrzębie III coal mine. These are the "Jas I" Shaft and the "Jas IV" Shaft.

SRK maintains the "Ventilation and Filling Shaft" of the former "Powstańców Śląskich" Pumping Station, which has ventilation, emergency and inspection functions for the private Eko-Plus mine.

The SRK Branch - Central Mine Drainage Plant (CZOK) maintains 28 shafts of closed mines in which drainage areas, called "Pumping Rooms", operate. The panes are grouped in two Divisions:

- Division I – Submersible Pumping Stations (PG) with 7 closed shafts
- Division II – Stationary Pumping Stations (PS) with 22 active shafts

3.8.1 "Paweł" shaft - CZOK, Ruch I, PG "Saturn"

The Paweł shaft is a shaft transformed into the "Saturn" PG, located in Czeladź Piaski (Fig. 37).

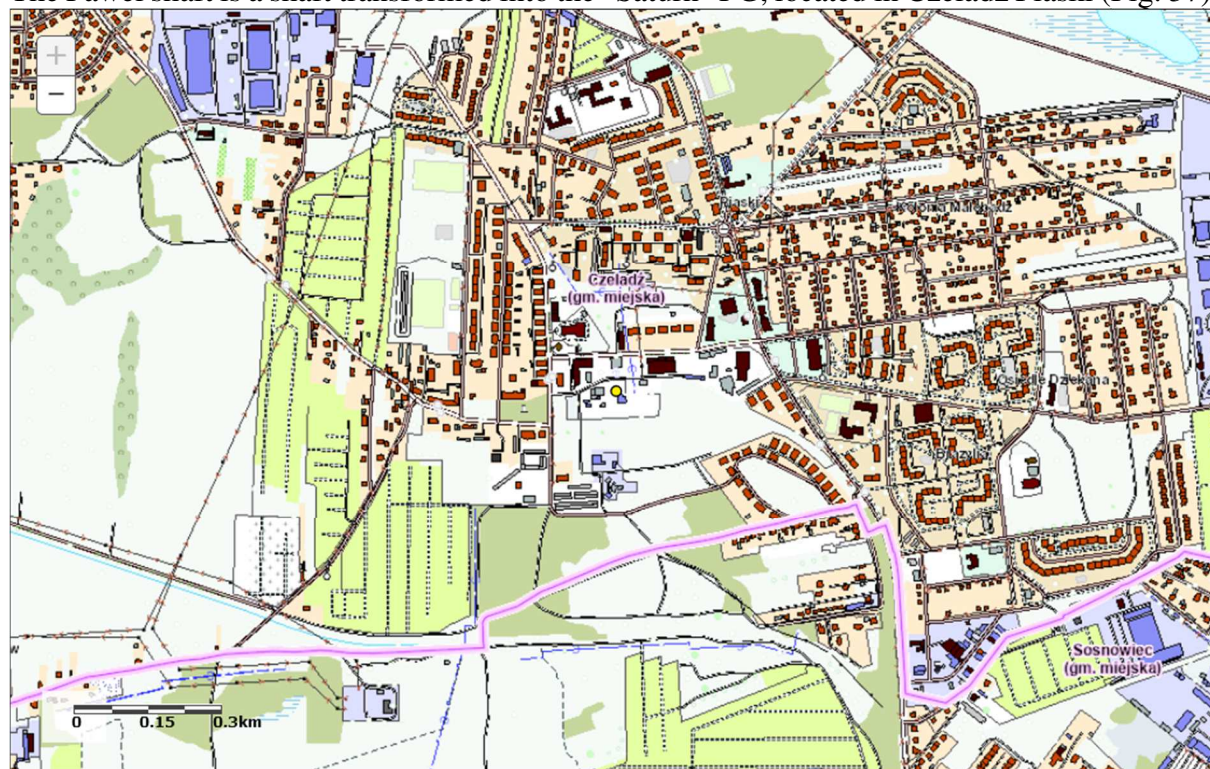


Fig. 37 SRK, CZOK, Ruch I - location of the "Paweł" shaft of the PG "Saturn" plant in Piaski

Before filling the plug, the "Paweł" shaft was 242.60 m deep and 6.4 m in diameter. The shaft bottom is located at an altitude of 276.56 m above sea level. (Fig. 38).



Fig. 38 PG "Saturn" - Bottom of the "Paweł" Shaft, at the back there is a device for **lowering** the pumps into the shaft [1]

During the transformation into a submersible pumping station, the "Paweł" shaft was partially flooded. The permissible damming level is +90.0 m above sea level, which corresponds to a depth of 193.56 m, the maximum pumping level is +86.0 m above sea level, the minimum pumping level is +83.0 m above sea level. Submersible pumps are lowered at the ends of steel pipes into the shaft inside protective pipes placed in the shaft's charging plug (fig. 39).

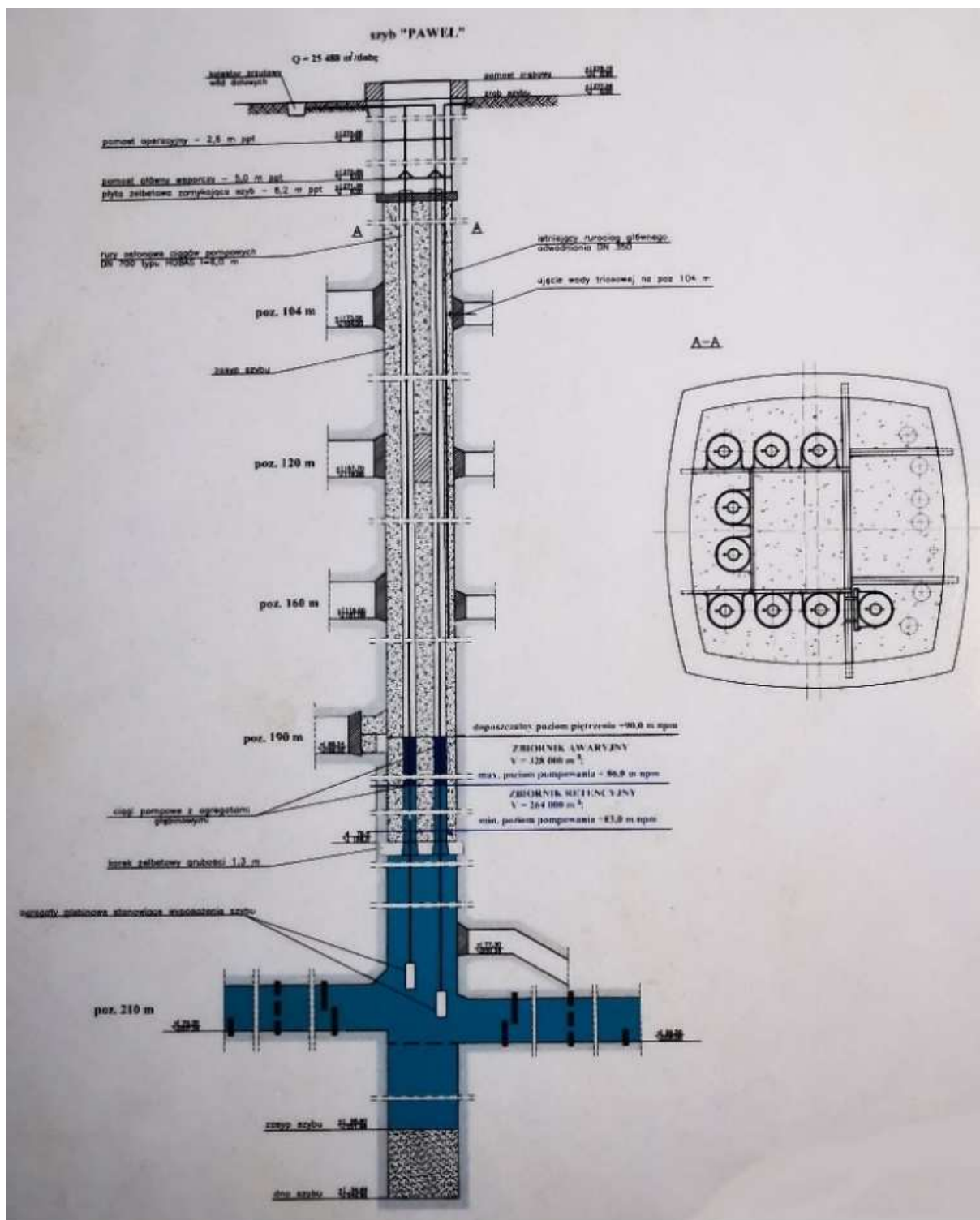


Fig. 39 PG „Saturn” – Paweł shaft cross-section [7]

3.8.2 Gigant Shaft – CZOK, Division II, PS „Pstrowski”

The "Gigant" shaft is an intake shaft, transporting materials and people, with two compartments, used by PS "Pstrowski", located in Zabrze Rokitnica (Fig.40).



Fig. 40 SRK, CZOK, Ruch II - location of the "Gigant" shaft of PS "Pstrowski" in Zabrze Rokitnica

The "Gigant" shaft has a depth of 874.55 m and a diameter of 8.0 m. The shaft provides levels of 575 m and 825 m. The shaft bottom is located at an altitude of 280.73 m above sea level. The shaft has a brick reinforcement with cement mortar - thickness 0.76 m (3 bricks). It is equipped with a 60 m high steel trestle tower. In the southern section there is a single-rope hoist with 4-story cages, used for moving people and transporting materials. The lift in the northern section was closed and replaced with CZOK pipelines. On the south-eastern side of the shaft from the level 825 m to the shaft bottom there is a ladder compartment (Fig. 41).



Fig. 41 PS "Pstrowski" - trestle tower of the "Gigant" shaft in Zabrze Rokitnica, 2021 [19]

Quite a large amount of water is pumped out through the "Gigant" shaft, not exceeding 20 m³/min.

3.9 BOGDANKA shafts

Lubelski Węgiel "Bogdanka" S.A. owns one hard coal mine in the Lublin Coal Basin. Six shafts located in three areas. There is no methane gambling in the mine. The mine has a large water inflow to the workings, exceeding 15 m³/min.

3.9.1 Shaft 1.5 – „Nadrybie” area

Shaft 1.5 is a peripheral intake shaft located in the "Nadrybie" Area in Nadrybie (Fig. 42).

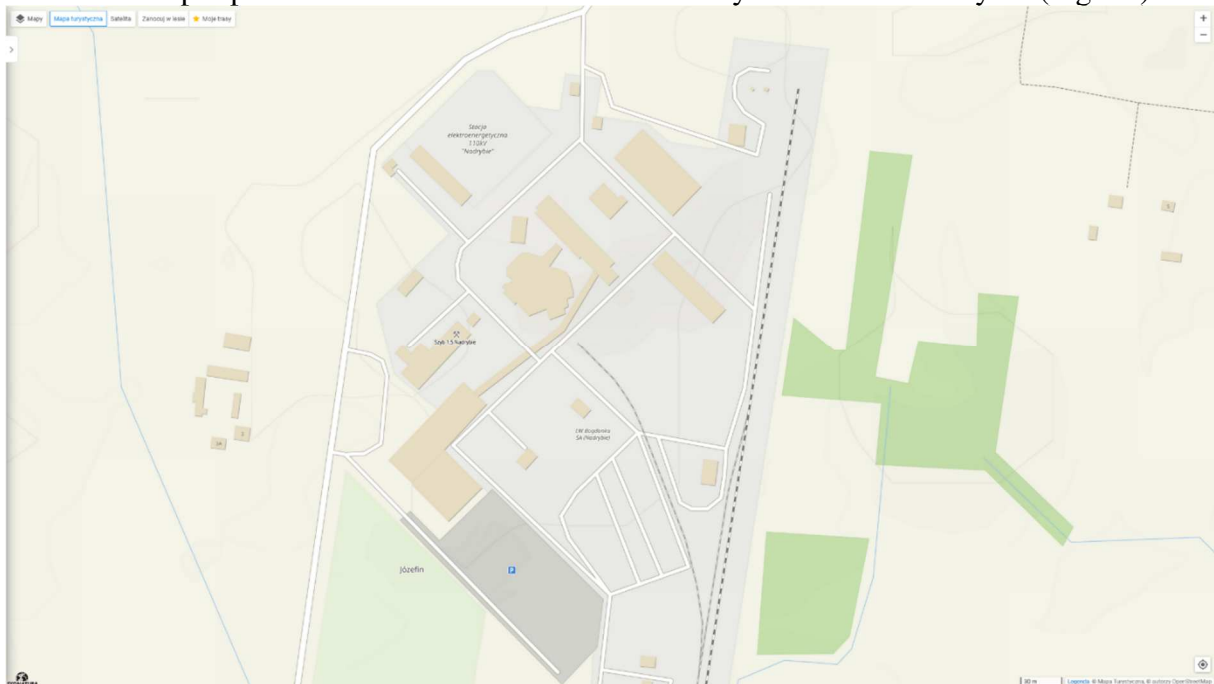


Fig. 42 “Nadrybie” area – location of the peripheral Shaft 1.5

Shaft 1.5 has a depth of 989.50 m and a diameter of 7.5 m. The shaft is connected to the level of 960 m. The shaft bottom is located at an altitude of 172.70 m above sea level. It has no tower. It is connected to the air intake building (Fig. 43).



Fig. 43 LW "Bogdanka" building above the shaft of Shaft 1.5 in the "Nadrybie" Division, 2014 [12]

There are plans to adapt Shaft 1.5 for coal mining (Fig. 44).



Fig. 44 LW "Bogdanka" Plan to adapt the Shaft 1.5 in Nadrybie to extract mined material [11]

3.10 Summary review of the mine shafts in Poland

As part of Task 2.1, all operating mine shafts in Poland were identified and a huge amount of data describing them was collected. Then, an extensive database of 169 shafts from hard coal mines and 12 attributes was created, in which the obtained information was systematized (MS Excel sheet).

Attributes are as follows: name of the mine shaft, name of the mining plant with the name of the plant's division, name of the entrepreneur managing the mining plant, basic parameters of the shaft: depth, diameter, absolute height of the shaft bottom, methane carrying capacity category of the existing mining workings, quantitative characteristics of water inflow to the workings, comments covering other information including location of the shaft, period of development, description of the shaft cross-section with details of the shaft inlets, type of reinforcement, equipping the shaft with a tower and hoisting devices, ventilation, drainage, etc. Availability of space for construction of the required upper water reservoir for each shaft location was analysed.

Shafts of liquidated mines that have been converted into submersible pumping stations should be omitted in the assessment as they cannot be used for underground pumped-storage power plants. The reason is the physical impossibility of lowering the hydro set deeper into the shaft through the shielding pipes in the shaft closing plug. An example of the structure of a shaft plug is illustrated by Fig. 39.

4. Identification and characteristic of mine shafts in Czech Republic

4.1 Coal Mine ČSM

ČSM Mine (former name - Důl Československé mládeže) - a hard coal mine in Stonawa, a village in the Moravian-Silesian region in the Czech Republic, belonging to the company OKD. The mine includes two mining plants: ČSM North (Sever) and ČSM South (Jih). The area of the mining area is 26 km² and is located in Stonawa, Karwina, Olbrachcice and Kocobędz.



Fig.45 Mining areas of the Sever and Jih plants

Each plant has two shafts, one of which is an intake shaft and the other an outlet, ventilation shaft.

All shafts belonging to ČSM have a diameter of 7.5 m and a cross-section of 44 m².

The Sever intake shaft is 1104.4 m deep, is a shaft for moving people and is equipped with a two-cage extraction device. The Sever outlet ventilation shaft is 1005 m deep and is equipped with a mining skip.

The Jih intake shaft is 1103.9 m deep, is a shaft for moving people and is equipped with a two-cage extraction device and a transport container for transporting long elements. The Jih outlet ventilation shaft is 972.1 m deep and is equipped with a mining skip.



Fig. 46 Shafts of the Sever and Jih mining plants

4.2 Coal Mine ČSA

ČSA Mine (former name - Důl Československá armády) is a former mining complex of the OKD company, in the Moravian-Silesian in the Czech Republic, consisting of two mining plants:

- Jan Karel,
- Doubrava.

The area of the mining area was 26 km² and was located in Karvina, Orlová and Doubrava. Mining ended in February 2021.

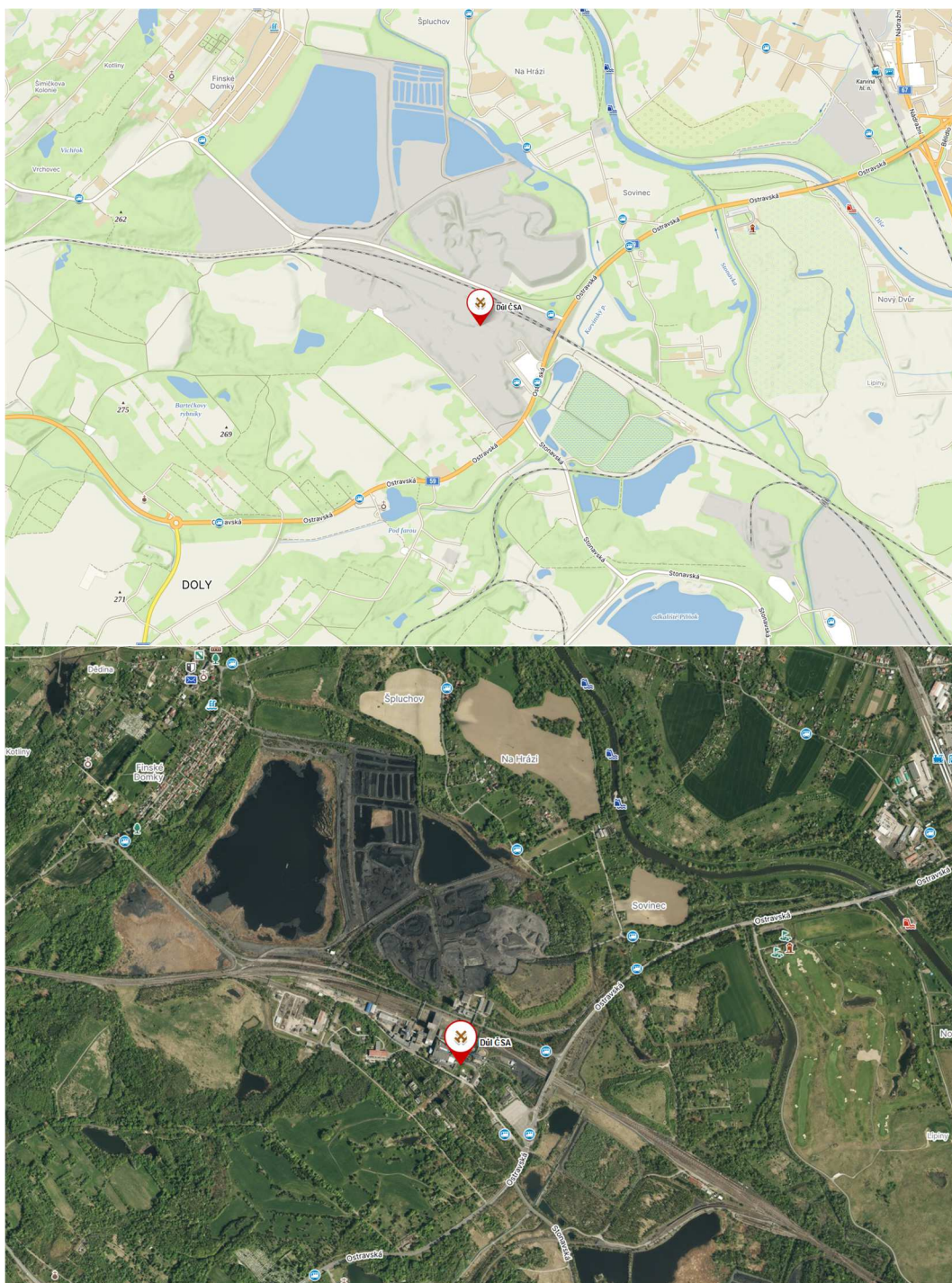


Fig. 47 Location of Coal mine ČSA

The mine has three shafts: Jan (intake), ČSA 2 (intake) and ČSA 3 (outlet).

All shafts have a diameter of 7.5 m. The Jan shaft is an intake shaft equipped with a mine hoist with a four-level cage and a depth of 962.2 m. The ČSA 2 shaft is an intake shaft also equipped with a mine hoist with a four-level cage and a depth of 1,049.3 m. The ČSA 3 shaft is an outlet shaft with a depth of 994.8 m and equipped with a two-compartment mining skip.



Fig. 48 ČSA 2 i ČSA 3 shafts



Fig. 49 Jan shaft

4.3 Coal Mine Darkov

The Darkov mine is a former hard coal mine of the OKD company, located on the border of the Stonava commune and the Darkov district in Karviná. Together with the 9 Maja mine, Darkov was part of the internal organizational unit of the OKD company called Důl Darkov. Mining ended in February 2021

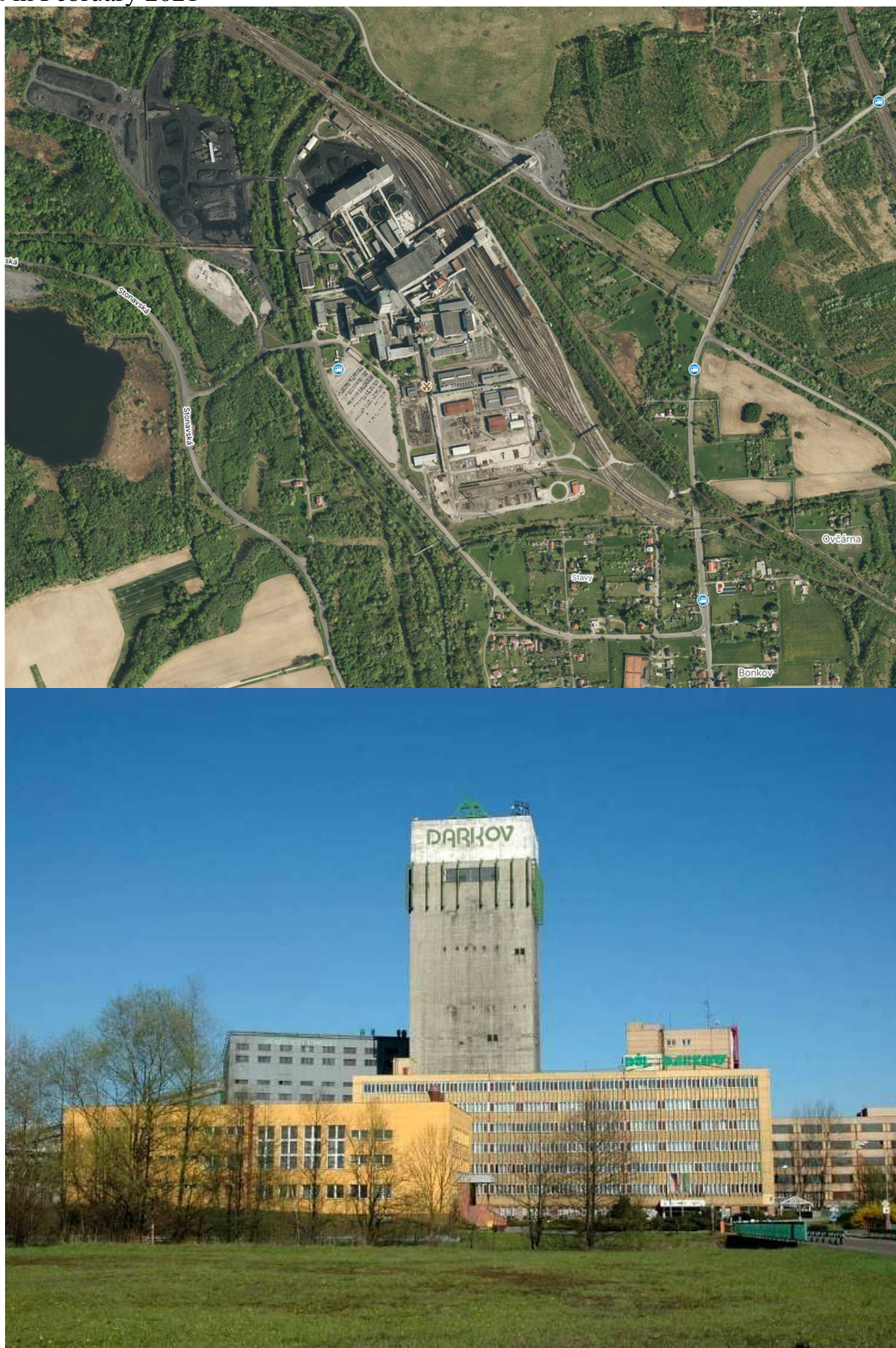


Fig.50 Coal Mine Darkov

In the case of the Darkov mine, work on filling the shafts is already underway.

The mine had three shafts: Da-1 (inlet), Mir 5 (inlet) and Mir 4 (outlet). All shafts had a diameter of 7.5 m.

The Da-1 shaft is an intake shaft with a depth of 878.3 m equipped with a cage extraction mechanism. The Mir 5 shaft is an inlet shaft with a depth of 887.2 m also equipped with a hoisting mechanism. The Mir 4 shaft is an outlet shaft, 1011.5 m deep, equipped with a mining skip.

5. Identification and characteristic of mine shafts in Slovenia

5.1 General outline and mine access system

Premogovnik Velenje (CMV) operates in uniquely shaped coal deposit that could be best described as lens- kidney shaped single coal seam with maximum thickness of approximately 160 m. Its dimensions spans over 8 x 2,5 kilometres across the Šalek valley. Depth of the seam varies between surface outcrops and approximately 500 m.

Due to specific lignite deposit geometry, most of mine infrastructure had included shafts for main mine supply, material transport and ventilation. Despite given facts, main coal transport system relies on drift that connects surface (coal processing plant) with main mine transportation system. Another operational drift connection remained in most North-Eastern part of the mine for the purpose of partial ventilation network fresh air supply and drain water pipeline layout.

In total, nowadays the mine operates with 6 shafts and two drifts. The shafts functions are primarily ventilation and transport, whereas drifts are used for mined coal transport and water drainage pipeline.

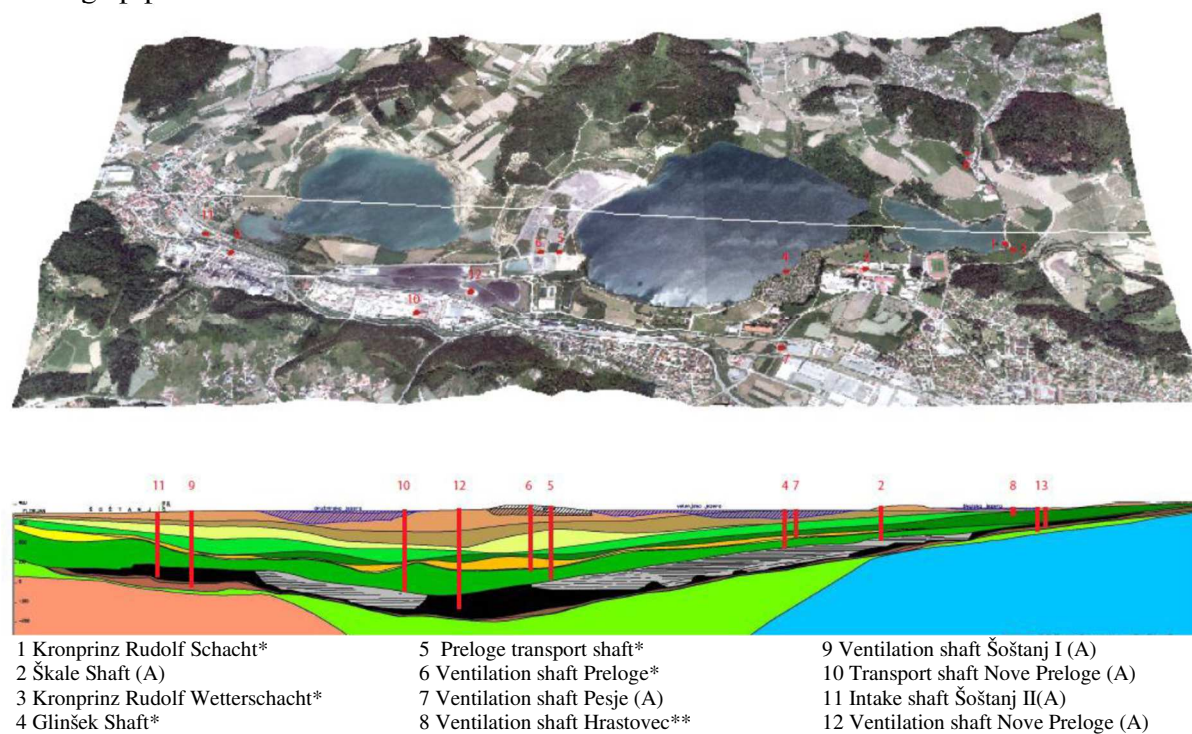


Fig. 51 Premogovnik Velenje shaft outline, surface and cross section presentation

5.2 History of mine shaft construction

Over the coal mine history, several shafts had been built, starting with research shaft in Škale region dating in the year 1887 (Kronprinz Rudolf Schacht, depth 118,20 m), which was followed by main shaft for staff, material and coal transport in 1888 (Kaiser Franz Josef Schacht, depth 168 m) and later, in 1889 connected by mine network with first shaft for mine ventilation purposes. Additional ventilation shaft (Kronprinz Rudolf Wetterschacht, depth 93,5 m) was built in 1893. By 1905, additional ventilation shaft was built (Westlicher Wetterschacht/ Glinšek, depth 178 m + additional 17,4 m).

After the Second World War, the increased need for coal called for new shaft in central region of coal deposit. In year 1949, the new Preloge transport shaft (373 m) was finalized and put into operation couple years later. Beside the transport shaft, a new Ventilation shaft Preloge was built (1958) nearby with total depth 336 m. Due to geo-mechanical influences, both shafts faced severe deformations and were later decommissioned like the most of earlier listed shafts.

The only remaining shaft from mine earliest days is Škale Shaft (previously known as Kaiser Franz Josef Schacht, depth 168 m), where nowadays mine museum takes place.

Table 1 Shaft Škale - main data

Škale Shaft (Jašek Škale)	
Shaft construction year	1888
Shaft original function	Ventilation (Return)
Shaft depth	168,0 m
Shaft shape and dimensions (diameter)	Circular, 3,90 m
Shaft support and lining	Brick, bolts, concrete repairs
Existing head gear	Hauling device, two sided transport cage



Fig. 52 Škale Shaft

5.3 Modern era shafts

Current shaft configuration dates back to period between 1970s' and 1990s' when four shafts had been built and the additional from 2017.

Chronologically the shafts follow as: Ventilation shaft Pesje (1973), Ventilation shaft Šoštanj I (1980), Transport shaft Nove Preloge – NOP (1984/1987), Intake shaft Šoštanj II (1993) and Ventilation shaft Nove Preloge II – NOP II (2017).

Another ventilation connection between mine and surface needs to be addressed in the list of facilities, which is Ventilation shaft Hrastovec. It was in use until early 2000s' and due to location in solid rock, it remains in moderately good condition. Despite its relatively low depth (42,8 m) it still comes into account by attempts of various pilot or small scale projects.

5.3.1 Ventilation shaft Pesje (1973)

Mine network development called for new ventilation scheme, which was provided by new ventilation shaft inclusion in relative vicinity of mine work of given area. The shaft designed depth was 141 m and it took just over one year to successfully connect the shaft to mine.

Table 2 Shaft Pesje - main data

Ventilation Shaft Pesje (Zračilni Jašek Pesje)	
Shaft construction year	1973
Shaft original function	Ventilation (Return)
Shaft depth	141,76 m
Shaft shape and dimensions (diameter)	Circular, 4,0 m
Shaft support and lining	Steel arch, bolting, mesh, concrete lining (0,30 m)
Existing head gear	Ventilation unit (two mine fans)

Ventilation shaft Pesje will be replaced by new-built Ventilation Shaft NOP II in 2024. Most likely the shaft will not be decommissioned in total and will remain as a back-up unit for the planned remaining mine operational period.



Fig. 53 Ventilation Shaft Pesje

5.3.2 Ventilation shaft Šoštanj I (1980)

In 1970s' and 1980s', the mine plans included development of new exploitation area in Northern and Western part of deposit and after the assessment of given conditions, the location for Ventilation shaft Šoštanj I was chosen and in nowadays western mine borderline. Despite the Western exploitation had not been developed, the shaft plays key role in actual ventilation scheme and will remain in function until the end of mine operations.

Table 3 Shaft Šoštanj I - main data

Ventilation Shaft Šoštanj I (Zračilni Jašek Šoštanj I)	
Shaft construction year	1980
Shaft original function	Ventilation (Return)

Shaft depth	234,72 m
Shaft shape and dimensions (diameter)	Circular, 5,90 m
Shaft support and lining	Steel arch, bolting, mesh, concrete lining (0,30 m)
Existing head gear	Ventilation unit (two mine fans)



Fig. 54 Ventilation Shaft Šoštanj I

5.3.3 Transport shaft Nove Preloge – NOP (1984/1987)

In the beginning of 1980, construction of the new main mine shaft begun and with its 416 m depth, the shafts' importance remained until the present day.

Shaft construction took four years, additional connecting objects and facilities were finalized by 1987.

The shaft operates on daily basis by transporting staff, materials, consumables and equipment to and out of the mine. The two-sided two-level cage system allow transport of up to 70 employees in single run or material/equipment transport in dimensions of approximately 4,5 x 2 m.

The NOP shaft will remain also for mine closure activities as it represents the most effective mine supply facility.

Table 4 Shaft Nove Preloge - main data

Transport shaft Nove Preloge - NOP (Prevažalni jašek Nove Preloge - NOP)	
Shaft construction year	1984
Shaft original function	Staff transport, material and equipment transport
Shaft depth	416,42 m
Shaft shape and dimensions (diameter)	Circular, 7,20 m
Shaft support and lining	Steel arch, bolting, mesh, concrete lining (0,30 m)
Existing head gear	Hauling device, two sided transport cage



Fig. 55 Transport Shaft Nove Preloge - NOP

5.3.4 Intake shaft Šoštanj II (1993)

Mine plans in 1990s' showed the need to provide more efficient ventilation network for North-Western part of the mine and after the completion of Ventilation shaft Šoštanj I, engineer started the search for optimal intake ventilation location. The location was chosen in vicinity of Ventilation shaft Šoštanj I and construction started in 1988. The Intake shaft Šoštanj II was completed and connected to mine network in middle of 1993. The location is very favourable due to the low subsidence impact and relatively short ventilation pathways to active working areas.

Table 5 Shaft Šoštanj II - main data

Intake shaft Šoštanj II (Vstopni zračilni jašek Šoštanj II)	
Shaft construction year	1993
Shaft original function	Ventilation (Intake)
Shaft depth	332,57
Shaft shape and dimensions (diameter)	Circular, 5,0 m
Shaft support and lining	Steel arch, bolting, mesh, concrete lining (0,40 m)
Existing head gear	/



Fig. 56 Intake Shaft Šoštanj II

5.3.5 Ventilation shaft Nove Preloge II – NOP II (2017)

As the active mining area started to decrease and with a focus on reducing mined coal transport distances, the decision for new shaft in closest vicinity of surface stockpile was made. The primary idea included skip equipped transport system for mined coal with underground staging bunkers. Construction begun in 2011, but after the conditions and circumstances varied from planned, the idea was modified to reduce the planned depth and purpose of the shaft to Ventilation shaft Nove Preloge II – NOP II.

The shaft was connected to the mine in 2017, other construction works continued and in 2023 the double fan ventilation unit was finalized.

Table 6 Shaft Nove Preloge II - main data

Ventilation shaft Nove Preloge II – NOP II (Zračilni Jašek Nove Preloge II – NOP II)	
Shaft construction year	2017/2023
Shaft original function	Ventilation (Return)
Shaft depth	390,70
Shaft shape and dimensions (diameter)	Circular, 6,15 m
Shaft support and lining	Steel arch, bolting, mesh, concrete lining (0,60+ m)
Existing head gear	Ventilation unit (two mine fans)



Fig. 57 Ventilation Shaft Nove Preloge II – NOP II

6. Multicriteria system for assessment of mine shafts and underground workings

During the work carried out as part of this issue, a multi-criteria system for assessing the shafts was developed regarding the possibility of their future use for an underground pumped-storage power plant.

6.1 Shaft evaluation criteria

The factors determining the potential possibility of using the decommissioned shaft for the purposes of an underground pumped-storage power plant were identified. The criteria for assessing the shafts were based on these factors.

6.1.1 Shaft depth

Depth of the shaft is the parameter with the greatest impact on the amount of water energy that can be stored. This energy, given by the following formula:

$$E = H_u \cdot V_z \cdot \rho \cdot g$$

is directly proportional to the effective fall H_u of the water turbine. The greater the effective fall of the turbine, the smaller volume of water V_z needs to be stored, so the smaller the upper and lower water reservoirs will be.

After substitution:

$$V_z = Q_p \cdot t_p$$

we get:

$$E_p = H_u \cdot Q_p \cdot t_p \cdot \rho \cdot g$$

The above relationship shows that the shorter the time for pumping water t_p into the upper water tank or the lower the volumetric efficiency of the pump Q_p , the lower the energy consumption for pumping E_p will be, which will result in a higher efficiency of the energy storage.

The smaller water volume allows for reduced turbine throughput and pump efficiency. Therefore, the diameter and weight of the pipes will be smaller. Therefore, the installation cost will be lower.

The shaft itself can be used as a groundwater reservoir, isolating it from the side workings. This is the easiest method of storing the bottom water. In this case, for a given volume of the lower reservoir V_{zd} , its height H_z is inversely proportional to the square of the shaft radius $D_{zd}/2$.

The mine's side workings can also be used as a tailwater reservoir. To prevent rock from washing out and contaminants from penetrating into the stored water, it is advisable to insulate the tank walls. Some limitations result from the use of flexible support in workings and there is a risk of cross-section clamping. In the case of a tank in road headings, its length is inversely proportional to the cross-sectional surface area of the working

Temperature of the rock mass increases with depth, so water stored at greater depths will heat up more. The heat collected from the rock mass can be extracted from water in a heat exchanger on the surface, which is an additional bonus of the deep location of the groundwater reservoir.

6.1.2 Surface area for upper water reservoir

Near the shaft, on the land belonging to the mine, there must be an area available for the construction of an upper water reservoir with a size ranging from several to several dozen ares, depending on the effective fall of the water turbine used. As the effective fall increases, the upper water reservoir decreases and thus the required area of land adjacent to the shaft decreases.

6.1.3 Shaft configuration

Since ventilation must be provided in the shaft, the shaft used for the PSH installation should be connected to another shaft. It is beneficial to have a slight distance between the shafts.

6.1.4 Hoisting devices

Due to the need to supervise the operation and service of the hydroelectric set located at the bottom of the mine, access is necessary via an inspection and emergency hoist installed in one of the connected shafts. The hoist must also be able to transport material for installation and repair purposes.

6.1.5 Methane content in mine workings

In the case of methane mines, methane is constantly extracted from goafs, which may be impossible to effectively damming it in underground conditions. Due to the probable movements of the rock mass, leaks may appear in the dam, which will allow methane to penetrate into the development area of the underground pumped-storage power plant. Moreover, there is a risk of methane being released into the used working. Therefore, continuous monitoring of methane concentration is necessary in methane mine workings. The presence of methane in the workings connected to a given shaft creates a need for an explosion-

proof construction for the hydro set, exciter and power supply and control system, as well as the use of safety systems, what results in higher investment costs. There is a need to increase the ventilation efficiency in proportion to the amount of methane released, which, together with monitoring, increases the operating costs of the system.

6.1.6 Shaft dewatering

When selecting a shaft suitable for installation of an underground pumped-storage power plant, the balance of groundwater flowing from all workings connected to the shaft should be taken into account. This additional volume of mine water, with a high degree of salinity, high content of minerals, metal compounds, and often also radium, should not mix with the water circulating in the pumped-storage power plant system and should be discharged to the collector using a separate pumping system. In addition to the costs associated with operating of the additional pump station, this may generate a problem of purifying the discharged mine water.

When selecting a shaft for the UPSH installation, it should be checked whether the permissible damming level of the designed lower reservoir does not pose a risk of water leaking into neighbouring mines.

6.2 Scoring for each criterion

The conditions presented above were included in mathematical relationships, and specific scores reflecting their impact on the efficiency of the potential energy storage system located in the assessed mine shaft were assigned to each parameter or pairs of parameters. These scores are discussed below and presented in the below tables.

6.2.1 Shaft depth

Table 7 shows the calculated effective fall of the H_U turbine depending on the depth of the H_S shaft and its diameter D_{zd} , assuming that the bottom water reservoir fills the cross-section of the shaft. Calculations were performed for the amount of stored energy $E = 10$ MWh, assuming the efficiency of the system $\eta = 0.7$.

Table 7 Calculated effective falls of the turbine H_U depending on the shaft height H_S and diameter D_{zd}

Effective fall of the turbine H_U [m]												
$D_{zd} \backslash H_S$ [m]	1100	1050	1000	950	900	850	800	750	700	650	600	550
9	1013	958	903	848	792	735	677	618	545	480	412	309
8,5	1003	948	892	836	779	713	653	591	527	460	364	237
8	991	935	879	822	756	696	634	571	505	413	297	
7,5	976	920	855	797	737	675	612	529	457	348		
7	951	894	835	775	713	635	568	497	392	255		
6,5	929	869	809	734	669	602	508	429				
6	889	827	763	698	610	536	424					
5,5	850	769	701	630	527	403						
5	781	689	613	500								

Table 8 presents the scores for the above-calculated effective falls of the turbine H_U depending on the pairs of parameters: the shaft depth H_S and its diameter D_{zd} , assuming that the bottom water reservoir fills the cross-section of the shaft with a diameter D_{zd} . 0 was assigned to values of the arithmetic mean of the fall H_U , and the remaining values were given proportionally from 10 for the largest depths and cross-sections to -10 for the smallest depths and cross-sections. The number of -100 points was assigned to the depth-diameter pairs of the shaft, for which it is impossible to build the necessary bottom water reservoir in the shaft, which would enable the storage of 10 MWh of energy.

Table 8 Scoring for effective falls of a turbine H_U depending on shaft depth H_S and diameter D_{zd}

Scores for the effective turbine falls H_U [m] (depending of the shaft depth H_S an a diameter of a bottom reservoir D_{zd} in the shaft)												
$D_{zd} \backslash H_S$ [m]	1100	1050	1000	950	900	850	800	750	700	650	600	550
9	10	9	7	6	4	3	1	0	-2	-4	-5	-8
8,5	10	8	7	5	4	2	1	-1	-3	-4	-7	-10
8	9	8	7	5	3	2	0	-1	-3	-5	-8	-100
7,5	9	8	7	4	3	1	0	-2	-4	-7	-100	-100
7	8	7	6	4	2	0	-1	-3	-6	-10	-100	-100
6,5	8	6	5	3	1	-1	-3	-5	-100	-100	-100	-100
6	7	5	4	2	0	-2	-5	-100	-100	-100	-100	-100
5,5	6	4	2	0	-3	-6	-100	-100	-100	-100	-100	-100
5	4	2	0	-3	-100	-100	-100	-100	-100	-100	-100	-100

Table 9 shows the calculated volumes of the reservoir V_z , allowing for storage of 10 MWh of energy, depending on the turbine effective fall H_U , and the number of points assigned to them, designated for the bottom water reservoir built in the side workings of the mine. 0 was assigned to the arithmetic mean volume of the reservoir tank V_z and the remaining values got proportionally from 10 points for the largest volumes to -10 points for the smallest volumes.

Table 9 Tank volumes V_z depending on the turbine effective fall H_U and the points assigned to them

Reservoir volume [m³]															
H_u [m]	1000	950	900	850	800	750	700	650	600	550	500	450	400	350	300
V_z [m ³]	5246	5523	5829	6172	6558	6995	7495	8071	8744	9539	10493	11659	13116	14990	17488
score	10	10	9	8	8	7	6	5	4	3	1	0	-3	-6	-10

6.2.2 Surface area for upper water reservoir

Scoring for shafts depending on the availability of space for construction of the top water reservoir is defined in Table 10.

Locations of the shafts with the available space necessary for the development of a top water reservoir were assigned 2 points. Scoring of a well has been reduced to -2 points when it is not possible to build this reservoir due to lack of available space.

Table 10 Scoring regarding the space availability for constructing the top water reservoir

Scoring depending on area availability for constructing the top water reservoir	
enough available area	2
unavailable area	-2

6.2.3 Shaft configuration

Depending on the shaft configuration, each shaft got the number of points defined in Table 11. The operating conditions of the equipment of a pumped-storage power plant located underground in a mine can be compared to the operating conditions of a stationary pumping station. In both cases, ventilation of the working is needed, for which two shafts are required. 2 points were given to the situation, where there is a connection between the considered shaft and the adjacent shaft was assigned. When the connected shaft is located far away, the number of points is 0. A single shaft got a negative -5 points due to difficulty in ventilation.

The assumptions of the Hybrid Energy Storage System (HEES) specify location of each energy storage facility within one post-mining area, vicinity of the shaft selected for storing the compressed fluids and a thermal energy storage facility is preferred. Such a location got 5 points.

Table 11 Scoring for the shaft configuration

Scoring depending on the shaft configuration	
neighbouring shaft for storage of compressed fluids	5
2 connected neighbouring shaft	2
2 distant connected shafts	0
a single shaft	-5

6.2.4 Hoisting devices

Depending on the availability of hoisting devices, each shaft got the number of points defined in Table 12.

If the considered shaft has a shaft tower with an active hoist for transportation of materials and people, then it got 2 points. 0 points were given to the case in which there is no hoist for transportation of materials and people, but the existing shaft tower in one of the shafts is adapted to install an auxiliary emergency-inspection mine shaft hoist. Then there are additional costs of installation, servicing and renovation of the underground pumped storage power plant. The case of lack of lifting devices in connected shafts and failure to adapt the shafts to their installation received -2 points.

Table 12 Scoring for availability of hoisting devices

Scoring of the availability of hoisting devices	
shaft tower with material and people transportation hoist in at least 1 shaft	2
adaptation to the installation of an auxiliary emergency and inspection hoist in one of the shafts	0
no hoisting devices in the connected shafts	-2

6.2.5 Methane content in mine workings

Depending on the category of methane hazard occurring in the workings of a given mine, individual shafts were assigned the number of points defined in Table 13.

Shafts in non-methane mines 5 points were given as they do not require of explosion-proof equipment and efficient ventilation. Methane mine shafts got negative points, lowering their scoring in proportion to the growing methane hazard category. Category I was got -1 point, category II -2 points, category III -3 points, and category IV -4 points. A higher methane hazard category means a larger amount of methane released, so ventilation efficiency and its cost must be higher

Table 13 Scoring depending on the category of methane hazard

Scoring depending on methane content of mine workings	
non-methane	5
methane hazard category I	-1
methane hazard category II	-2
methane hazard category III	-3
methane hazard category IV	-4

6.2.6 Dewatering of mine workings

Depending on the water conditions in the given mine working each mine shaft got the score number defined in Table 14.

The case when the balance of water inflow to the workings of a given mine is negative got 5 points. There is no need to install and maintain drainage systems. When the water inflow balance is positive and does not exceed 1 m³/min, the amount of energy for drainage is small in relation to the amount of energy stored in the pumped-storage power plant. This case got 3 points. 0 points were given, when the balance of water inflow to the mine workings is greater than 1 m³/min and does not exceed 3 m³/min. For an intensive inflow of groundwater into mine workings exceeding 3 m³/min, -3 points are given.

Table 14 Scoring for dewatered workings

Scoring depending of water balance flowing to the working	
≤ 0 m³/min	3
above 0 m³/min i ≤ 1 m³/min	3
above 1 m³/min i ≤ 3 m³/min	0
above 3 m³/min	-3

6.3 Importance of each criterion

In addition to the points, all criteria got a specific importance presented in Table 15, as their percentage impact on the overall assessment of each shaft.

Table 15 Importance of each criterion

Importance of each criterion	
effective fall of the turbine H_u	50%
surface area for upper water reservoir	10%
space for construction of the reservoir	10%
scoring of the hoisting machines	10%
methane hazard	10%
dewatering	10%
Total	100%

6.4 Summary of multicriterial system for shafts assessment

As a result of defining the score for each parameter and assigning importance for the evaluation criteria, it became possible to select the mine shafts that best meet the necessary requirements. Logical functions were built that were used to automatically determine scores for each criterion based on data collected for each shaft, such as: depth and diameter of the shaft, availability of space for the development of a top water reservoir, shaft configuration, methane hazard category and drainage of workings.

Mathematical formulas were created, based on defined importance and designated partial scores, allowed for determining the total score for the analysed cases.

The developed multi-criteria shaft evaluation system allows for sorting the records of "Mine shafts in Poland" database against the total score to select the shafts that best meet the given criteria.

7. Selecting the shafts suitable for PSH implementation

As a result of scientific analysis of the material and the use of a multi-criteria shaft evaluation system, total scores were assigned to all shafts. As a result of sorting the database records regarding the total score for the ground water reservoir in the shaft, the shafts with the highest scores were selected. The list of Polish shafts is presented in Table. 16, Czech shafts in Table 17, and Slovenian shafts in Table 18.

7.1 Shafts with PSH implementation with a bottom water reservoir in Poland

The highest score of 5.2 was obtained by the "II" shaft belonging to the Budryk coal mine. It is a shaft with a depth of 1,157 m and a diameter of 9 m. The next places included the shafts belonging to the "ROW" coal mine - shaft "8" located in the area of the "Jankowice" mine and "Leon IV" shaft located in the area of the "Rydułtowy" mine.

However, due to the planned use of two adjacent or closely located shafts for energy storage in a pumped storage power plant in a form of compressed gases, the most favourable locations were the following three pairs of shafts already mentioned in Milestone 1:

- Shafts II and III located on the area of the Budryk coal mine,
- Shafts 2.1 and 2.2 located on the area of the Bogdanka Coal Mine,
- Grunwald II and V shafts belonging to the "Halemba" and "Bielszowice" plants, respectively, which are parts of the "Ruda" coal mine.

A particularly interesting pair are the shafts located in the area of Budryk coal mine, because one of them, as a result of a separate analysis based on different criteria, was selected as a compressed gas storage facility.

Table 16 Results of selecting the shaft for a reservoir for PSH in Poland (scoring >4.0)

No.	Entrepreneur	Mining plant	Division	Shaft	Depth [m]	Diameter [m]	Total score tank in shaft
1	2	3	4	5	6	7	8
13	JSW	KWK Budryk		II	1157,45	9,00	5,2
42	PGG	KWK ROW	Jankowice	8	1103,70	8,50	5,0
51	PGG	KWK ROW	Rydułtowy	Leon IV	1210,70	8,50	4,9
11	JSW	KWK Borynia-Zofiówka-Bzie	Bzie	1-Bzie Jan Paweł	1164,00	8,00	4,8
12	JSW	KWK Budryk		I	1157,20	9,00	4,7
16	JSW	KWK Budryk		VI	1319,60	9,00	4,7
169	Bogdanka	LW "Bogdanka"		2.1	1097,74	7,50	4,6
98	PGG	KWK Staszic-Wujek	Murcki-Staszic	VII	1126,00	9,00	4,6
14	JSW	KWK Budryk		III	1089,89	9,00	4,4
63	PGG	KWK Ruda	Halemba	Grunwald III	1112,50	7,50	4,4
146	SRK	Oddział CZOK	PS Śląsk I	I	1081,00	8,00	4,4
168	Bogdanka	LW "Bogdanka"		2.2	1018,25	7,50	4,3
58	PGG	KWK Ruda	Bielszowice	V	1111,60	7,50	4,2

7.1.1 Shaft II of KWK Budryk mine

Shaft II is an exhaust ventilation shaft located on the area of the Main Plant in Ornontowice (fig.).

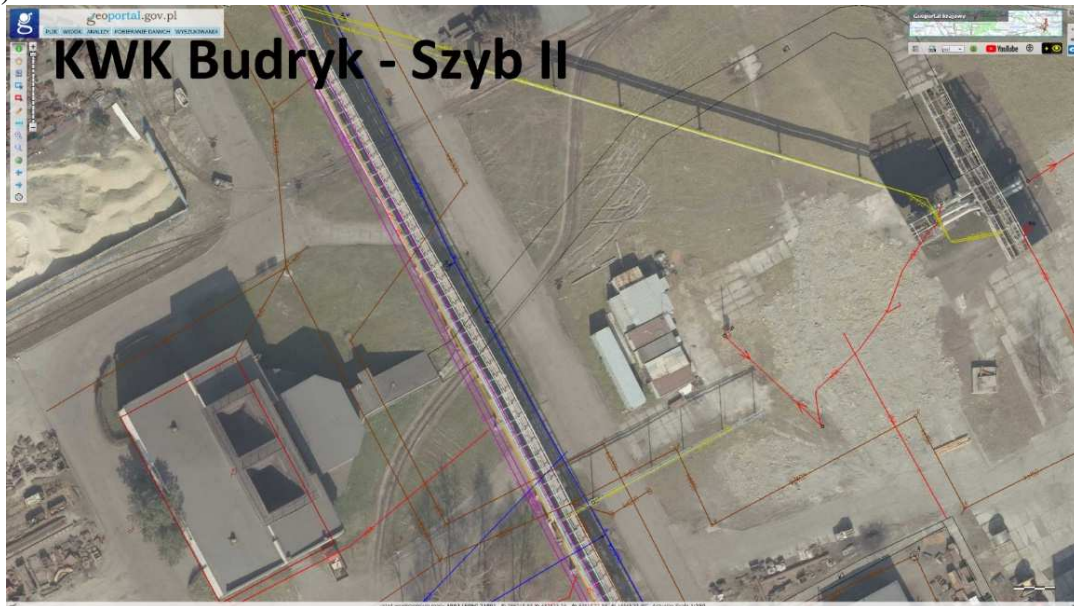


Fig. 58 KWK Budryk – location of the Shaft II and the station of main fans

Its sinking began in 1979, and on September 22, 1984, Shaft II reached a depth of 1157.45 meters with a diameter of 9.0 meters. The top of the shaft is situated at an elevation of 292.60 meters above sea level and lacks a headframe (Fig. 59). The station is equipped with two main ventilation fans.



Fig. 59 KWK "Budryk" – top of Shaft II and main fan station, 2020 [3]

The mine is classified in the IV category of methane hazard. The methane bearing capacity of the goafs after mining, which in the case of the "Budryk" Coal Mine can be assumed at a level of about 20 m³/min. Next to Shaft II, there is a building housing the degassing station with an

installation of four cogeneration units with a total power of 8 MW. The mine is characterized by a high water inflow close to 5 m³/h.

7.1.2 Shaft II of KWK Budryk mine

Shaft III is an intake, extraction, and service/material shaft, located on the area of the main plant of KWK "Budryk" in Ornontowice, adjacent to Shaft II (Fig. 60).



Fig. 60 KWK "Budryk" – Location of Shaft III on the area of the main plant

The shaft sinking began in October 1979 and was completed on March 8, 1984. Its depth is 1089.89 meters, and its diameter is 9.0 meters. It provides access to the 700m and 1050m levels, where the main pumping station is located. The top of the shaft is situated at an elevation of 293.0 meters above sea level. It is equipped with a steel headframe. The shaft has two compartments: a skip compartment and a cage compartment (Fig. 61).



Fig. 61 KWK "Budryk" – headframe of Shaft III [14]

7.1.3 Shaft 2.1 – "Stefanów" Region

Shaft 2.1 is an exhaust ventilation and extraction shaft, located in the "Stefanów" Region in Stefanów (Fig. 62).

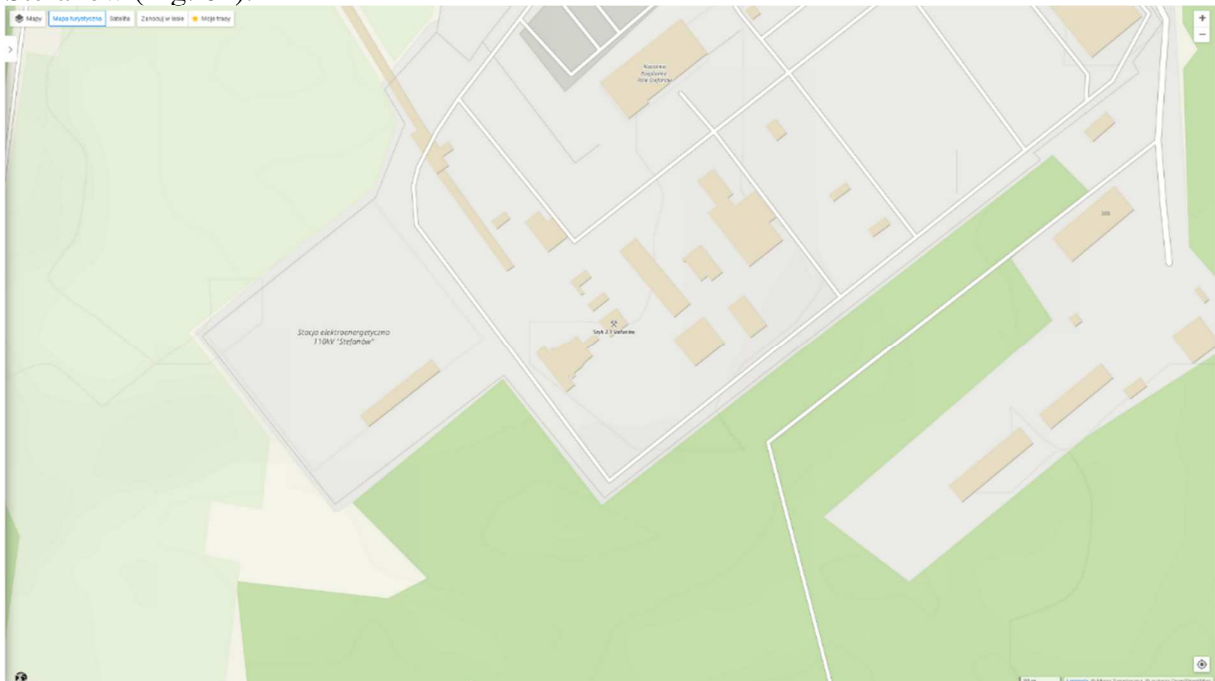


Fig. 62 "Stefanów" Region – Location of Shaft 2.1

The sinking of Shaft 2.1 was carried out between 1982 and 2008. The shaft has a depth of 1097.74 meters and a diameter of 7.5 meters. It features a concrete lining with tubings in the section between -563.0 and -783.3 meters. The shaft provides access to the 880m and 990m levels. The top of the shaft is situated at an elevation of 171.70 meters above sea level. It is

equipped with a 72-meter-high steel headframe and one compartment with two 40-ton skips (Fig. 63).

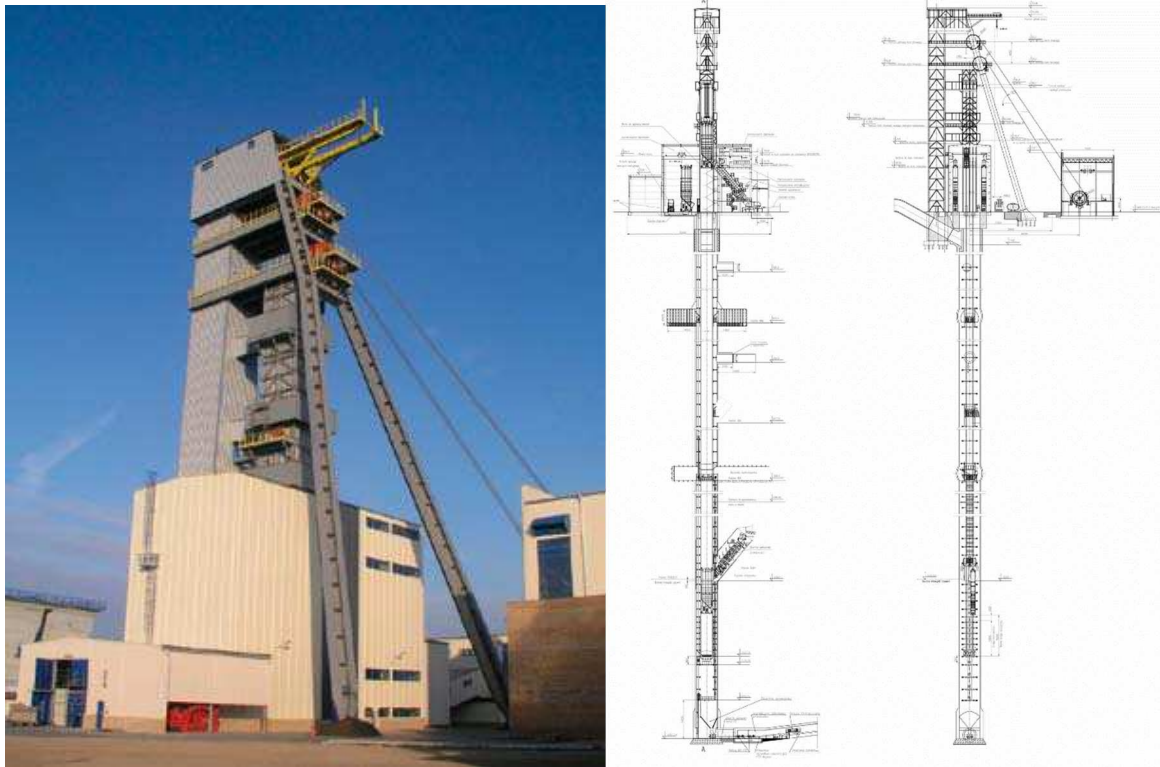


Fig. 63 LW "Bogdanka" – Headframe of Shaft 2.1 in the "Stefanów" Region [11] and cross-section of the shaft, 2016 [9]

Next to Shaft 2.1, there is a main fan station with two fans.

7.1.4 Shaft 2.2 – "Stefanów" Region

Shaft 2.2 is an intake, service, and material shaft, located in the "Stefanów" Region in Stefanów, adjacent to Shaft 2.1 (Fig. 64).

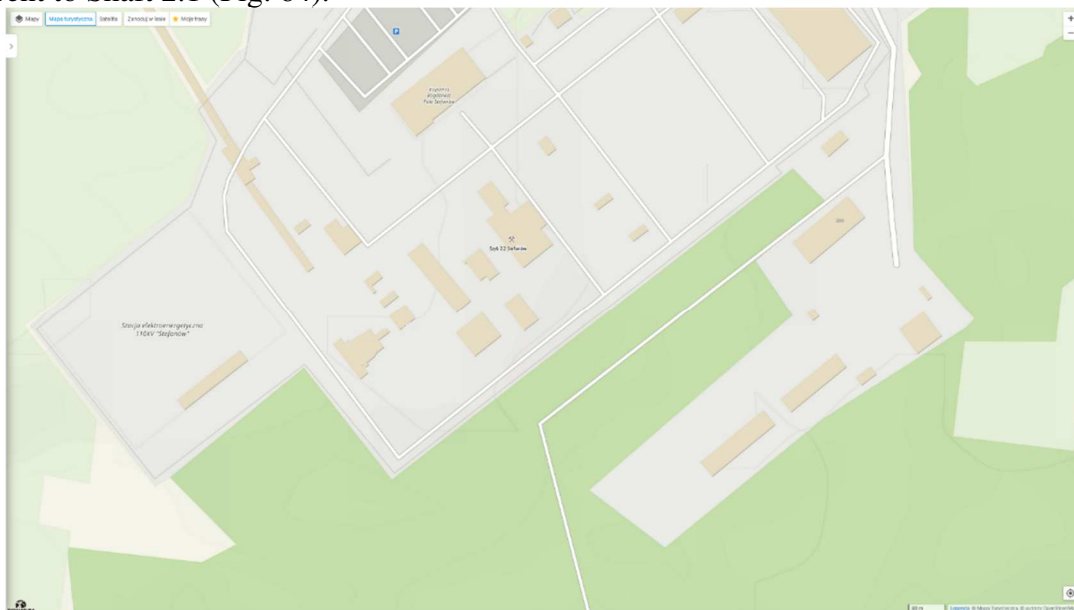


Fig. 64 "Stefanów" Region – Location of Shaft 2.2

The sinking of Shaft 2.2 was carried out between 1981 and 1987, when it reached a depth of 1018.25 meters with a diameter of 7.5 meters. In 1989, the shaft was flooded. It was cleared in 2005. The shaft provides access to the 880m and 990m levels. The top of the shaft is situated at an elevation of 172.60 meters above sea level. It is equipped with a steel headframe with cages (Fig. 65).



Fig. 65 LW "Bogdanka" – Headframe of Shaft 2.2 in the "Stefanów" Region, 2014 [13]

The mine does not have a methane hazard, but it is characterized by a high water inflow of about 17 m³/min.

7.1.5 Shaft "Grunwald III" – KWK "Ruda", "Halemba" Section

Shaft "Grunwald III" is an intake and extraction shaft, located on the area of the main plant of the "Halemba" Section in Ruda Śląska Kłodnica (Fig. 66).

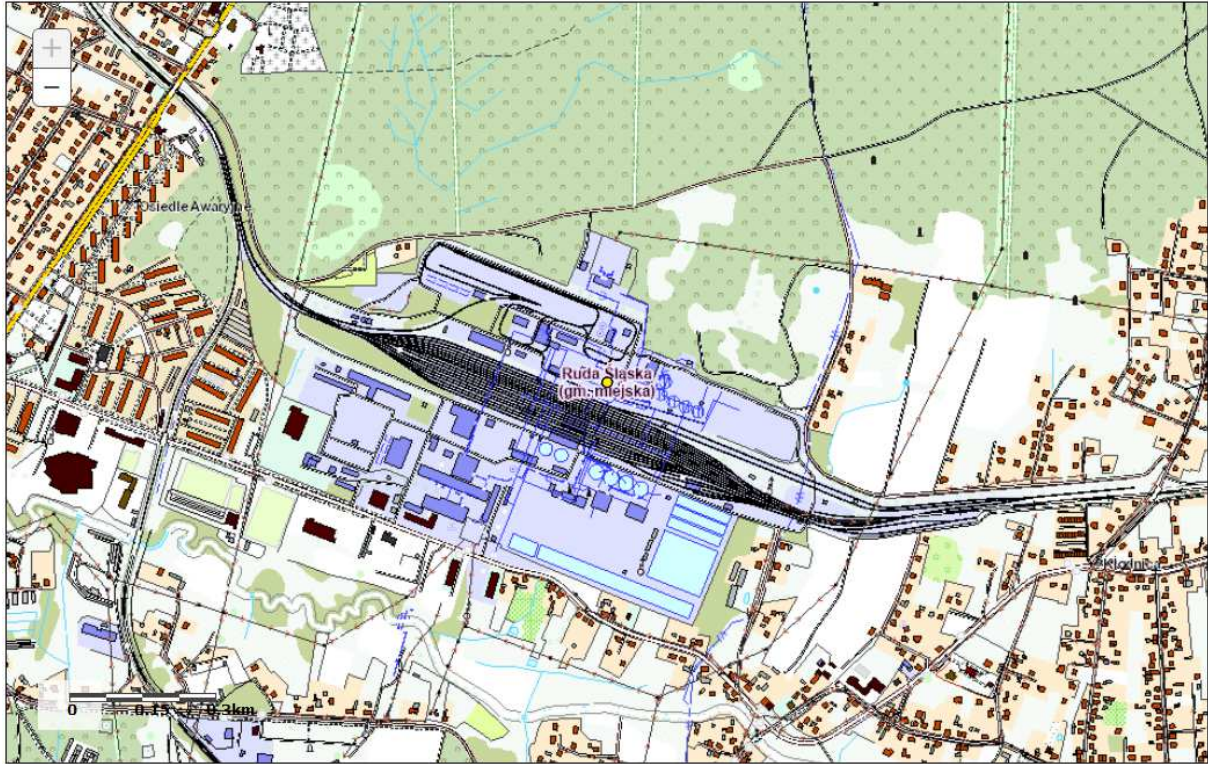


Fig. 66 "Halemba" Section – Location of Shaft "Grunwald III" on the area of the main plant

The sinking of Shaft "Grunwald III" was carried out in 1980. The shaft reached a depth of 1112.50 meters with a diameter of 7.5 meters. The shaft provides access to the 830m and 1030m levels. The top of the shaft is situated at an elevation of 261.27 meters above sea level. It is equipped with a 96-meter-high tower headframe and two skip compartments (Fig. 67).



Fig. 67 "Halemba" Section – Tower headframe of Shaft "Grunwald III", state in 2012 [14]

The mine is classified in the II category of methane hazard. It is anticipated that after 2030, methane emissions will decrease. The mine is characterized by a high water inflow into the workings, exceeding 10 m³/h. The water is pumped to sedimentation tanks and discharged via a collector to Kłodnica. The "Halemba" Section has a ventilation connection with the "Bielszowice" Section, located about 3 km away, to which over 3000 m³/min of air is directed.

7.1.6 Shaft V – KWK "Ruda", "Bielszowice" Section

Shaft V is an intake, extraction, emergency, and service shaft, located on the premises of the main plant of the "Bielszowice" Section in Ruda Śląska Bielszowice (Fig. 68).



Fig. 68 "Bielszowice" Section – Location of Shaft V on the premises of the main plant

The construction of Shaft V was carried out in the 1970s and 1980s. The shaft has a depth of 1111.60 meters and a diameter of 7.5 meters. The shaft provides access to the 642m, 840m, and 1000m levels. The top of the shaft is situated at an elevation of 246.36 meters above sea level. It features a tower headframe (Fig. 69). It is equipped with two compartments: the first is equipped with two 22-ton skips from the 840m level, and the second with a skip-cage from the 1000m level.



Fig. 69 "Bielszowice" Section – Headframe of Shaft V, state in 2024 [20]

The mine is classified in the IV category of methane hazard. It has a high water inflow into the workings, reaching 10 m³/h. The water is pumped to sedimentation tanks and discharged to Kochłówka.

In the immediate vicinity of Shaft V, there is a main fan station at the exhaust Shaft IV, equipped with two main ventilation fans, which can be used for ventilation of the UPSH installation after the construction of a supply channel from Shaft V, approximately 120 meters long. Energy infrastructure is also available.

7.2 Shafts with PSH implementation with a bottom water reservoir in the Czech Republic

The analysis of mine shafts in the Czech Republic included shafts from the ČSM, ČSA, Darkov, and Jeremenko coal mines. Except for the ČSM mine, the shafts in the other mining operations are either in the process of being filled or have already been designated for filling. Therefore, only the shafts from the ČSM mine were subjected to a multi-criteria analysis.

The ČSM mine consists of two parts: "Sever" and "Jih," each containing two shafts: an intake (service and material) shaft and an exhaust shaft (equipped with an extraction skip). Based on the collected data, for the purposes of constructing a pumped storage hydropower (PSH) plant, the shafts located in the Sever field were selected. An additional argument for choosing these shafts is the selection of one of the Sever field shafts for compressed air energy storage.

Table 17 Results of selecting the shaft for a reservoir for PSH in the Czech Republic

No.	Entrepreneur	Mining plant	Division	Shaft	Depth [m]	Diameter [m]	Total score tank in shaft
1	2	3	4	5	6	7	8
1	OKD	ČSM	ČSM Sever	Sever (exhaust ventilation)	1005,0	7,5	3,7
2	OKD	ČSM	ČSM Sever	Sever (intake)	1104,4	7,5	5,5
3	OKD	ČSM	ČSM Jih	Jih (exhaust ventilation)	972,1	7,5	2,7
4	OKD	ČSM	ČSM Jih	Jih (intake)	1103,9	7,5	5,2

The selected shafts are described in section 4 of this report.

7.3 Shafts with PSH implementation with a bottom water reservoir in Slovenia

Analysis of active mine shafts in Slovenia revealed that the only operating mine, Velenje, has six active shafts with depths ranging from 141.76 meters to 416.42 meters and diameters ranging from 3.9 meters to 7.2 meters. In each case, there is enough space for an upper water reservoir, and practically no inflow of groundwater.

The shafts identified in Milestone 1 have the most favourable parameters for energy storage in a pumped storage hydropower plant, primarily in terms of depth (H) and shaft diameter (D):

- Nove Preloge Transport Shaft (H = 416.42 m, D = 7.2 m)
- Nove Preloge Ventilation Shaft (H = 390.7 m, D = 6.15 m)

However, due to the relatively small depths of the shafts (<500 m), it is not possible to meet the project's assumed storage capacity requirements. Therefore, the identified and analyzed shafts in Slovenia cannot be used.

Table 18 Results of selecting the shaft for a reservoir for PSH in Slovenia

No.	Entrepreneur	Mining plant	Division	Shaft	Depth [m]	Diameter [m]	Total score tank in shaft
1	2	3	4	5	6	7	8
1	Premogovnik Velenje, d. o. o.	Velenje	-	Transport shaft Nove Preloge (A)	416,42	7,2	-49,1
2	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Nove Preloge (A)	390,7	6,15	-49,4
3	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Pesje (A)	141,76	4	-49,4
4	Premogovnik Velenje, d. o. o.	Velenje	-	Intake shaft Šoštanj II(A)	332,57	5	-49,4

The shafts located in Slovenia are described in section 5 of this report.

7.4 Further actions

The selected shafts will undergo detailed analysis to determine the optimal location. The selection process will take into account the results of other teams' analyses, assessing the remaining components of the Hybrid Energy Storage System (HESS), i.e. compressed fluid energy storage and thermal energy storage.

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Appendix 1

Results of MSDA analysis for the database of shafts and neighboring objects potentially suitable for pumped-storage power plant

Poland

No.	Company	Mine	Division	Shaft	Depth [m]	Diameter [m]	Total score tank in shaft
1	2	3	4	5	6	7	8
1	JSW	KWK Borynia-Zofiówka-Bzie	Borynia	I	936,95	7,20	0,8
2	JSW	KWK Borynia-Zofiówka-Bzie	Borynia	II	980,00	7,20	2
3	JSW	KWK Borynia-Zofiówka-Bzie	Borynia	III	868,65	7,20	0
4	JSW	KWK Borynia-Zofiówka-Bzie	Borynia	V	847,50	5,50	-50
5	JSW	KWK Borynia-Zofiówka-Bzie	Borynia	VI	740,39	8,00	-1,5
6	JSW	KWK Borynia-Zofiówka-Bzie	Zofiówka	Iz	982,76	7,20	1,9
7	JSW	KWK Borynia-Zofiówka-Bzie	Zofiówka	IIz	1071,00	7,20	3,2
8	JSW	KWK Borynia-Zofiówka-Bzie	Zofiówka	IIIz	742,00	5,50	-50,1
9	JSW	KWK Borynia-Zofiówka-Bzie	Zofiówka	IVz	930,90	7,50	1,4
10	JSW	KWK Borynia-Zofiówka-Bzie	Zofiówka	Vz	907,50	8,00	1,4
11	JSW	KWK Borynia-Zofiówka-Bzie	Bzie	1-Bzie Jan Paweł	1164,00	8,00	4,8
12	JSW	KWK Budryk		I	1157,20	9,00	4,7
13	JSW	KWK Budryk		II	1157,45	9,00	5,2
14	JSW	KWK Budryk		III	1089,89	9,00	4,4
15	JSW	KWK Budryk		V	1005,00	9,00	2,8
16	JSW	KWK Budryk		VI	1319,60	9,00	4,7
17	JSW	KWK Knurów-Szczygłowie	Knurów	Jan (III)	1023,44	7,50	3,3
18	JSW	KWK Knurów-Szczygłowie	Knurów	Aniołki	471,80	6,00	-50,5
19	JSW	KWK Knurów-Szczygłowie	Knurów	Foch I	676,80	6,00	-49,5
20	JSW	KWK Knurów-Szczygłowie	Knurów	Foch II	694,62	6,00	-49,7
21	JSW	KWK Knurów-Szczygłowie	Knurów	Paweł	868,50	6,00	-0,5
22	JSW	KWK Knurów-Szczygłowie	Knurów	V	549,80	7,20	-50,5

D.2.1. Guidelines on the adaptation and use of inactive shafts possible to energy storage
Project: 101112380 – HESS – RFCS-2022

23	JSW	KWK Knurów-Szczygłowie	Szczygłowie	I	874,80	7,20	0,5
24	JSW	KWK Knurów-Szczygłowie	Szczygłowie	II	720,00	7,20	-2,5
25	JSW	KWK Knurów-Szczygłowie	Szczygłowie	III	946,91	6,00	0,5
26	JSW	KWK Knurów-Szczygłowie	Szczygłowie	IV	328,00	7,50	-50,5
27	JSW	KWK Knurów-Szczygłowie	Szczygłowie	VI	867,00	9,00	1,4
28	JSW	KWK Pniówek		Ludwik	920,90	8,00	1,5
29	JSW	KWK Pniówek		II	1039,70	8,00	3,7
30	JSW	KWK Pniówek		III	865,30	7,50	0,7
31	JSW	KWK Pniówek		IV	969,04	7,50	1,2
32	JSW	KWK Pniówek		V	992,00	7,50	1,6
33	PGG	KWK ROW	Chwałowice	I	415,66	5,00	-50
34	PGG	KWK ROW	Chwałowice	II	723,58	7,00	-3
35	PGG	KWK ROW	Chwałowice	V	401,80	6,00	-51
36	PGG	KWK ROW	Chwałowice	VII	543,00	7,50	-51
37	PGG	KWK ROW	Chwałowice	VIII	729,70	8,50	-1,5
38	PGG	KWK ROW	Jankowice	2	436,30	6,60	-50
39	PGG	KWK ROW	Jankowice	³ (Poniatowski)	421,30	6,80	-50,2
40	PGG	KWK ROW	Jankowice	4	273,50	5,00	-51
41	PGG	KWK ROW	Jankowice	7	634,20	7,50	-50,2
42	PGG	KWK ROW	Jankowice	8	1103,70	8,50	5
43	PGG	KWK ROW	Marcel	III (Julia)	866,65	7,00	0,1
44	PGG	KWK ROW	Marcel	IV (Bartek)	755,75	4,00	-50,7
45	PGG	KWK ROW	Marcel	Marklowice I	592,52	4,50	-49,7
46	PGG	KWK ROW	Marcel	I (Wiktor)	615,48	4,20	-49,7
47	PGG	KWK ROW	Marcel	II (Antoni)	1011,28	5,50	1,3
48	PGG	KWK ROW	Marcel	Marklowice II	556,75	7,50	-50,1
49	PGG	KWK ROW	Marcel	Podsadzki	359,66	3,00	-49,9
50	PGG	KWK ROW	Rydułtowy	Leon II	838,80	7,32	-0,8
51	PGG	KWK ROW	Rydułtowy	Leon IV	1210,70	8,50	4,9
52	PGG	KWK ROW	Rydułtowy	Powietrzny I	582,50	4,50	-50,9
53	PGG	KWK ROW	Rydułtowy	Powietrzny V	592,40	5,00	-51,1
54	PGG	KWK Ruda	Bielszowice	I	687,50	5,50	-50,1

D.2.1. Guidelines on the adaptation and use of inactive shafts possible to energy storage
Project: 101112380 – HESS – RFCS-2022

55	PGG	KWK Ruda	Bielszowice	II	970,87	5,58	-0,3
56	PGG	KWK Ruda	Bielszowice	III	1055,19	7,20	3,4
57	PGG	KWK Ruda	Bielszowice	IV	637,70	7,00	-50,5
58	PGG	KWK Ruda	Bielszowice	V	1111,60	7,50	4,2
59	PGG	KWK Ruda	Bielszowice	VI	1023,26	7,50	2,7
60	PGG	KWK Ruda	Bielszowice	Pawłów Grn. I	801,65	6,50	-1,6
61	PGG	KWK Ruda	Bielszowice	Pawłów Grn II	691,40	7,50	-4
62	PGG	KWK Ruda	Halemba	Grunwald II	587,63	7,50	-49,9
63	PGG	KWK Ruda	Halemba	Grunwald III	1112,50	7,50	4,4
64	PGG	KWK Ruda	Halemba	Grunwald IV	1057,60	6,50	3,1
65	PGG	KWK Ruda	Halemba	Wschodni	801,00	7,50	-0,7
66	PGG	KWK Ruda	Halemba	Północny I	506,00	6,00	-50,3
67	PGG	KWK Ruda	Halemba	Północny II	663,00	8,50	-2,5
68	PGG	KWK Piast-Ziemowit	Piast	I	675,00	7,50	-2,7
69	PGG	KWK Piast-Ziemowit	Piast	II	710,50	7,50	-1,4
70	PGG	KWK Piast-Ziemowit	Piast	III	671,80	7,50	-2,7
71	PGG	KWK Piast-Ziemowit	Piast	IV	656,00	6,50	-49,4
72	PGG	KWK Piast-Ziemowit	Pompownia Wola	1 (K-1)	670,00	7,50	-3,7
73	PGG	KWK Piast-Ziemowit	Ziemowit	I	670,70	7,10	-4,2
74	PGG	KWK Piast-Ziemowit	Ziemowit	II	667,50	5,50	-49,2
75	PGG	KWK Piast-Ziemowit	Ziemowit	III	710,00	7,50	-1,4
76	PGG	KWK Piast-Ziemowit	Ziemowit	Szewczyk	659,00	7,00	-4,4
77	PGG	KWK Piast-Ziemowit	Ziemowit	W1 (Wiatrok)	580,50	5,00	-49,8
78	PGG	KWK Piast-Ziemowit	Ziemowit	W2	651,75	7,50	-3,7
79	PGG	KWK Bolesław Śmiały		Aleksander I	430,00	5,00	-49,2
80	PGG	KWK Bolesław Śmiały		Aleksander II	366,16	3,50	-50,2
81	PGG	KWK Bolesław Śmiały		Aleksander III	447,00	7,50	-49,4
82	PGG	KWK Bolesław Śmiały		Bujaków II	688,50	7,50	-3,3
83	PGG	KWK Sośnica		III d. Christian Kraft	583,26	6,80	-50,1

D.2.1. Guidelines on the adaptation and use of inactive shafts possible to energy storage
Project: 101112380 – HESS – RFCS-2022

84	PGG	KWK Sośnica		IV	814,20	7,50	-0,1
85	PGG	KWK Sośnica		V	561,70	7,50	-50,7
86	PGG	KWK Sośnica		VII	1047,00	8,00	3,2
87	PGG	KWK Sośnica		VI	992,36	8,00	2,4
88	PGG	KWK Sośnica		Bojków	584,88	5,50	-50,3
89	PGG	KWK Sośnica		Podsadzkowy	56,00	3,00	-50,5
90	PGG	KWK Staszic-Wujek	Wujek	Lechia	710,84	7,50	-1,9
91	PGG	KWK Staszic-Wujek	Wujek	Krakus	729,58	7,50	-2,1
92	PGG	KWK Staszic-Wujek	Wujek	Wentylacyjny I	613,39	5,50	-50,1
93	PGG	KWK Staszic-Wujek	Wujek	Wentylacyjny II	690,57	5,00	-50,1
94	PGG	KWK Staszic-Wujek	Murcki-Staszic	I	794,10	7,20	-1,7
95	PGG	KWK Staszic-Wujek	Murcki-Staszic	II	751,00	7,20	-1,5
96	PGG	KWK Staszic-Wujek	Murcki-Staszic	IV	655,50	7,00	-5
97	PGG	KWK Staszic-Wujek	Murcki-Staszic	V	571,40	7,00	-50
98	PGG	KWK Staszic-Wujek	Murcki-Staszic	VII	1126,00	9,00	4,6
99	PGG	KWK Staszic-Wujek	Murcki-Staszic	Zygmunt	659,00	7,50	-3,9
100	PGG	KWK Mysłowice-Wesoła	Wesoła	Bronisław	529,58	7,10	-50,3
101	PGG	KWK Mysłowice-Wesoła	Wesoła	Piotr	895,30	7,50	0,2
102	PGG	KWK Mysłowice-Wesoła	Wesoła	Karol	746,00	7,50	-2,5
103	PGG	KWK Mysłowice-Wesoła	Wesoła	Wacław	721,00	7,20	-3,3
104	PGG	KWK Mysłowice-Wesoła	Wesoła	Wentylacyjny II	493,75	6,00	-50,3
105	PKW	Zakład Górniczy Brzeszcze		Andrzej I	236,50	4,00	-50,1
106	PKW	Zakład Górniczy Brzeszcze		Andrzej II	536,00	5,00	-50,1
107	PKW	Zakład Górniczy Brzeszcze		Andrzej V	740,00	8,00	-1,8
108	PKW	Zakład Górniczy Brzeszcze		Andrzej VIII	1040,00	7,50	2,7
109	PKW	Zakład Górniczy Brzeszcze		Andrzej IX	727,30	8,00	-2,2
110	PKW	Zakład Górniczy Janina		Janina I	310,50	4,40	-49,6
111	PKW	Zakład Górniczy Janina		Janina III	394,80	7,50	-49,2
112	PKW	Zakład Górniczy Janina		Janina IV	369,50	5,50	-49,2
113	PKW	Zakład Górniczy Janina		Janina VI	822,50	7,50	0,8

D.2.1. Guidelines on the adaptation and use of inactive shafts possible to energy storage
Project: 101112380 – HESS – RFCS-2022

114	PKW	Zakład Górniczy Janina		Zachodni	235,90	4,00	-50,7
115	PKW	Zakład Górniczy Sobieski		Sobieski III	526,00	7,50	-49,2
116	PKW	Zakład Górniczy Sobieski		Traugutt II	410,60	5,20	-49,2
117	PKW	Zakład Górniczy Sobieski		Kazimierz	754,00	7,50	-0,6
118	PKW	Zakład Górniczy Sobieski		Leopold	301,82	4,60	-49,8
119	PKW	Zakład Górniczy Sobieski		Karolina	502,62	4,50	-49,8
120	PKW	Zakład Górniczy Sobieski		Helena	526,00	6,70	-49,8
121	PKW	Zakład Górniczy Sobieski		Grzegorz	353,00	7,50	-49,9
122	SRK	Oddział CZOK	PG Saturn	Paweł	193,56	6,40	-50,1
123	SRK	Oddział CZOK	PG Grodziec	II	219,34	7,50	-50,1
124	SRK	Oddział CZOK	PG Nivka-Modrzejów	Kazimierz I	412,27	6,00	-50,1
125	SRK	Oddział CZOK	PG Katowice	Bartosz II	457,53	6,00	-50,1
126	SRK	Oddział CZOK	PG Kleofas	Fortuna II	570,50	6,30	-50,1
127	SRK	Oddział CZOK	PG Gliwice	II	380,13	6,40	-50,1
128	SRK	Oddział CZOK	PG Wieczorek II	Roździeński	609,63	7,50	-50,1
129	SRK	Oddział CZOK	PS Siemianowice	Bańgów	336,00	6,50	-49,4
130	SRK	Oddział CZOK	PS Siemianowice	Siemianowice III	360,16	5,00	-49,4
131	SRK	Oddział CZOK	PS Siemianowice	Kolejowy I	542,20	4,80	-48,8
132	SRK	Oddział CZOK	PS Siemianowice	Zygmunt August II	638,50	5,00	-49,4
133	SRK	Oddział CZOK	PS Jan Kanty	Witold I	290,30	5,20	-49
134	SRK	Oddział CZOK	PS Jan Kanty	Witold II	336,30	6,00	-49,4
135	SRK	Oddział CZOK	PS Pstrowski	Gigant	874,55	8,00	2,4
136	SRK	Oddział CZOK	PS Pstrowski	Staszic	594,00	4,00	-49
137	SRK	Oddział CZOK	PS Szombierki	Ewa	837,80	5,00	-48,8
138	SRK	Oddział CZOK	PS Dębieńsko	V Zachodni	587,17	6,00	-49,4
139	SRK	Oddział CZOK	PS Dębieńsko	Król Jan III	799,40	5,10	-48,8
140	SRK	Oddział CZOK	PS Boże Dary	I	508,31	5,00	-49
141	SRK	Oddział CZOK	PS Boże Dary	II	618,78	5,00	-48,6
142	SRK	Oddział CZOK	PS Makoszowy	I	883,00	5,73	-1,8
143	SRK	Oddział CZOK	PS Makoszowy	Północny	865,00	7,50	0,9

D.2.1. Guidelines on the adaptation and use of inactive shafts possible to energy storage
Project: 101112380 – HESS – RFCS-2022

144	SRK	Oddział CZOK	PS Mysłowice Wesoła I	Wschodni II	515,80	5,50	-49,7
145	SRK	Oddział CZOK	PS Mysłowice Wesoła I	Wschodni I	336,20	4,00	-49,9
146	SRK	Oddział CZOK	PS Śląsk I	I	1081,00	8,00	4,4
147	SRK	Oddział CZOK	PS Pokój I	Wanda	846,85	7,50	0,5
148	SRK	Oddział CZOK	PS Centrum	Budryk	982,26	7,60	3,4
149	SRK	Oddział CZOK	PS Centrum	Staszic	776,99	6,00	-48,6
150	SRK	Oddział CZOK	PS Bolko	Bolko	128,90	4,50	-49,2
151	SRK	Oddział w Jastrzębiu Zdroju	KWK Jastrzebie III	Jas I	1091,75	7,20	3,1
152	SRK	Oddział w Jastrzębiu Zdroju	KWK Jastrzebie III	Jas IV	892,10	6,00	-1,4
153	SRK	EKO-PLUS		Went - Pods	336,30	6,00	-48,8
154	EKO-PLUS	EKO-PLUS		Kopernik	676,10	6,60	-48,8
155	SILESIA	KWK SILESIA		Nr 1	518,62	4,20	-50,1
156	SILESIA	KWK SILESIA		Nr 2	515,30	4,60	-50,3
157	SILESIA	KWK SILESIA		Nr 3	592,00	5,20	-50,1
158	SILESIA	KWK SILESIA		Nr 5	291,68	6,50	-51,1
159	SILTECH	ZG SILTECH		Mikołaj	429,30	4,00	-49,4
160	WĘGLOKOKS	KWK Bobrek- Piekary	Bobrek	Józef	871,21	6,40	-0,4
161	WĘGLOKOKS	KWK Bobrek- Piekary	Bobrek	Bolesław	779,53	6,00	-49,4
162	WĘGLOKOKS	KWK Bobrek- Piekary	Bobrek	Ignacy	642,60	6,00	-49,4
163	WĘGLOKOKS	KWK Bobrek- Piekary	Bobrek	Zbigniew	756,10	5,00	-49,4
164	Bogdanka	LW "Bogdanka"		1.2	995,00	6,00	1,8
165	Bogdanka	LW "Bogdanka"		1.3	1030,15	7,50	3,6
166	Bogdanka	LW "Bogdanka"		1.4	995,82	7,50	2,8
167	Bogdanka	LW "Bogdanka"		1.5	989,50	7,50	2,4
168	Bogdanka	LW "Bogdanka"		2.2	1018,25	7,50	4,3
169	Bogdanka	LW "Bogdanka"		2.1	1097,74	7,50	4,6

Czech Republic

No.	Company	Mine	Division	Shaft	Depth [m]	Diameter [m]	Total score
1	2	3	4	5	6	7	8
1	OKD	ČSM	ČSM Sever	Sever (exhaust ventilation)	1005,0	7,5	3,7
2	OKD	ČSM	ČSM Sever	Sever (intake)	1104,4	7,5	5,5
3	OKD	ČSM	ČSM Jih	Jih (exhaust ventilation))	972,1	7,5	2,7
4	OKD	ČSM	ČSM Jih	Jih (intake)	1103,9	7,5	5,2
5	OKD	ČSA	-	Jan	962,2	7,5	NA
6	OKD	ČSA	-	ČSA 2	1049,3	7,5	NA
7	OKD	ČSA	-	ČSA 3	994,8	7,5	NA
8	OKD	Darkov	-	Da-1	878,3	7,5	NA
9	OKD	Darkov	-	Mír 5	887,2	7,5	NA
10	OKD	Darkov	-	Mír 4	1011,5	7,5	NA
11	OKD	Jeremenko	-	Jeremenko 1	819,0	5	NA
12	OKD	Jeremenko	-	Jeremenko 2	1062,0	7,5	NA

Slovenia

No.	Company	Mine	Division	Shaft	Depth [m]	Diameter [m]	Total score
1	2	3	4	5	6	7	8
1	Premogovnik Velenje, d. o. o.	Velenje	-	Transport shaft Nove Preloge (A)	416,42	7,2	-49,1
2	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Nove Preloge (A)	390,7	6,15	-49,4
3	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Pesje (A)	141,76	4	-49,4
4	Premogovnik Velenje, d. o. o.	Velenje	-	Intake shaft Šoštanj II(A)	332,57	5	-49,4
5	Premogovnik Velenje, d. o. o.	Velenje	-	Škale Shaft (A)	168	3,9	-49,6
6	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Šoštanj I (A)	234,72	5,9	-49,8
7	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Hrastovec** (Sealed short mine-surface ventilation connection)	42,8	ND	NA

D.2.1. Guidelines on the adaptation and use of inactive shafts possible to energy storage
Project: 101112380 – HESS – RFCS-2022

8	Premogovnik Velenje, d. o. o.	Velenje	-	Kronprinz Rudolf Schacht* (Decomissioned)	118,2	ND	NA
9	Premogovnik Velenje, d. o. o.	Velenje	-	Kronprinz Rudolf Wetterschacht* (Decomissioned)	93,5	ND	NA
10	Premogovnik Velenje, d. o. o.	Velenje	-	Glinšek Shaft* (Decomissioned)	178+17,4	ND	NA
11	Premogovnik Velenje, d. o. o.	Velenje	-	Preloge transport shaft* (Decomissioned)	373	ND	NA
12	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Preloge* (Decomissioned)	336	ND	NA

Information:

ND - no data, the shaft is being filled or liquidated

NA – no assessment, due to the status of the shaft, no results were obtained

PART 2

Guidelines on the adaptation of inactive mines for energy storage using CAES systems

Contents:

1. Problems with energy storage and the possibilities of solving them on the example of Polish, Czech Republic and Slovenia	85
1.1 CAES technology and its adaptability in the shafts of inactive mines	85
1.2 Storage potential in shafts in Polish, Czech Republic and Slovenia	87
1.3 Basic information about mine shafts and selected problems related to their adaptation to energy storage	89
2. Basic assumptions of multi-criteria analysis	90
3. Shaft height parameter	91
3.1 Shaft width parameter	92
3.1.1 Summary of geometric parameters	94
3.2 Shaft Type Parameter	94
3.3 Parameter of Shaft Casing Quality	96
3.4 Parameter of sealing inlets on the shaft	98
3.5 Hydrogeological parameters	102
3.6 Water inflow parameter	102
3.7 Parameter of the suffocation phenomenon	103
3.8 Water aggressiveness parameter	103
4. Tabular presentation of the analysis using the point method based on an example	104
5. MCDA software for shaft selection	106
6. Literature	106

1. Problems with energy storage and the possibilities of solving them on the example of Polish, Czech Republic and Slovenia

Some European countries, especially the former Eastern Bloc countries, are much more backward in terms of the energy transformation taking place in the European Union than their western neighbours. Thus, they face the challenge of providing capacity to balance renewable energy and ensuring adequate energy buffers to guarantee the stable operation of power and heating networks. This challenge coincides with another one, i.e. the abandonment of hard coal mining and combustion and the closure of mines. Existing works shows [1] that there is a need to balance both these processes. One of the ideas is to use part of the underground infrastructure, including hard coal mines, but also copper mines or other raw materials for the purpose of building energy storage facilities [2]. According to the concept, it would be a compressed air energy storage (CAES) [3, 4, 5, 6]. Such a way of using mine shafts would allow for the reclamation of post-mining areas in accordance with the idea of circular economy by reusing very expensive and difficult to construct structures such as mine shafts. The construction of this type of storage would allow for effective energy storage at the peak of renewable energy generation, [1] which would improve the quality of life of the inhabitants of the former mining industry zones and improve the local natural environment, which has been degraded for years by the above-average industrialization of the regions. The following report presents a preliminary analysis of the use of this potential for energy storage purposes in Adiabatic Compressed Air Energy Storage (A-CAES) systems with Thermal Energy Storage (TES) using a multi-criteria system for assessing mine shafts in terms of their suitability for conversion into energy storage.

1.1 CAES technology and its adaptability in the shafts of inactive mines

The possibility of using the workings of inactive mines for energy storage using CAES systems is a concept protected by a European patent [8]. It is largely based on the use of the vertical excavation support (mine shaft) as a compressed air reservoir and the surrounding rock mass as its support. The potential high stability and weight of the rock mass provide excellent support for the shaft lining, making it an alternative that can successfully compete with above-ground thick-walled tanks [9, 10]. Simple adaptation assumptions assume a process identical to the process of decommissioning a shaft during the first steps, followed by construction and assembly works on the storage itself.

The construction of CAES in mine shafts requires geomechanical analyses to be carried out, which will ultimately confirm the feasibility of the investment and determine the parameters necessary to design structural details in the selected location. The paper presents such analyses made with the use of the Universal Distinct Element Code (UDEC) software of itasca international.

This program simulates a quasi-static or dynamic load response of media containing many intersecting structures. Analysis of the results showed that subjecting the shaft lining to cyclic stresses in the opposite direction to the originally assumed one does not adversely affect its integrity. This clearly demonstrates the technical feasibility of using the shaft of a disused mine as a compressed air storage facility, even at a storage pressure of 10 MPa. This simulation clearly confirms the feasibility of the shaft project. It also provides the basis for creating individual analyses and geomechanical models for each object. Due to the general nature of the analysis presented in the report, it is not possible to include the parameter of maintaining the integrity of the shaft in filling cycles checked by means of a geomechanical model as presented

above. This requires too complicated analyses assuming a precise recognition of the rock mass structure along the entire depth of the shaft. These analyses will be necessary in the further steps of selecting shafts for adaptation and creating designs for individual adaptations. It will be impossible to create such complex models for each object, which is the basis for developing a method of initial selection. CAES technology is classified as a large-scale energy storage system [11]. The life cycle of a CAES power plant is divided into three stages: charging, energy storage and discharging. During the charging stage, the system draws electricity from the grid to power the air compressor, which compresses the air from ambient pressure (in an open system) to the upper pressure limit in the compressed air reservoir [12]. During the energy storage stage, the air compressed to the maximum pressure level remains stored in the reservoir. During the discharge stage, the stored air is expanded and directed to the combustion chamber, where it is used to burn fuel, and then the exhaust gases are directed to the expander and electricity is produced. This division of the energy storage system life cycle allows for price arbitrage in the energy market and energy consumption during periods of low prices (low demand or significant overproduction of energy from other sources) and energy production during periods of high prices (high demand or low production of energy from other sources [13]. For this reason, CAES systems are indicated as potential systems for balancing shortages in the power grid, as well as being an alternative source of energy in the event of a failure and an integrator of renewable energy sources and the power system [14]. Currently, there are two commercial power plants of this type in the world – Huntorf in Germany [15] and McIntosh in the United States [16]. The Huntorf power plant, commissioned in 1978, was originally a balancing element for the nearby Unterweser nuclear power plant and was its emergency power source in the event of a lack of external power from the grid (black start capability). It is equipped with a 68 MW compressor and a 321 MW expander. During the charging stage, the air flow is maintained at 108 kg/s, and during the unloading stage at 455 kg/s. The compressed air reservoir consists of two salt caverns with a capacity of 140,000 m³ and 170,000 m³ respectively. The fuel is natural gas, although research work on the use of hydrogen in the combustion process has begun [17]. The McIntosh power plant in the USA was launched in 1991. Compared to the Huntorf, it is equipped with a heat exchanger between the exhaust gases leaving the expander and the compressed air in front of the combustion chamber. The power plant consists of a compressor with a capacity of 49 MW and an air stream of 89.4 kg/s during the charging stage and an expander with a capacity of 110 MW and a flue gas mass stream of 154.2 kg/s during the discharge stage. The capacity of the salt cavern is 538,000 m³, and the maximum permissible pressure in the compressed air reservoir is 77.9 bar [18]. For the proposed adiabatic systems, the fuel combustion process is replaced by the use of Thermal Energy Storage (TES) [19]. The heat required to raise the enthalpy of the air before the expansion process comes from the charging stage of the system. During the process of compressing air, its temperature increases. In diabatic CAES systems, the intercooling of the compressor is implemented by means of a liquid refrigeration circuit. With A-CAES systems, the heat of gas compression is stored and transferred to the expanded gas during the charging stage [20]. One of the projects implementing the adiabatic CAES system was ADELE, which investigated the potential of an energy storage system with a capacity of around 1 GWh using a salt cavern with a capacity of more than 350 000 m³ as a compressed air reservoir. The declared power of the compressor was about 200 MW, and the air expander was about 260 MW. The biggest technological challenge was the high-pressure, above-ground heat storage system, which in one of the concepts was defined as a prestressed concrete structure with a height of about 50 meters and a height of 24 meters. The technological complexity of the TES storage tank and, consequently, its cost meant that the conclusion from the work was that the implementation of an adiabatic compressed air energy storage system was not economically justified at the electricity prices of the time [21]. Reducing the costs of implementing the energy

storage system is also possible by using the existing infrastructure and structures, because one of the costly components of the CAES system is the leaching of the salt cavern, which is also an ecological challenge due to the need to manage or utilise the resulting brine. Kim and others [22] explored the possibility of using underground tunnels dug into the rock as a reservoir of compressed air. The analysis included strength and permeability tests of underground structures, as well as thermodynamic calculations of the entire system, taking into account air losses during the storage stage. Bartela et al. [2] proposed the concept of using post-mining mine shafts as a reservoir of compressed air. The concept is distinguished by the placement of the TES tank in the mine shaft, which reduces the need for a thick-walled tank due to the relatively small pressure difference between the inside of the heat tank and the compressed air reservoir. Compared to the ADELE project, the heat storage located in the mine shaft is characterized by increased slenderness, which results in increased air pressure losses during the charging and discharging stage, but has a positive effect on the exergetic efficiency of heat storage due to the reduced conduction field in the accumulation material, which has been confirmed experimentally and numerically [20].

1.2 Storage potential in shafts in Polish, Czech Republic and Slovenia

In Poland, there are about 228 active and non-decommissioned mine shafts (Fig. 1), most of them are located in Upper Silesia and belong to hard coal mines, the rest are shafts belonging to the copper mines of KGHM Polska Miedź SA in western Polish. Shafts belonging to the Bogdanka coal mine in the east and shafts belonging to the Kłodawa salt mine in Central Poland. According to the guidelines described below, 52 shafts will be suitable for reuse, with optimal storage operating parameters. This number may change depending on the market situation. Taking into account the dimensions of these shafts, the potential storage volume can be estimated at a minimum of 3100 megawatt hours, assuming that all of them meet only the minimum height and diameter criteria. In fact, the real potential of existing mine shafts is even greater. This capacity corresponds to 150% of the total energy capacity of the upper water reservoir of the Porąbka-Żar pumped-storage power plant and almost five times the capacity of the Żydowo pumped-storage power plant [23]. This huge potential can be squandered by the standard process of decommissioning the shaft by backfilling. Much smaller storage potentials are represented by shafts located in Slovenia and the Czech Republic. This is related to the long-term and progressive process of liquidation of mining plants. Currently, in the Czech Republic (Fig. 3), 7 shafts have been inventoried, each of them with parameters corresponding to today's market needs. The facilities located in Slovenia (Fig. 2) include 5 shafts suitable for adaptation, but due to smaller than the limit dimensions, the profitability of their operation may be lower.

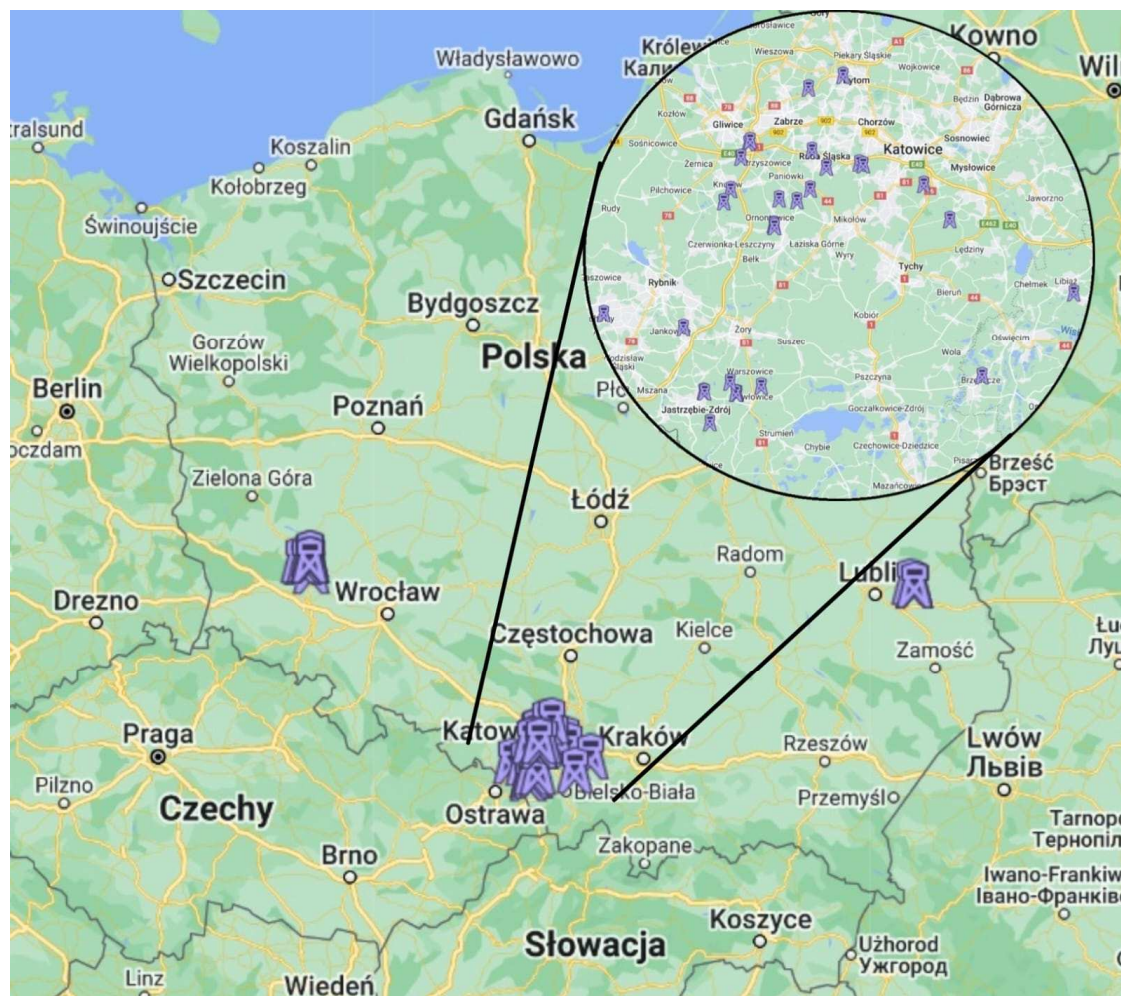


Figure 1 Map of mining shafts in Poland

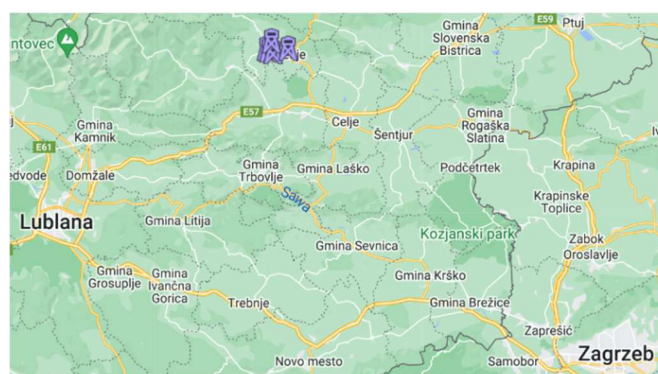


Figure 2 Map of mining shafts in Slovenia



Figure 3 Map of mining shafts in Czech Republic

1.3 Basic information about mine shafts and selected problems related to their adaptation to energy storage

A mine shaft is a vertical or sloping mining excavation directly connected to the surface of the earth. In their original purpose, shafts are used to transport crew, excavated material, utilities and ventilation of the mine. Mine shafts are complex structures, the construction of which requires advanced methods in the field of underground construction. Due to the vertical structural division, the shaft consists of:

- the upper section, i.e. the shaft collar connecting the shaft with the surface,
- the middle section, i.e. the main component,
- individual shafts stations,
- the lower section, located below the lowest shaft bottom. This section, called the sump, is responsible for collecting water and dirt.

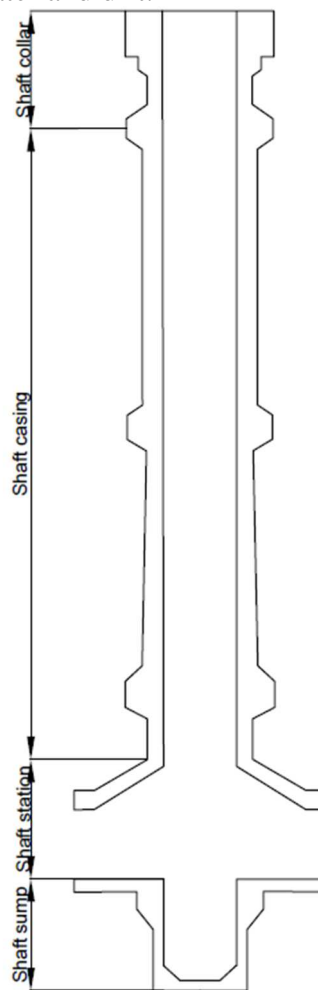


Figure 4 Construction of a mining shaft

Mine shafts are also divided according to their functions, m.in.:

- shafts for transporting excavated material,
- ventilation shafts,
- supply and exit shafts.

This division is important because each of the above-mentioned types is characterized by a different specificity of adaptation to the CAES system. Ventilation only shafts are characterized by small internal development, usually limited to cable routes or pipelines. They are also shafts

with a smaller cross-section. In the case of the implications of the CEAS system, such a shaft does not require the disassembly of a large number of devices, but it will usually present a much lower storage potential due to the smaller diameter. Shafts for transporting excavated material, people or materials are characterized by much larger diameters and are usually the shafts with the largest diameters in a given mine. However, this entails the need to dismantle all equipment and repair the casing, m.in. in the places where the girders and the guiders structure are located. The two largest areas of adaptation of the shaft to the new role can be divided into works related to the condition of the shaft lining and inlets to a given shaft, and works related to the inflow and migration of water within the shaft, consisting in sealing the structure and preventing the phenomenon of suffosion.

Shafts, as solid and extremely expensive structures, differ significantly from other underground mining excavations. The vast majority of horizontal workings are built on a temporary basis, and their useful life, with minor exceptions, does not exceed several years. The shafts are built with use throughout the life of the mine in mind. When designing the operation, their protection is taken into account by defining the so-called protective pillars around. These are areas of the rock mass excluded from operation in order to minimize the impact of rock mass movements within the shaft. This strengthens the safety and vitality of the building.

The scope of work needed to adapt the shaft to the new role includes well-known and commonly used mining methods, which are described in individual subsections of chapter 3.

2. Basic assumptions of multi-criteria analysis

MCDA(Multi-criteria decision analysis) [24] can be understood both as a way of thinking about decision-making and a set of specific tools. Its main goal is to organize the available options – from the most to the least advantageous. Different options can lead to the achievement of several goals to a greater or lesser extent, and none of them will be perfect in terms of all criteria. In addition, there are often conflicts or compromises between goals. For example, more cost-effective solutions tend to be more expensive. Costs and benefits are a typical example of conflicting goals, but so can short-term versus long-term benefits, or higher risks associated with a seemingly better option. MCDA is a method for analyzing complex problems that include both financial and non-financial goals. It involves breaking down a problem into smaller, more manageable parts to allow data analysis and evaluation of each one. These parts are then reassembled to provide policymakers with a coherent picture of the whole. The purpose of MCDA is to support the thinking and decision-making process, not just decision-making. As a set of techniques, MCDA offers a variety of ways to break down a complex problem, measure how well each option is meeting its goals, assign weights to those goals, and reassemble the pieces.

The basic assumption of creating a preliminary analysis for the selection of mine shafts for the purpose of creating energy storage facilities in them is a quick and cheap estimation of the storage capacity of a given country, region or mining plant to be decommissioned. The main objective of the analysis is to pre-select wells for the next individual analysis using geomechanical and thermodynamic models. The analysis assumes three main categories:

- Geometry
- Casing
- Hydrogeology

The geometry category focuses on the aspects of shaft geometry affecting the potential energy resources to be stored by estimating the parameters of the shaft lining height and width that will form the compressed air reservoir. The allocation of the highest number of points is dictated by

the condition of economic profitability of the investment. Energy prices will determine the commercial profitability of the investment, but at the same time they do not rule out the possibility of its implementation with a significant outlay of funds in relation to the expected returns.

The category of hydrogeology has also been divided into three subcategories. One of them, describing the chemistry of waters, received a higher percentage share and a fixed share ratio compared to the other subcategories. Other subcategories, as in the case of engineering works, have a variable percentage depending on the expenditure needed to solve the problems they bring.

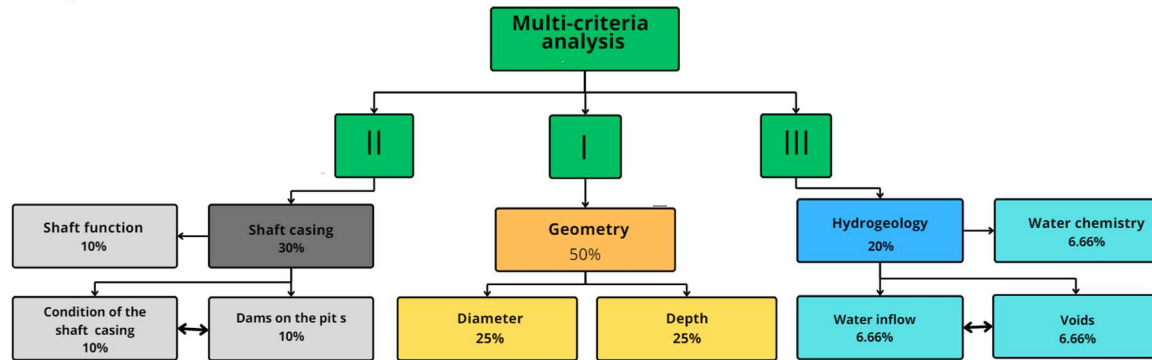


Figure 5 Distribution of weights in multi-criteria analysis

The main objective of the analysis is the initial and rapid selection of wells for further individual analysis based on advanced geomechanical and thermodynamic models. Preselection allows for quick and economical selection of objects that have adaptation potential. This gives you the opportunity to create plans that assume in advance the possibilities of using the continuously operating infrastructure. Thanks to this, all works can be planned in advance and implemented smoothly immediately after the decommissioning of mining plants. The storage potential analysed in this way makes it possible to estimate the storage capacity of post-mining infrastructure at the regional or national level. This will make it easier to plan future investments in the energy storage sector.

3. Shaft height parameter

The height of the H-shaft is one of the key parameters affecting the compressed air reservoir capacity of the CAES system, which directly translates into the energy capacity of the energy storage system. For highly urbanized and industrial areas, in the vicinity of which there are both mines and centralized electricity generation units, it is most advantageous to implement large energy storage systems. They can provide a safety reserve for critical urban and industrial systems, as well as balance electricity demand and thus reduce the shutdown of fossil fuel units. For this reason, mine shafts with a depth of 800 meters were taken into account, which both ensures sufficient energy capacity of the system when it is necessary to use part of the volume for the heat storage tank and structures protecting the upper part of the compressed air reservoir. The shaft height, which is one of the components of the parameters used to determine the volume of the mining shaft, translates in proportion to the final value of the compressed air reservoir capacity. In the CAES system, air is the main working medium, whose compressed and expanded stream directly translates into the power of the machines used (compressor and expander), and thus into the consumption and production of electricity. The larger the stream of expanded air during the discharge stage, the more energy the system can transfer to the power grid. The volume of the VCAES shaft was defined by the equation:

$$V_{CAES} = \pi * ((D^2)/4) * H \quad (1)$$

where D is its inner diameter and H is its height.

Figure 6 presents the results of electricity production from the adiabatic CAES system depending on the height of the post-mining mine shaft and the volume of the compressed air reservoir, assuming that the diameter of the shaft is 7.5 meters and the diameter of the TES storage tank is 5 meters.

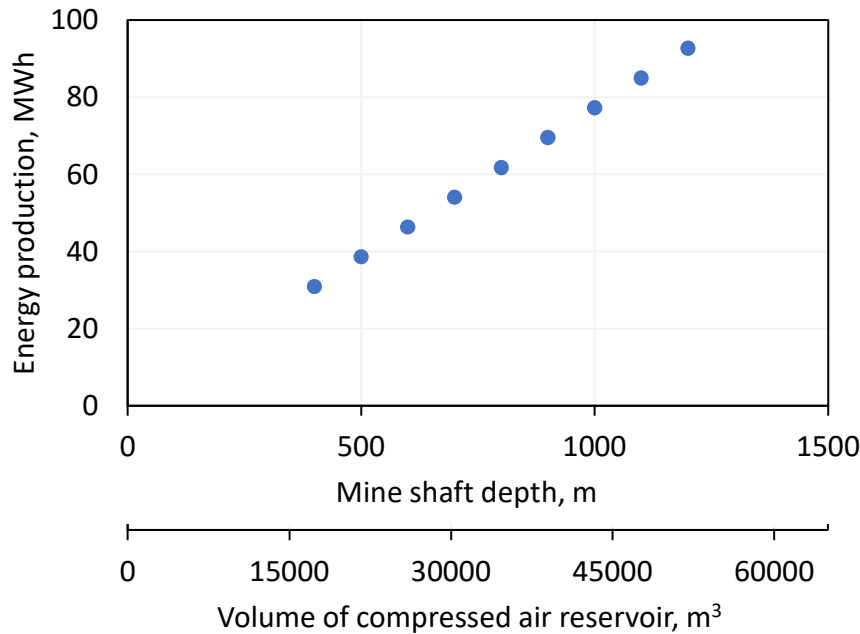


Figure 6 Electricity production from the adiabatic CAES system depending on the shaft height and compressed air reservoir volume.

The energy value, shown in Figure 6, is produced during the 4 hours of the discharge stage of the compressed gas energy storage system.

On the basis of the above analysis, three criteria related to the height of the shafts were adopted for the preliminary analysis of the shafts. The shaft height below 800 m is a criterion that eliminates the shaft from further considerations due to the lack of economic justification of the installation, the depth between 800 m and 1000 m gives a score of 5, between 1001-1150 m a score of 7, and above 1150 a score of 10.

3.1 Shaft width parameter

The width of the shaft is the second decision parameter that directly translates into the available energy capacity of the energy storage system. The studied concept of adiabatic CAES assumes the use of a TES storage tank within the shaft space, which determines the minimum diameter of the post-mining shaft. Studies have shown that increasing slenderness increases the exergetic efficiency of the heat storage process and maintaining a higher storage temperature, however, it leads to an increase in pressure losses of the flowing medium – both due to the increase in flow velocity and the elongation of the storage tank itself due to the need to maintain the same volume of accumulation material. Therefore, it was determined that the minimum diameter of the TES tank would be 5 meters without taking the external thermal insulation. Due to the need

to provide inspection access and thermal insulation, it was assumed that the minimum diameter of the shaft must be 7.5 m.

Figure 7 shows the value of the air pressure drop flowing through the TES tank depending on the diameter of the mine shaft and the diameter of the heat tank depending on it, with the assumption of providing inspection space.

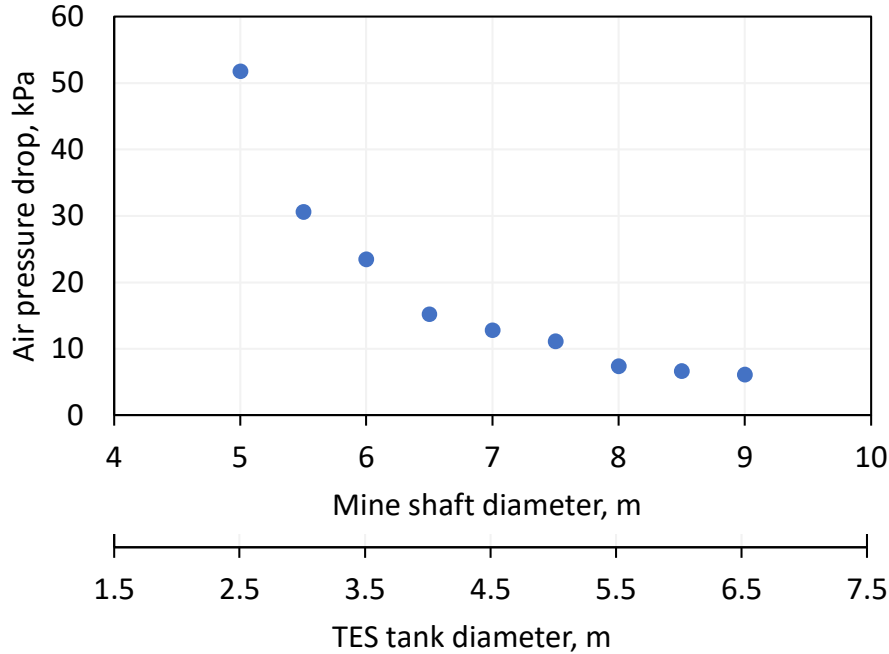


Figure 7 Value of the pressure drop of the air flowing through the TES tank depending on the diameter of the shaft.

The results presented in Figure 7 were obtained assuming a constant length of the shaft, which, with its variable diameter, also led to a reduction in the volume of the compressed air reservoir. Despite the reduction in the diameter and volume of the mine shaft, there was a significant increase in the decrease in air pressure flowing through the heat storage tank during the discharge stage. This is the result of a reduction in the cross-section of the gas flow, which consequently leads to an increase in the flow velocity and, as a result, an increase in the drop in air pressure. The abrupt increase in the value of the air pressure drop observed between the shaft diameter of 7.5 m and 8 m, 6 m and 6.5 m and 5 m and 5.5 m results from the increase in the number of heat storage segments that were required to store a certain amount of heat. The value of the pressure drop shown in Figure 7 was calculated by using the numerical model presented in [2, 25] and solving the Ergun's equation for the subsequent time steps of the charge and discharge stage [26].

On the basis of the above analysis, four sub-criteria related to the diameter of the shafts were adopted for the preliminary analysis of the shafts. The diameter of the shaft below 7.5 m is a criterion that eliminates the shaft from further considerations due to the lack of possibility of installing a heat storage tank, the diameter between 7.5 m and 7.99 m gives a score of 5, between 8.00-8.49 m a score of 8, and above 8.50 a score of 10.

3.1.1 Summary of geometric parameters

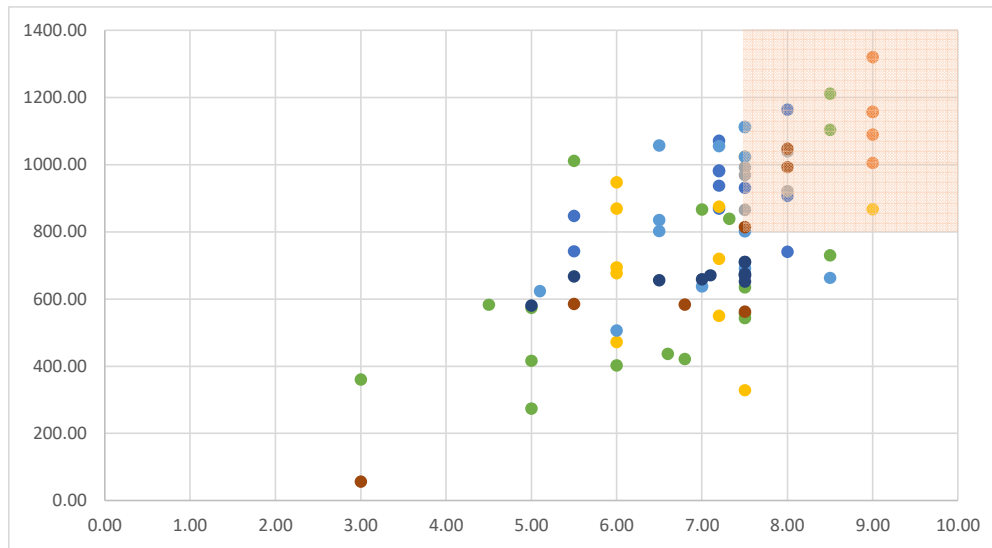


Figure 8 Mining shafts in Poland meeting the criteria

Figure 8 shows mining shafts in Poland that meet the criteria of minimum characteristic dimensions. The use of specific lower limits of the characteristic dimensions of the post-mining shaft guarantees a minimum volume of compressed air reservoir of approximately 35,000 m³. If a mine shaft with the maximum available dimensions (diameter equal to 9 m and height equal to 1320 m) is used, the volume of the compressed air reservoir is about 84,000 m³.

A thermodynamic analysis of the A-CAES system was carried out according to the computational model presented by Bartel and Ochmann. In addition, the minimum and maximum system pressures were assumed according to the Huntorf plant's specifications of 20 bar and 68 bar, respectively. The analysis showed that for a minimum assumed shaft volume of around 35 000 m³, the energy generated during the 3 hours of the discharge stage is 178 MWh, which is about 12 % of the Huntorf plant's potential. This value directly corresponds to the relationship between the volume of the salt cavern there and the volume of the post-mining mine shaft.

3.2 Shaft Type Parameter

Shafts are the most common way of accessing a mineral deposit in underground mines. Usually, at least 2 shafts are built, one deeper is used for transport and ventilation, and the other as an exhaust shaft. Due to the different purpose of the shafts, they differ in equipment. The equipment of ventilation shafts is limited to the ladder compartment of new pipelines and cable routes. This is due to the need to provide a large airflow and not disturb it with other equipment. Ventilation shafts are the easiest to adapt due to the negligible need to disassemble the equipment. The transport and skip shafts are densely enclosed not only with a ladder compartment, new cable routes and pipelines, but also with cranes supporting the skip and hoisting equipment. Dismantling such equipment involves not only the removal of steel structures, but also securing the in-depth areas of the shaft lining created after their disassembly. The whole work requires large expenditures in difficult access, therefore a smaller coefficient for shafts without equipment is assumed.



Figure 9 A notch in the shaft casing left by a girder

Figure 9 shows the loss of the casing after the disassembly of the girders, this process must be completed with the reconstruction of this part of the casing before it is strengthened and sealed as part of the adaptation to the energy storage, if necessary. The process of removing girders and guides from the shaft is a natural step in the decommissioning of the shaft. This process is well known and successfully used in decommissioning works. Renovation of the shaft casing, consisting in filling in the gaps left by the above-mentioned elements, is also a commonly used practice in shaft works.

Figure 10 shows the differences in the equipment of individual types of mining shafts. Black is used to mark the places where the equipment elements are inserted into the casing, which after disassembly of these elements will require filling in the notches.

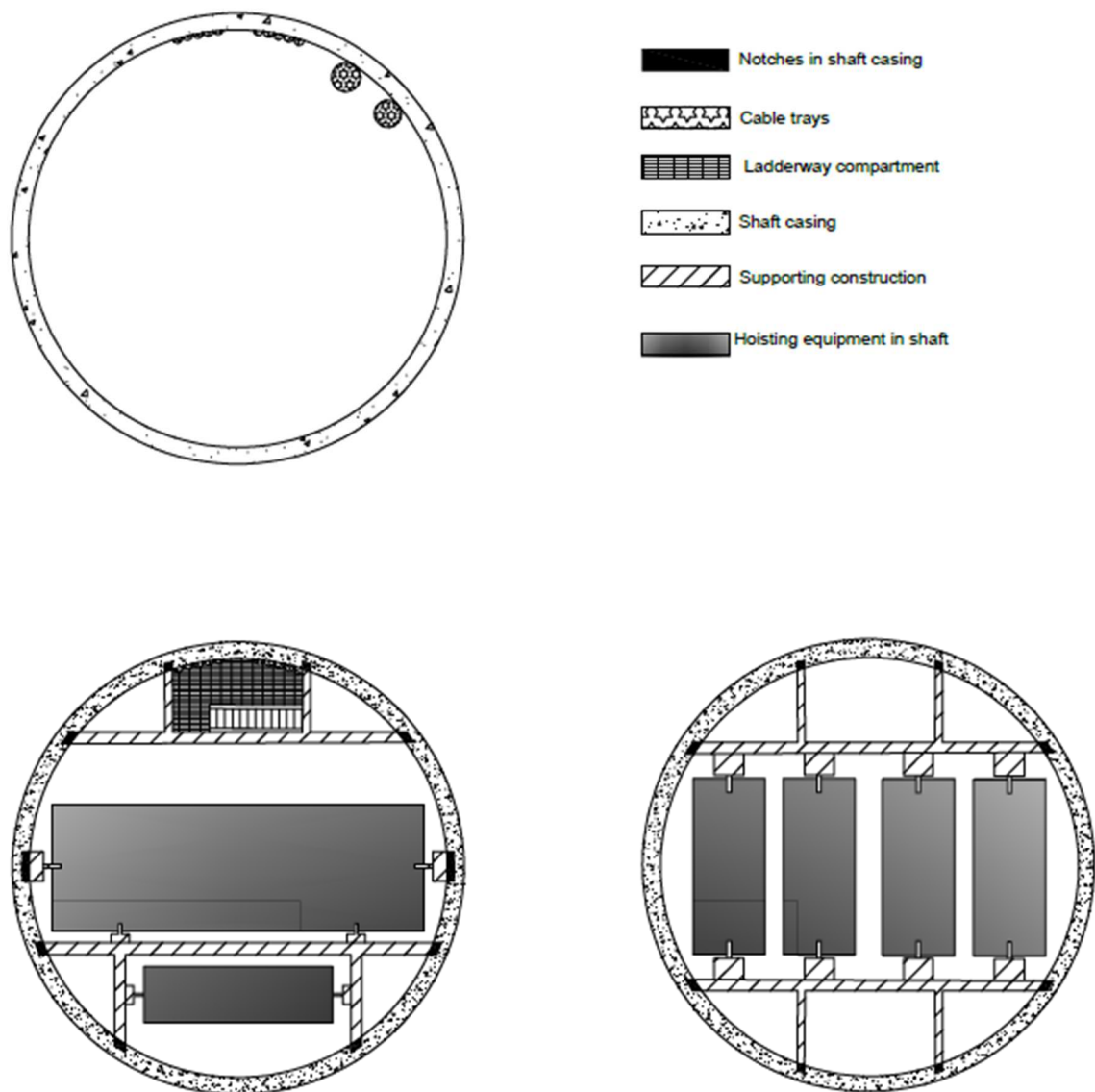


Figure 10 Shaft discs for various purposes, ventilation, transport of people and materials, skip

On the basis of the above data, two sub-criteria related to the type of shafts were adopted for the preliminary analysis of the shafts. The ventilation shaft receives 10 points, the shafts intended for transporting crew and excavated material receive 1 point.

3.3 Parameter of Shaft Casing Quality

This parameter is calculated on the basis of the consumption of the material (shotcrete) [27, 28, 29, 30, 31] needed to strengthen and repair the fragments of the shaft casing that require it. It is assumed that the performance of works consisting in the disassembly of shaft equipment elements, and thus the repair of the casing defects caused by the removal of those parts of the equipment that were integrated with the casing, are included in the shaft type parameter. The basis for estimating the total area of the places requiring reinforcement should be the inspection

carried out before the commencement [32, 33] of decommissioning works or the result of the last technical inspection of the shaft, which in accordance with the Polish law takes place every 5 years.

To calculate the parameter of restoration of the state of the casing, the volume of cubic meters of shotcrete used to strengthen the casing must be calculated. The following should be performed: Inspect the shaft casing [34], which will show the number of running meters that require reinforcement ($m_{\max}$). Calculate the volume of a cylinder V_f whose radius r will be equal to the radius of the shaft pipe and calculate the volume of the cylinder V_{nf} , whose radius will be smaller than the shaft pipe by a layer of planned shotcrete.

$$V_f - V_{nf} = V_o \quad (2)$$

Example:

3 fragments of the shaft casing, the diameter of which is 8 m, should be strengthened. a fragment requiring the application of a 20-centimeter layer of shotcrete and a ten-centimeter layer in two subsequent fragments, each 10 m high. The reinforcements required to be carried out in the example shaft qualify it as a shaft with good casing quality

$$V_{o1} = 60 \text{ m}^3$$

$$V_{o2} = 12 \text{ m}^3$$

$$V_{o3} = 12 \text{ m}^3$$

$$V_{o3 \text{ total}} < 400 \text{ m}^3$$

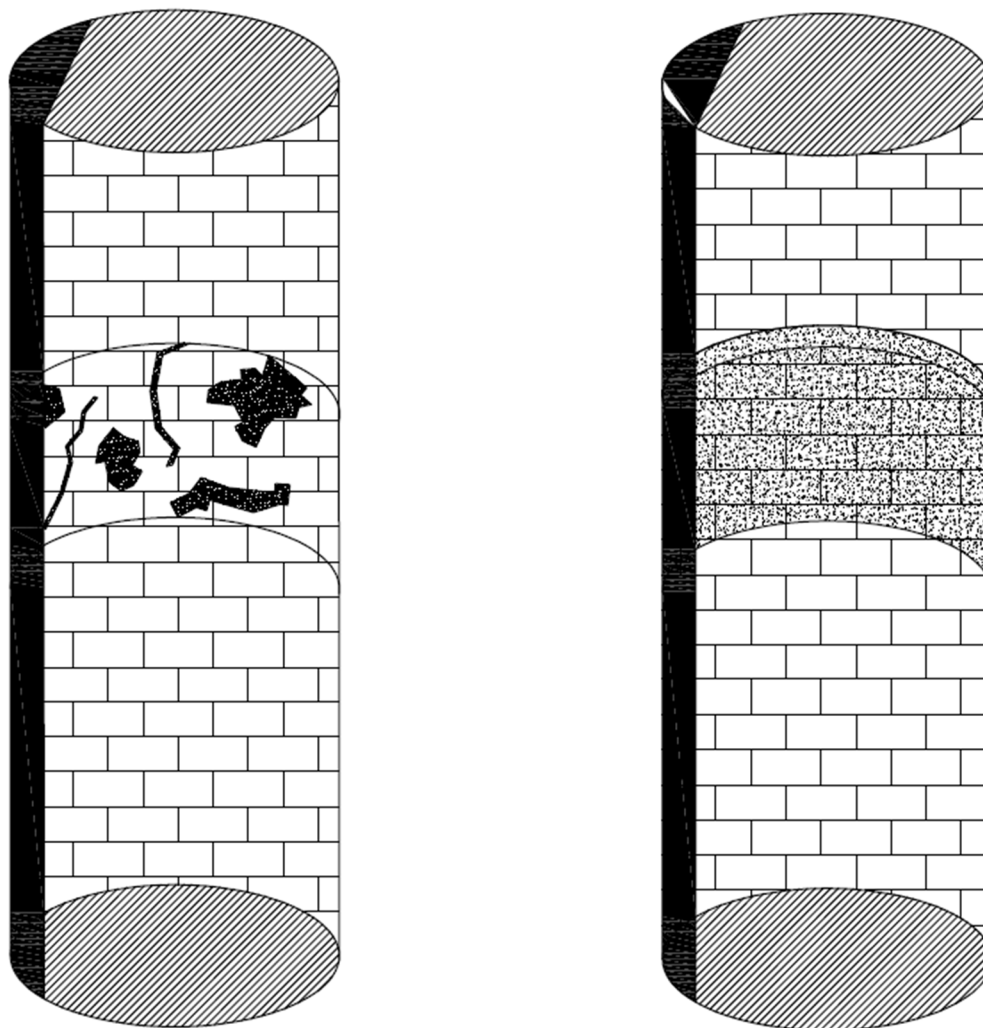


Figure 11 Graphical representation of a corroded section of the casing reinforced with shotcrete

On the basis of the above analysis, three sub-criteria related to the quality of the shaft lining were adopted for the preliminary analysis of the shafts. Poor quality of the casing in many places requiring the use of over 1000m³ of shotcrete - 1 point, average quality of the casing requiring consumption between 450 m³ and 1000 m³ - 5 points. Good quality of the casing requiring the consumption of less than 450 m³ of shotcrete - 10 points.

3.4 Parameter of sealing inlets on the shaft

Determining the need to adapt the shaft to air compression consists, m.in other things, in the need to estimate the costs of plugging the inlets to the shaft inlet. The technology of plugging inlets to the shaft is a technology commonly used during mine decommissioning processes. A dam built on each of the inlets will allow to isolate the shaft from other workings. This reduces the supply of water, gases and seals the entire tank. For the purpose of adapting the existing infrastructure, it should be assumed that multi-segment water dams with a pyramid-shaped segment structure should be used. This is due to the fact that it works at pressures higher than

0.5 MPa. The share of costs in this area, as in the case of shaft casing renovation, is estimated at material costs.

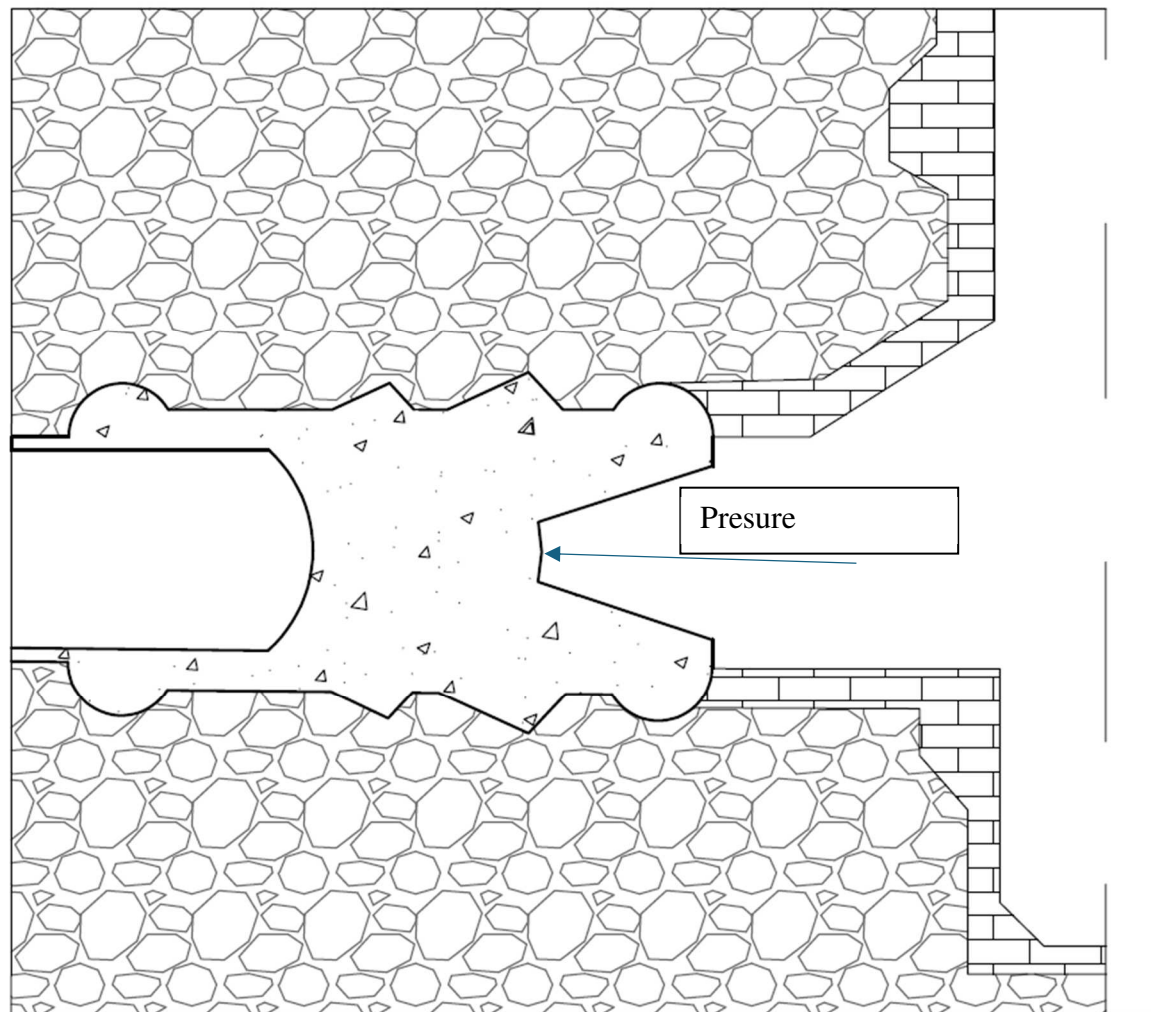


Figure 12 Pyramid dam built for the construction of a CEAS installation in the shaft

Calculation of the size of a water dam such as in Figure 12 on the example of the shaft discussed in the geometric parameter should be considered for the working pressure of the dam above 0.5 MPa, therefore all calculations of the parameters of this dam should be assumed as for concrete pyramid dams. The calculations are carried out as for two cylinders inscribed in the dam at right angles [35].

The thickness of a concrete pyramid dam should be calculated in centimeters according to the formula: d_t

$$d_t \geq \frac{p_x * r}{2k_c - p_x} + \frac{a^2}{8r} \quad (3)$$

The inner radius r (in the horizontal cross-section) of the dam should be taken for rocks with a strength of:

- to 30 MPa $r = 2,0 a$,
- above 30 MPa $r = 1,5 a$.

The inner radius r (in the vertical cross-section) should be taken for rocks with strength:

- to 30 MPa $r = 2,0 b$,
- above 30 MPa $r = 1,5 b$.

The angle of inclination of the dam retaining planes to the roadway axis should be assumed for rocks with compressive strength: $\alpha/2$

- to 30 MPa $\alpha/2 = 15^\circ$,
- above 30 MPa $\alpha/2 = 20^\circ$.

The thickness of the pyramid dam should be checked at: d_t

-shearing according to the formula

$$d_t \geq \frac{p_x ab}{2l\tau} \quad (4)$$

- pressure on the rock according to the pattern

$$d_t \geq \frac{p_x ab}{k_s l \sin \frac{\alpha}{2}} \quad (5)$$

where:

- b – the height of the excavation in the breach, cm;
- τ - design Value on wall of dam material by PN-84/B-03264
- k_s – allowable compressive stress for rocks, MPa;
- $l = 2(a+b)$ – dam circuit, cm.

Depending on the size of the dammed excavation and the exact working pressure of the storage, it is possible to achieve a dam thickness of over 250 cm for one segment. In this case, a multi-resisting dam should be used. Its thickness should be calculated using the formula:

$$d_t \geq \frac{p_x r}{2Nk_s - p_x} + \frac{a^2}{8r} \quad (6)$$

where:

N - the number of dam steps (i.e. the number of retaining planes, or the number of notches around the circumference).

The thickness of a multi-stage pyramid dam should be checked due to: d_t

– shearing of the dam and rock mass structure material according to the formula:

$$d_t \geq \frac{p_x ab}{2Nl\tau} \quad (7)$$

– pressure on the rock according to the formula:

$$d_t \geq \frac{p_x ab}{2Nk_s l - \sin \frac{\alpha}{2}} \quad (8)$$

The total thickness of a multi-stage retaining dam should be calculated using the formula D_t

$$D_t = Nd_t + c(N - 1) \quad (9)$$

where:

c- The distance between retaining notches (single dams placed one behind the other) depends on the type of rocks and is:

- 80 cm for rocks with a strength of up to 20 MPa,
- 50 cm for rocks with a strength above 20 MPa.

The above calculation sequence allows us to calculate the number of running meters of concrete needed to stop the shaft bottom. In this part of the shaft analysis, we are able to use basic and publicly available data such as:

- type of housing,
- height of the housing,
- width of the enclosure,
- type of rocks and their parameter, R_c
- pre-approved type of concrete for the construction of the dam,

calculate the volume of the dam, thus estimating the material consumption. Thanks to this knowledge, we can correlate the cost of repairing the shaft casing with the cost of damming the shaft. This procedure will allow you to properly select scales for individual structural aspects.

Example: Example of a pyramid dam for a shaft with dimensions $H = 4.2$ m and $S = 6.1$ and a shape shown in Figure 13, located in medium-grained sandstone with a medium grain of average parameter R_c 50 MPa. The thickness of the dam was calculated for $r = 1.5a$. C20/25 concrete with a design strength of 13.3 MPa was installed. A hydrostatic pressure corresponding to the maximum operating pressure of the storage of 10 MPa was assumed.

Using the calculation formulas presented above, the result was obtained in the form of a three-step dam with a total thickness of 5.29 m. The consumption of concrete needed to plug such a shaft is about 130m³.

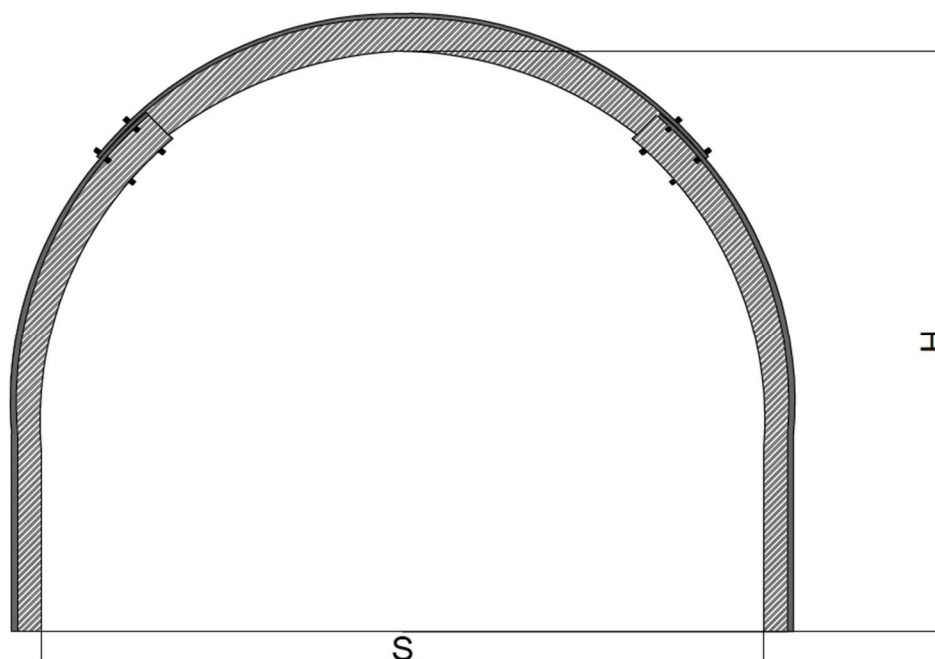


Figure 13 LP casing

On the basis of the above calculations, three criteria related to the installation of plugs on the shafts were adopted for the preliminary analysis of the shafts. Large volume of plugs on the shaft requiring consumption of over 1000 m³ of concrete 1 point, average volume of plugs on the shaft requiring consumption between 1000 m³ and 450 m³ 6 points. Small volume of plugs on the shaft requiring consumption of less than 450 m³ of concrete 10 points.

3.5 Hydrogeological parameters

Shafts of hard coal mines are exposed to natural geological and hydrological factors adversely affecting the condition of their support. A serious source of threat to the stability of the shaft is the chemical and, above all, mechanical action of water. This threat results not only from the amount of water inflow to the shaft, but also from the possibility of mechanical suffosion. This phenomenon consists in the washing away of fine grains and clay particles by water, especially from the layers of overburden directly surrounding the shafts. Over time, it leads to voids and changes in the configuration of the support load from the rock mass. Voids behind the shaft lining may cause damage to the shaft and the formation of surface-type sinkholes threatening the stability of the infrastructure in its vicinity. In addition, they prevent the counteracting tensile stresses acting on the shaft pipe under the operating conditions of the compressed air storage. Another threat from groundwater is the possible content of aggressive compounds that can affect the corrosion rate of the casing and equipment inside the shaft.

3.6 Water inflow parameter

In order to estimate the impact of hydrogeological conditions on the possibility of building a compressed air storage facility in a mine shaft decommissioned, the inflow rate should be taken into account. This parameter depends on the tightness and integrity of the shaft lining and

hydrogeological conditions in its surroundings. Permanent inflows with a small flow rate (of the order of $n \cdot 10^{-2} \text{ m}^3/\text{min}$) can be removed on an ongoing basis or cyclically, e.g. from the shaft with the use of appropriate pumping systems. Larger inflows are of course possible to remove, in this case it is necessary to take into account the increased costs and technical difficulties associated with the maintenance of appropriate drainage infrastructure. The basic concept of the storage assumes that it is fully tight, so the water inflows to the inside of the shaft must be stopped. The degree of complication of this operation results directly from the amount of inflowing water. The division is presented in Table 1:

Table 1 Scoring of water inflow to the shaft

No water supply	$Q = 0$	10 Points
Insignificant water inflow	$Q \leq 1/\text{min}$	6 Points
Significant inflow of water	$Q > 1/\text{min}$	1 Point

Table 1 above shows that very large groundwater inflows can be expected, even above 600 l per hour. However, when assessing this parameter, dry glass will receive 10 points, a shaft with an inflow not exceeding 10 litres per minute – 6 points, and a shaft with a significant inflow of more than 10 litres per minute – 1 point.

3.7 Parameter of the suffocation phenomenon

Voids behind the shaft lining may cause damage to the shaft and the formation of surface-type sinkholes threatening the stability of the infrastructure in its vicinity. In addition, they prevent the counteracting tensile stresses acting on the shaft pipe under the operating conditions of the compressed air storage. One of the most important advantages of using a mine shaft as a gas storage facility is that its casing rests against the surrounding rock massif, thus significantly increasing the resistance of the casing to the forces generated by the compressed air inside it. Void detection can be done using non-invasive geophysical methods such as GPR (Ground Penetrating Radar) or seismic methods. This allows for a quick examination of the condition of the rock mass behind the support without adversely affecting its condition. For this parameter, the scoring included in the table was used:

Table 2 Suffocation parameter scoring

Numerous voids behind the housing, the threat of emptiness	1
Few small voids, no threat	6
No voids	10

3.8 Water aggressiveness parameter

Water entering the shaft can have a degrading effect on the casing material. In order to determine the aggressiveness of water towards the shaft pipe lining, the water composition is interpreted (e.g. in accordance with the PN-80/B-01800 standard "Anti-corrosion protection in construction. Concrete and reinforced concrete structures. Classification and determination of environments") – Table 1. This assessment is also made on the basis of PN-EN 206+A2:2021-08 – Table 2.

Table 3 Degrees of water aggressiveness according to PN-80/B-01800

Type of aggressiveness	Aggressiveness Index	Unit Measure	Degree of water aggressiveness			
			la ₁	la ₂	ma	ha
Leaching	T _w	°n	6 > T _w ≥ 3	T _w < 3	-	-
Acid	H ⁺	pH	7 > pH ≥ 6,5	6,5 > pH ≥ 5	5 > pH ≥ 4,5	pH < 4,5
Carbonate	aCO ₂	mg/l	5 < aCO ₂ ≤ 10	10 < aCO ₂ ≤ 40	aCO ₂ > 40	-
Magnesium	Mg ²⁺	mg/l	150 < Mg ²⁺ ≤ 1000	1000 < Mg ²⁺ ≤ 2000	Mg ²⁺ > 2000	-
Ammonium	NH ₄ ⁺	mg/l	10 < NH ₄ ⁺ ≤ 100	100 < NH ₄ ⁺ ≤ 500	NH ₄ ⁺ > 500	-
Sulfate	SO ₄ ²⁻	mg/l	250 < SO ₄ ²⁻ ≤ 350	350 < SO ₄ ²⁻ ≤ 500	500 < SO ₄ ²⁻ ≤ 1000	SO ₄ ²⁻ > 1000

Table 4 Limit values of exposure classes according to PN-EN 206 regarding chemical corrosive aggressiveness of groundwater

Parameter	Unit	XA1 Chemical environment not very aggressive	XA2 Medium-Aggressive Chemical Environment	XA3 Highly aggressive chemical environment
pH	mg/dm ³	≤ 6,5 ≥ 5,5	< 5,5 ≥ 4,5	< 4,5 & ≥ 4,0
Mg ²⁺	mg/dm ³	≥ 300 ≤ 1000	> 1000 ≤ 3000	> 3000 & do nasycenia
NH ₄ ⁺	mg/dm ³	≥ 15 ≤ 30	> 30 ≤ 60	> 60 & ≤ 100
SO ₄ ²⁻	mg/dm ³	≥ 200 ≤ 600	> 600 ≤ 3000	> 3000 & ≤ 6000
CO ₂ agr.	mg/dm ³	≥ 15 ≤ 40	> 40 & ≤ 100	> 100 & do nasycenia

For the Data presented in the tables, the following score is proposed:

For low aggressiveness of waters: la₁ or la₂ or XA1, we assume 10 points. For medium aggressiveness: ma or XA2 we take 6 points, for high aggressiveness ha or XA3 we take 1 point.

4. Tabular presentation of the analysis using the point method based on an example

The elements of the multi-criteria analysis presented in the second chapter are presented in a tabular form.

CRITERIA		WEIGHTAGE	LEVELS			
Volume/energy capacity	Depth	25%	<800	800-949	950	>1149
	Diameter	25%	<7,5	7,5-7,99	8,00-8,49	>8,50
Underground construction/integrity	Type	10%		Haulage	Man/supply	Ventilation
	Casing integrity	10%		>1000m ³	1000m ³ -450m ³	>450m ³
	Inlet plugs	10%		>1000m ³	1000m ³ -450m ³	>450m ³
Rock mass/hydrogeology	Water chemistry	6,7%		aggressive -0	medium aggressive -6	inert -10
	Water ingress	6,7%		>10 l/min	<10 l/min	0 l/min
	Suffosion voids	6,7%		numerous	few	none/not detected
		max				
		100%				

Figure 14 Individual components of the multi-criteria analysis

The geometric parameters of the shaft received 50% of all analysis weights. Engineering parameters divided into the shaft type parameter, the parameter of sealing the inlets to the shaft and the parameter of restoring the construction state received 30% of all weights, with the proviso that 20% will be divided on the basis of a comparative analysis of the material costs of performing the tasks of sealing the inlets to the needs and restoring the condition of the support, described in detail in the third and fourth subsections of chapter 3. Parameters related to hydrogeology received 20% of all weights evenly distributed at 6.66% each.

Criteria	Level	Score
Shaft depth	<800	0
	800-949	5
	950-1149	8
	1150 >	10
Shaft diameter	<7,5	0
	7,5-7,99	5
	8,00-8,49	8
	8,50>	10
Shaft type	Ventilation	10
	Man and/or supply shaft	1
	Haulage shaft	1
Shaft casing integrity		
	>1000m ³	1
	1000m ³ -450m ³	5
	>450m ³	10
Cubic meters of soil		
	>1000m ³	1
	1000m ³ -450m ³	5
	>450m ³	10
Water inflow		
	0 l/min	10
	<10 l/min	6
	>10 l/min	1
Chemical composition		
	inert	10
	medium aggressive	6
	highly aggressive	0
Shaft surrounding suffosion voids	th	
	none/not detected	10
	few	6
	numerous	1

Figure 15 Scoring of individual analysis parameters

5. MCDA software for shaft selection

For the purposes of the analysis, software has been developed to enable the initial selection of shafts as described in the above study, in a quite simple and intuitive way. The program was written in Python. Software written in Python is characterized by its readability and simplicity, making it accessible for both beginners and experienced developers. It offers a rich standard library and extensive support for various programming paradigms, including procedural, object-oriented, and functional programming. Additionally, Python's dynamic typing and interpreted nature enable rapid development and prototyping. The software is an application that implements the principles outlined in the guidelines for simple and easy analysis of individual shafts. The creation of the software was accompanied by the idea of promoting the large-scale use of post-mining infrastructure for energy storage purposes. With this tool, it will be possible to easily and quickly identify the potential of post-mining infrastructure.

The figure displays three instances of the HESS (Hazardous Environment Shaft Selection) software interface. Each instance shows a set of input parameters for a shaft and a resulting score. The first instance shows a shaft with a depth of 1250, diameter of 9, and a score of 10.00. The second instance shows a shaft with a depth of 1000, diameter of 7.6, and a score of 5.55. The third instance shows a shaft with a depth of 700, diameter of 7.6, and a score of 0.00, with a red warning message indicating 'Shaft depth or diameter scales < 0'.

Shaft depth	Shaft diameter	Score
1250	9	10.00
1000	7.6	5.55
700	7.6	0.00

Figure 16 Example of using shaft assessment tool

As shown in Figure 16, three shafts with different parameters were evaluated. The software analyzed the data according to the rules presented in the report and scored each shaft. In the case of the last shaft, due to insufficient depth, the result was critical.

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