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Availability of domestic gypsum resources versus the predicted decline in synthetic gypsum production

Introduction

In response to the need to mitigate the environmental impact of conventional energy production, since the 1990s, coal- and lignite-fired power plants have been increasingly equipped with systems for particulate matter removal. They are flue gas desulfurization (FGD) and the subsequent reduction of nitrogen oxides. Among the available FGD technologies, the wet limestone (lime) scrubbing process has proven to be the most effective and environmentally sustainable. A key by-product of this process is synthetic gypsum, whose physicochemical properties are comparable to those of natural gypsum derived from primary geological deposits.

In countries where electricity generation has historically relied heavily on coal combustion, such as Poland and Germany, synthetic gypsum dominates the gypsum market. Its share in the total amount of gypsum processed by the building materials industry ranges from 60% to 75%.

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Driven by global climate protection goals, the energy sector has entered a new phase of transformation in the 21st century, focused primarily on the reduction of CO_2 emissions. Power generation based on renewable energy sources, such as solar and wind, has been gradually replacing coal-fired installations. This tendency is already evident in Poland, where a declining share of coal (hard coal and lignite) in the national energy mix has been observed, in line with the strategic objectives outlined in *Poland's Energy Policy until 2040* (PEP2040 2021). Full decarbonization of the Polish energy sector is projected to occur in the coming decades (Weiss et al. 2025). A direct consequence of the ongoing energy transformation will be a significant reduction in the availability of synthetic gypsum. In the absence of large-scale CO_2 sequestration technologies for coal-based power generation, the phase-out of such installations will effectively eliminate the primary source of synthetic gypsum. This impending shortage requires proactive adaptation by the gypsum industry to ensure a continuous supply of raw materials. Therefore, a predictable solution to the gypsum shortage is to increase the mining of natural gypsum from primary deposits.

However, the expansion of natural gypsum mining poses several challenges. Across Europe, mining activities, particularly those involving new operations, are frequently met with substantial social resistance. Moreover, a considerable number of documented gypsum deposits are located in areas under environmental or landscape protection. This imposes significant regulatory and practical constraints on surface (opencast) mining activities, as described in this article.

In light of the mentioned limitations, a comprehensive review of documented gypsum deposits, as well as prognostic and prospective areas in Poland, has been conducted to assess their potential for future development. Based on this assessment, and considering environmental protection regulations, underground mining using the room-and-pillar method is proposed as a viable and sustainable alternative. This method of exploitation significantly reduces surface disruption and environmental impact. Furthermore, it enables the partial or complete relocation of initial processing stages into underground chambers. This approach helps minimize gas emissions and their impact on air quality.

Such operations fall within the framework of so-called "invisible" or "clean" mining, in which both exploitation and pre-processing take place underground. The large thickness of many Polish gypsum deposits makes them particularly suitable for the use of this method. It is worth noting that underground gypsum mining has been successfully implemented in other countries. Furthermore, it is currently enjoying renewed interest due to growing environmental concerns and stricter land-use restrictions.

The primary objective of this study is to identify and analyze the anticipated reduction in the supply of synthetic gypsum resulting from the progressive depletion of currently exploited lignite deposits in Poland and the gradual phase-out of coal in the power sector. In response to the projected supply deficit in the gypsum industry, the study proposes the development of selected natural gypsum deposits as a strategic measure to ensure long-term raw material security. The recommended approach involves the extraction of gypsum using underground mining methods combined with the relocation of initial processing operations to underground workings. Such a solution may significantly reduce the environmental impact of mining activities and increase the likelihood of obtaining social acceptance for new mining projects.

1. The potential of synthetic gypsum production in Polish conventional power plants: history and current status

Synthetic gypsum is a by-product of flue gas desulfurization (FGD) processes used in conventional coal- and lignite-fired power plants, most often by wet limestone washing. Following the removal of particulate matter by high-efficiency electrostatic precipitators, the flue gas stream is directed countercurrently through an absorber where sulfur dioxide (SO_2) reacts with a sorbent, typically finely ground calcium carbonate ($CaCO_3$). The principal reaction that occurs within the FGD unit can be represented by the following simplified equation:

$$CaCO_3 + 2H_2O + SO_2 + ½O_2 \rightarrow CaSO_4 \cdot 2H_2O + CO_2 \quad (1)$$

The resulting product, calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), commonly called synthetic gypsum or REA gypsum, has physical and chemical properties comparable to those of natural gypsum exploited from primary deposits. The quality and purity of synthetic gypsum are mainly influenced by two factors: the efficiency of particulate matter removal by electrostatic precipitators and the chemical composition of the limestone sorbent, particularly its $CaCO_3$ content (Galos et al. 2016). High calcium carbonate content is a key criterion in evaluating the suitability of limestone for FGD processes (Naworyta 2013).

Synthetic gypsum is now regarded as a valuable industrial raw material and plays an important role in the circular economy. It is extensively utilized in the construction industry for the production of plasterboards, gypsum blocks, adhesives and mortars, as well as in the cement industry (Wons and Niziurska 2013).

The amount of synthetic gypsum produced as a by-product of FGD in conventional power plants is primarily determined by three factors: the quantity of coal/lignite combusted, the average sulfur content, and the operational efficiency of the FGD installation. Prior to the widespread integration of renewable energy sources (RES) into the Polish power sector, forecasting synthetic gypsum production based on these parameters was relatively simple.

Until approximately 2010, electricity generation in Poland was largely proportional to the installed capacity of conventional coal- and lignite-fired power plants. Thus, projections of synthetic gypsum output could be reliably modeled using assumptions based on installed power capacity and expected FGD deployment. Several studies employed this methodology to forecast gypsum production (Uberman and Naworyta 1998; Naworyta 2013; Szlugaj and Naworyta 2015).

The earliest of these forecasts was developed at a time when FGD installations were only beginning to be implemented on a large scale in Polish power plants (Uberman and Naworyta 1998). This model incorporated both the installed capacity of professional (industrial scale) power plants and, more importantly, the anticipated plans for implementing FGD systems. Subsequent studies demonstrated that the 1998 forecast proved to be remarkably accurate, validating its assumptions and methodology (e.g., Szlugaj and Naworyta 2015). However, the reliability of such forecasting models has declined in recent years. Since 2015, the Polish energy sector has undergone a rapid transformation marked by a significant increase in installed RES capacity. This is particularly true for wind and photovoltaic systems, and, although at a slightly slower pace, a corresponding increase in electricity generation from these sources.

Figure 1 illustrates the evolution of the electricity generation structure in Poland from 2005 to 2024. The acceleration in the implementation of RES after 2015 is clearly visible. This structural change introduces variability into the previously stable relationship between installed capacity in coal- and lignite-fired power plants and actual energy production. As a result, it complicates synthetic gypsum production forecasts based on historical models.

In accordance with the principles of the European energy market, renewable energy sources (RES) are granted dispatching priority. Therefore, during periods of high energy production from non-emission sources (e.g., wind and solar), conventional power plants

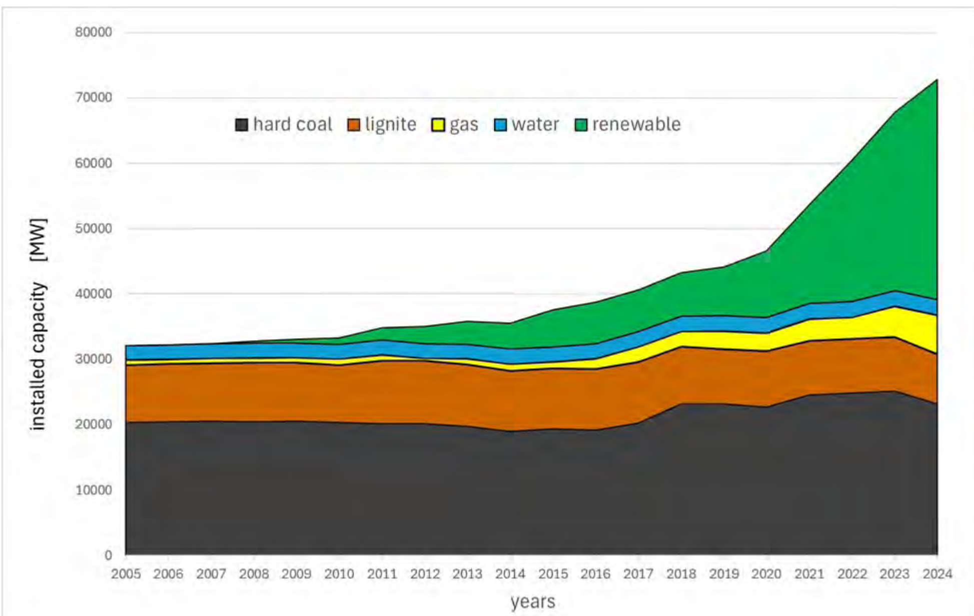

Fig. 1. Dynamics of changes in the structure of electricity generation capacity in Poland in the years 2005–2024 (based on PSE 2025; Naworyta and Urbański 2025, supplemented)

Rys. 1. Dynamika zmian struktury mocy zainstalowanej w Polsce w latach 2005–2024 are required to significantly reduce their electricity generation. This operational reduction directly translates into lower coal/lignite consumption, which in turn leads to decreasing the amount of synthetic gypsum generated in FGD processes. However, conventional power plants are not entirely decommissioned during RES surpluses. For example, during nighttime hours, when solar energy is unavailable, and wind generation may be insufficient, coal- and lignite-fired units often resume their role as primary electricity suppliers (e.g., Naworyta and Urbański 2025).

Given the increased volatility in coal-based electricity generation, estimating synthetic gypsum production now requires additional assumptions beyond installed capacity and coal/lignite sulfur content. Table 1 presents the theoretical synthetic gypsum production potential

Table 1. Installed capacity and synthetic gypsum production in selected power and CHP plants in Poland equipped with wet lime FGD systems in 2015 (based on Szlugaj and Naworyta 2015)

Tabela 1. Moc zainstalowana oraz produkcja gipsu w wybranych polskich elektrowniach i elektrociepłowniach wyposażonych w instalację odsiarczania spalin metodą mokrą wapienną w 2015 r.

Power or CHP plant	Primary fuel	Installed capacity (MW)	Possible gypsum production (thous. t/y)	Actual gypsum production (thous. t/y)
Bełchatów	lignite	5,096	1,700	1,300
Opole	hard coal	1,492	350	170
Opole 2x900*	hard coal	1,800	590	390
Kozienice	hard coal	4,072	590	390
Jaworzno 910*	hard coal	910	300	210
Jaworzno III	hard coal	1,345	240	200
Połaniec	hard coal	1,882	180	160
Turów*	lignite	490	150	110
Pątnów II	lignite	474	150	100
Łaziska	hard coal	905	140	125
Dolna Odra	hard coal	908	100	72
Rybnik	hard coal	900	100	80
Ostrołęka	hard coal	690	80	50
CHP Siekierki	hard coal	622/2068	80	65
CHP Kraków	hard coal	480/1644	60	50
CHP Wybrzeże	hard coal	221/822	55	45
CHP Wrocław	hard coal	311/1064	35	30
Total			4,910	3,577

thous t/y – thousand tons/year.
* Power plant units put into operation after 2015.
In the case of a combined heat and power plant (CHP) the electrical power/thermal power is given.

for individual Polish power plants and combined heat and power (CHP) plants equipped with wet lime FGD systems, based on their installed capacity (Szlugaj and Naworyta 2015). Only those plants using wet FGD technology are included (Table 1). Conversely, alternative desulfurization methods, such as dry and semi-dry FGD or fluidized bed combustion, produce by-products that do not meet the purity criteria required for gypsum applications (Galos et al. 2016). The power plants and CHP plants are ranked according to their estimated potential for synthetic gypsum production. However, actual gypsum production is usually lower due to a number of dynamic operational factors. Primarily, these include fluctuating demand on coal-fired units caused by the growing share of weather-dependent RES in the energy mix. Therefore, the figures in the last column of Table 1 were given based on actual data. They refer to electricity generation relative to the maximum output potential defined by installed capacity.

2. Forecast of synthetic gypsum production until 2040 based on energy sector decarbonization plans

A direct consequence of national and EU decarbonization strategies is the steady decline in the share of coal in the Polish energy mix. The volume of electricity production from lignite and hard coal in the years 2015–2024 shows a clear downward trend (Figure 2). The significant year-to-year fluctuations in the period 2020–2023 can be attributed to global socio-political and economic disruptions such as the COVID-19 pandemic and Russia's invasion of Ukraine (e.g., Widera et al. 2024a, b). In 2020, the economic slowdown associated with the pandemic led to a significant drop in electricity demand. The global economy, including Poland's, began to rebound in 2021, resulting in an increase in energy consumption. Despite short-term increases, the overall trend remains downward. Between 2015 and 2024, electricity generation from hard coal decreased by 22.6% and from lignite by 32.6% (Figure 2). This decline directly correlates with a reduction in synthetic gypsum production, as less coal is burned and fewer sulfur compounds require removal via FGD. Based on current operational data and extrapolated from energy production levels, it is estimated that Polish power and CHP plants produced ~2.6 Mt of synthetic gypsum in 2024.

In the coming years, the share of coal in the national energy mix will further decline. According to the projections outlined in PEP2040 (2021), electricity generation from hard coal is anticipated to reach 26.9 TWh by 2030, 21.8 TWh by 2035, and 18.2 TWh by 2040. At that same time, electricity production from lignite is projected to decline to 41.0 TWh, 18.1 TWh, and 4.6 TWh in the respective reference years (Figure 2; Mazanek and Świat 2022). The assumption that lignite-fired generation will reach 41.0 TWh in 2030 seems overly optimistic. For example, in 2024, it had already fallen below that threshold, reaching 36.1 TWh (Figure 2). Therefore, the PEP2040 (2021) projections may underestimate the pace of structural changes in the Polish power sector.

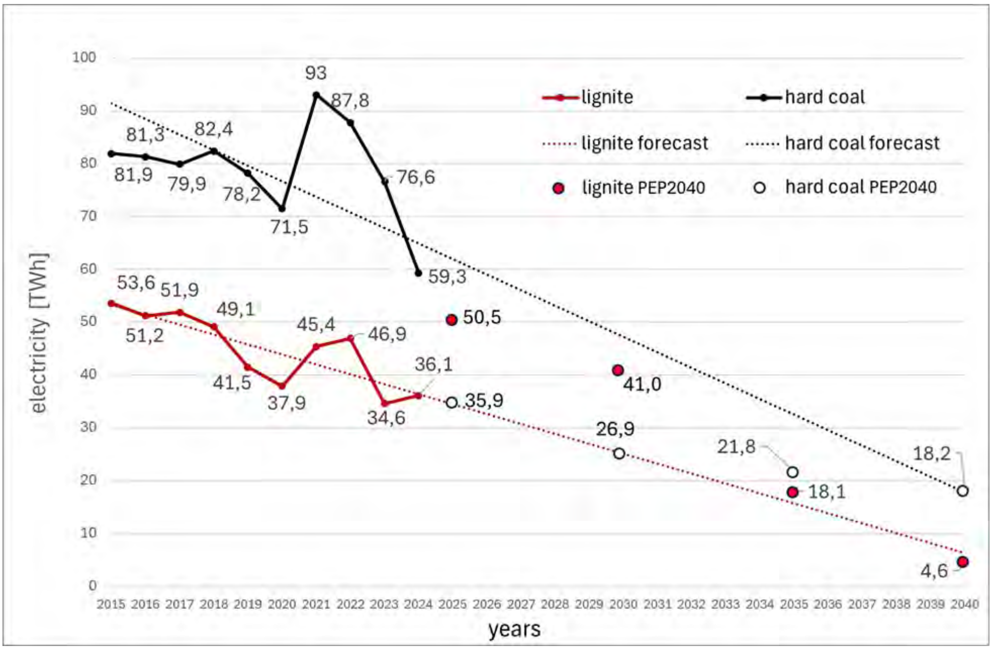

Fig. 2. Energy production from hard coal and lignite in 2015–2024 with a forecast until 2040 (based on PEP2040 2021; Mazanek and Świat 2022; PSE 2025)

Rys. 2. Produkcja energii z węgla kamiennego i brunatnego w latach 2015–2024 wraz z prognozą do roku 2040

Further reductions in lignite-based energy generation will result from geological and licensing constraints. The Tomisławice lignite opencast mine (Konin Lignite Mine), which supplies the Pątnów Power Plant (460 MW), is expected to deplete its economically viable reserves in 2026 (e.g., Kasztelewicz et al. 2025; Wachocki et al. 2025). This could result in the plant's closure. The Bełchatów Lignite Mine, which supplies lignite to the largest power plant in Poland, is projected to exhaust its resources by 2038 at the latest, in accordance with the current mining license. Meanwhile, the Turów Lignite Mine is expected to continue mining until 2044, although the possibility of earlier closure remains high due to regulatory, environmental, and economic pressures (e.g., Naworyta and Urbański 2025). In addition to resource depletion, the gradual decommissioning of aging generating units in Bełchatów and Turów will result in a steady decline in lignite consumption, even prior to the complete cessation of mining activities (e.g., Widera et al. 2024a, b).

The mentioned changes will have a direct and complex impact on the availability of synthetic gypsum produced from FGD systems in lignite-fired power plants. Table 2 presents a forecast of synthetic gypsum production based on projected electricity generation from hard coal and lignite over the period 2025–2040. The forecast is derived from a technical extrapolation of historical trends in relation to long-term targets for the use of fossil fuels in Polish electricity generation until 2040 (cf. Figure 2, PEP2040 2021 and Mazanek and Świat 2022). It should be noted that PEP2040 (2021) data for 2025 were intentionally excluded from the baseline scenario due to inconsistency with the observed trajectory of energy system transformation (Table 2).

The analysis of empirical data from recent years demonstrates that the PEP2040 (2021) assumptions for the near future (2025–2030) overestimate the persistence of coal in the energy mix. During the peak period of conventional power generation, namely in 2021–2022, electricity production from coal-fired power plants reached 138.4 TWh and 134.7 TWh, respectively (PSE 2025). During this period, synthetic gypsum production was estimated at ~3.5 Mt/y. In the following years, 2023 and 2024, as the share of RES increased substantially, electricity generation from coal dropped markedly to 111.2 TWh and 95.4 TWh, respectively (Figure 2). This led to a sharp decline in synthetic gypsum production to 2.9 Mt in 2023 and 2.5 Mt in 2024. Assuming a proportional relationship between hard coal/lignite combustion and gypsum production via FGD, a further reduction in synthetic gypsum supply is forecast. Most likely, its production will be around 1.9 Mt in 2030, then drop to 1.2 Mt in 2035 and reach only 0.6 Mt by 2040 (Table 2).

Table 2. Projected synthetic gypsum production based on forecasted electricity generation from hard coal and lignite in Poland in 2023–2040 (based on Figure 2)

Tabela 2. Prognoza produkcji gipsu syntetycznego na podstawie prognozowanej produkcji energii elektrycznej z węgla kamiennego i brunatnego w Polsce w latach 2023–2040 (na podstawie rys. 2)

Forecasts of electricity and synthetic gypsum production	2030	2035	2040
Electricity generation from hard coal (TWh)	47.2	32.5	17.8
Electricity generation from lignite (TWh)	25.1	15.7	6.3
Total electricity from hard coal and lignite (TWh)	72.3	48.2	24.1
Synthetic gypsum production from hard coal (Mt)	1.19	0.82	0.45
Synthetic gypsum production from lignite (Mt)	0.71	0.44	0.18
Total synthetic gypsum production (Mt)	1.90	1.26	0.63

Assuming an annual demand for gypsum products in Poland of ~4 Mt and maintaining the current level of natural gypsum mining levels at ~1 Mt/y, a significant supply shortage is anticipated after 2025. Based on the forecasted decline in synthetic gypsum production, the projected supply deficit may reach ~1.1 Mt by 2030, increase to 1.8 Mt by 2035, and expand further to 2.4 Mt by 2040 (Table 2). This anticipated supply gap poses a significant challenge to the domestic construction and gypsum processing industries. It also highlights the urgent need to secure alternative sources of raw material, primarily through the development and exploitation of natural gypsum deposits.

3. Gypsum resource in documented deposits and prospective areas

Gypsum and anhydrite deposits are relatively widespread in Poland. They are genetically associated with Permian, Triassic, Jurassic and Neogene sedimentary formations. These deposits are distributed in several major regions:

- the southwestern part of the country, encompassing the Lower Silesian, Lubusz, and Opole voivodeships;
- the southern and southeastern regions, including the Silesian, Lesser Poland, Świętokrzyskie, and Subcarpathian voivodeships;
- the west-central part of Poland, notably in the Greater Poland (Wielkopolska) region (Figure 3).

The distribution and geological variability of the mentioned deposits offer potential opportunities for expanding domestic gypsum exploitation. However, their development is constrained by multiple factors, including land use conflicts, environmental protection designations (e.g., Natura 2000 areas), and increasing societal resistance to opencast mining activities.

Among the various gypsum-bearing formations in Poland, the most economically significant are the Miocene gypsum deposits of the Carpathian Foredeep, particularly in the Ponidzie region. Zechstein gypsum and anhydrite deposits located in Lower Silesia are also important. In contrast, Zechstein evaporites found in the Polish Lowlands, especially

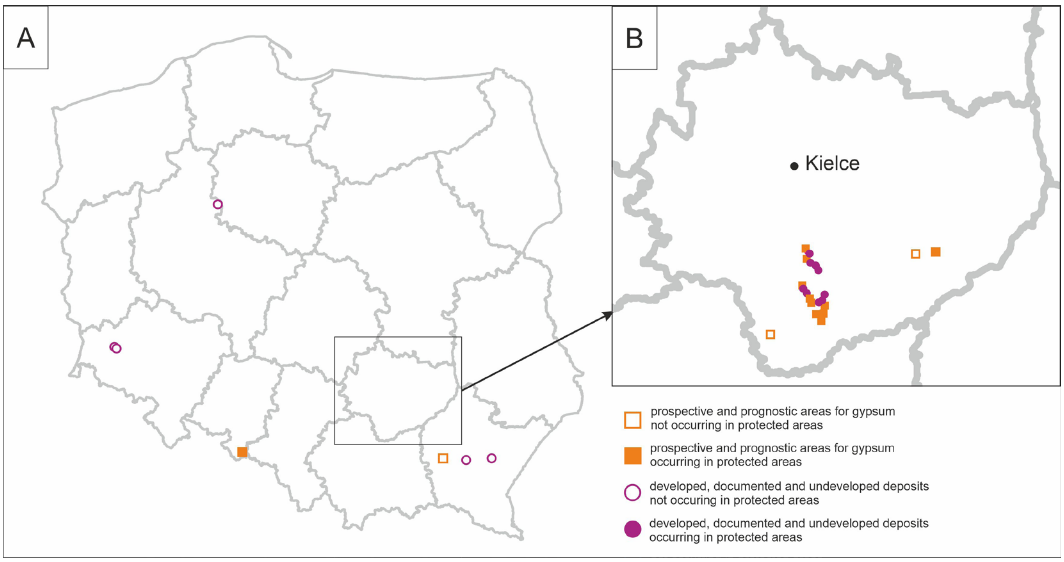

Fig. 3. Distribution of documented gypsum deposits in Poland (based on Kwiatkowska 2025)
A – Poland; B – Świętokrzyskie Voivodeship

Rys. 3. Rozmieszczenie udokumentowanych złóż gipsu w Polsce
A – Polska; B – województwo świętokrzyskie

as capping layers of salt domes in Wapno and Inowrocław, have historically held limited industrial significance (Figure 3; Mikulski et al. 2015; Sztromwasser et al. 2020).

In the southwestern part of Poland, Zechstein gypsums and anhydrites are found in several tectonic settings: the North Sudetic Synclinorium, the Fore-Sudetic Monocline (where they often occur as a by-product of copper ore mining), and the Żary Pericline. The Miocene (Middle Badenian) gypsums and anhydrites of the Carpathian Foredeep originated in a narrow evaporitic basin located on the foreland of the emerging Carpathians. Their current spatial arrangement is the result of complex tectonic processes. In the northern sector, these evaporites occur *in situ* within the Carpathian Foredeep. Toward the south, however, they have been partially incorporated into the Carpathian thrusts and nappes or uplifted at its margin (Kwiatkowski 1972). Lithologically, these deposits are dominated by primary gypsum, with subordinate anhydrite and secondary gypsum, sometimes interbedded with clay and carbonaceous layers. In many areas, gypsum crops out at the surface, although the northern boundary of their distribution is erosional and highly irregular. The vertical succession above the gypsum typically comprises: Upper Badenian clay–marl sequences, organodetrital limestones, and Sarmatian sands and gravels. Beneath the gypsum, the profile includes Lower Badenian clayey-sandy and carbonaceous sediments. Toward the southern margin of the basin, as depth increases (>250 m), gypsum transitions into anhydrite, and below ~500 m, only anhydrite remains (Kasprzyk 2005).

The national resource inventory of gypsum is based on two categories: legally recognized deposits with officially documented reserves, as reported by Szuflicki et al. (2021), and geological deposits, including prospective and prognostic areas, as defined by Szamałek et al. (2020b). Information on these areas is publicly accessible through databases and reports published by the Polish Geological Institute – National Research Institute (PGI-NRI) (EMGSP 2025). The initially recognized occurrences of gypsum, including documented deposits, are associated with shallow-lying sediments in the western, northern, and southern sectors of the Carpathian Foredeep, as well as on gypsum caps of salt domes in central and northwestern Poland. This study is limited to gypsum deposits. Although anhydrite deposits and related prospective areas are geologically and industrially relevant, they are excluded from further discussion and presentation of data below.

According to Polish mining regulations, a gypsum deposit is defined based on the following geological and mining parameters:

- maximum depth of the deposit floor – 50 m;
- minimum deposit thickness – 2 m;
- maximum overburden-to-deposit thickness ratio – 0.5;
- minimum gypsum content within the deposit profile – 80% (RMŚ 2015).

It should be emphasized that the above-listed criteria were established specifically for opencast mining operations and are not applicable in underground mining. From this point of view, the parameter relating to the ratio of the overburden thickness to the deposit thickness is particularly significant. Deposits that lie deeper than the prescribed limits do not qualify for opencast exploitation under current regulations. Consequently, these deeper-seated resources are typically classified as anticipated sub-economic reserves, also referred to as sub-balance resources (Nieć 2002).

Polish documented but currently undeveloped gypsum deposits are categorized according to their state of geological recognition. These deposits are: initially recognized – P, recognized in detail – R, and formerly exploited, but currently abandoned – Z. In addition to geological resource estimates and county-level location data, the last column provides the presence of protected natural areas that overlap with or are adjacent to the documented deposits (Table 3). Poland also has a number of prospective and prognostic areas of gypsum resources. Prospective areas are considered to be those where favorable geological conditions prevail, and preliminary data suggest the potential for economically viable gypsum deposits. On the other hand, prognostic areas are those where geological premises indicate the possibility of gypsum occurrence, but detailed data are lacking or insufficient for classification as a deposit (Table 4).

Table 3. Documented and undeveloped gypsum deposits in Poland (based on Czapowski 2024)

Tabela 3. Udokumentowane i niezagospodarowane złoża gipsu w Polsce

No.	Deposit name	Development status	Geological resources (thous. t)	County	Forms of nature protection
1	Łopuszka Wielka	Z	168	przeworski	–
2	Siedliska	R	3,952	rzeszowski	–
3	Gartatowice	Z	1,303	kielecki, pińczowski	Natura 2000 SAC "Ostoja Stawiany", Szaniecki Landscape Park
4	Łatanice–Skorocice	R	14,500	buski	Natura 2000 SAC "Ostoja Nidziańska", Nadnidziański Landscape Park
5	Siesławice	Z	2,100	buski	Solecko-Pacanowski Protected Landscape Area
6	Skorocice–Chotelek	R	22,337	buski	Natura 2000 SAC "Ostoja Nidziańska", Nadnidziański Landscape Park
7	Uników–Galów	R	37,311	buski, pińczowski	Buffer zone of the Nadnidziański Landscape Park
8	Uników–Galów–Szaniec	P	7,626	buski, pińczowski	Szaniecki Landscape Park
9	Winiary	R	46,496	pińczowski	Buffer zone of the Nadnidziański Landscape Park
10	Wapno	R	7,683	wągrowiecki	–

thous. t – thousand tons.
P – initially recognized.
R – recognized in detail.
Z – formerly exploited, but currently abandoned.

Table 4. Prospective and prognostic areas of gypsum deposits in Poland
(based on Szamałek et al. 2020b; Sztromwasser et al. 2020; EMGSP 2025)

Tabela 4 Perspektywiczne i prognostyczne obszary złóż gipsu w Polsce

Name of prospective/ prognostic area	Area (km^2)	Prospective/ prognostic resources (Mt)	Average floor depth (m)	Average deposit thickness (m)	Occurrence of nature protection
Gartatowice (N)	2.58	78.29	20	17	yes
Gartatowice (S)	0.58	9.84	12.5	9.5	yes
Bogucice	1.77	100.36	35	30	yes
Skotniki Górne	0.79	41.66	34.6	27.9	yes
Skotniki Dolne	0.23	5.82	15.8	13.4	yes
Łatanice	1.00	33.26	19.3	17.6	yes
Kobylniki E	0.10	5.67	44.5	30	yes
Kobylniki W	1.40	24.61	11.1	9.3	yes
Gorysławice	1.77	45.16	16.3	13.5	yes
Niedźwiada–Broniszów	0.76	59.00	48.95	35.5	no
Dzierżysław	0.80	86.56	100.0	35.6	yes
Skalbmierz	0.81	40.26	34.0	26.3	no
Staszów	1.71	118.29	43.0	36.6	urban area
Czajków	0.68	46.91	50.0	36.5	yes

Most of the documented Polish gypsum deposits and prospective areas are located within protected zones, including Natura 2000 sites (Tables 3, 4). As a result, their potential development through opencast mining may be significantly limited or even impossible. The presence of environmental protection over the deposits restricts the possibility of exploiting the gypsum resource, regardless of whether the deposit is classified as strategic (Mazurek and Szamałek 2022; Zajączkowski 2024; Zajączkowski and Stawczyk-Kłosowska 2025) or has legal status for resource protection (Mazurek et al. 2022).

4. Exploitation from primary gypsum deposits

In Poland, a national register of gypsum deposits and prospective resource areas has been kept for over 70 years (Szuflicki et al. 2021). During this period, the criteria for classifying mineral deposits and for assessing their resource potential have evolved significantly (Szamałek et al. 2020a; Bilans 2024). In practice, gypsum mining in Poland over the past three decades has been concentrated in a limited number of deposits. The main active and formerly active sites include:

- Borków–Chwałowice – annual production fluctuated between 220,000 tons and 600,000 tons;
- Leszcze – exploitation ranged from 260,000 to 720,000 t/y;
- Nowy Ląd – active until 2006; since 2005, the Radłówka deposit has been mined, with an annual production ranging from 3,000 to 33,000 tons;
- Lubichów – was exploited until 2005, and the production levels did not exceed 5,000 t/y.

The largest exploitation of gypsum from primary (natural) deposits currently takes place in the Nida River Valley (Figure 4). This area remains the main region for domestic gypsum production.

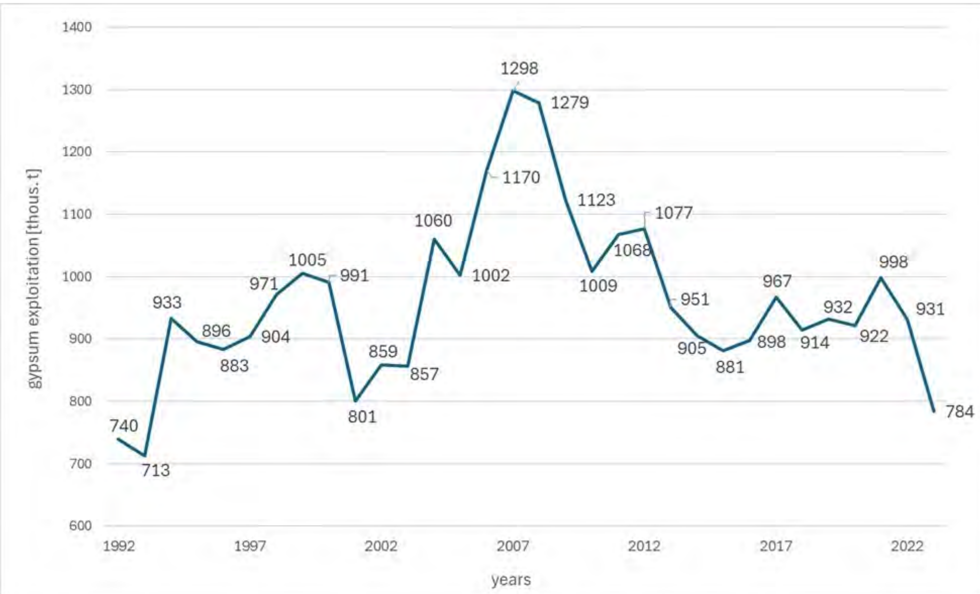

Fig. 4. Exploitation of gypsum (excluding anhydrites) from primary deposits in Poland in 1992–2023 (based on Tymiński 2025)

Rys. 4. Eksploatacja gipsu (bez anhydrytów) ze złóż pierwotnych w Polsce w latach 1992–2023

5. Prospective resources, raw material availability and demand forecast

Currently, opencast gypsum exploitation in Poland is governed by mining concessions granted for specific periods:

- Nowy Ląd deposit (Radłówka field) – valid until June 27, 2052;

- Leszcze deposit – valid until October 12, 2068;
- Borków–Chwałowice deposit – valid until December 31, 2025.

Among the above-listed gypsum deposits, the Leszcze and Borków–Chwałowice ones play a key role in securing the domestic supply. Due to the expiry of the Borków–Chwałowice concession, work is currently underway to extend its validity based on information from investors. Additionally, a concession for the exploration and exploitation of the deposit has been granted for the Bogucice prospective area, documented for the first time in the 1950s (Lazarek and Jurkiewicz 1951; Kowalski et al. 2025). In the public domain, a website can be found dedicated to the prepared project of exploitation of the deposit, which is currently in the phase of approval of geological documentation (Uników 2025).

The impending decline in synthetic gypsum production from FGD has been noted throughout the industry. This has prompted the preparation of new opencast natural gypsum mining projects. However, a significant increase in exploitation from the currently operating mines and from two additional projects at the planning stage appears unlikely. Therefore, fully compensating for the projected gypsum supply shortage will be very difficult, if not impossible (see Chapter 2).

The geological resources of documented but undeveloped Polish gypsum deposits are estimated at ~140 Mt (Table 3). On the other hand, gypsum resources in prospective areas are estimated at several hundred Mt (Table 4), which would theoretically be sufficient to cover the current domestic demand for up to 100 years. However, this estimation does not fully take into account: the recovery rate during mining operations (i.e., the proportion of the total resources that are technically and economically exploitable), geological uncertainty, especially for less explored (lower category) deposits, and most importantly, land use and environmental protection constraints, including Natura 2000 areas and landscape parks that cover many deposits. These factors show that the practical availability of gypsum resources is significantly lower than theoretical amounts might indicate. To date, gypsum imports to Poland have remained negligible (GUS 2024). Hence, given the expected decline in synthetic gypsum production in the coming years, it is very likely that imports will increase to compensate for the shortage in domestic supply.

6. Underground exploitation of gypsum in Poland and Germany

The choice of exploitation methods and techniques depends on numerous factors, including the structure and morphology of the deposit, the thickness of the overburden, hydrogeological conditions, and geomechanical properties. External factors, particularly the natural value and protection status of the land overlying the deposit, also play a significant role.

Given the difficulties in meeting gypsum demand from primary deposits through opencast mining, the option of underground exploitation of gypsum deposits in Poland should be seriously considered. Underground mining and pre-processing of gypsum offer the potential for significantly reducing the negative environmental impacts.

Underground mining of gypsum has historical precedent in Poland, as it was applied in the Dzierżysław and Łopuszka Wielka deposits (Woliński 1996). By comparison, this method is still actively used in Germany. Some underground gypsum mines, closed there for economic reasons in the early 2000s, are now being reopened due to changing market conditions (Henning 2025).

There are substantial similarities between the gypsum sector in Poland and Germany. In both countries, large amounts of synthetic gypsum are produced as a by-product of FGD in power plants. However, as part of the energy transitions, both nations will soon have to face a significant reduction in the availability of synthetic gypsum. In Germany, where ~10 Mt of gypsum and anhydrite are processed annually, about 40% originates from natural deposits, while the remainder is synthetic gypsum from lignite-fired power plants. Germany plans to phase out coal-fired energy production by 2038 to meet CO_2 reduction targets. This will effectively eliminate domestic supplies of synthetic gypsum. Similarly, it is expected that this (i.e., moving away from coal and the production of synthetic gypsum) will happen around 2040 in Poland.

Currently, gypsum and anhydrite are extracted at 63 locations in Germany, including nine sites applying partial or full underground mining methods. Seams 5 to 10 m thick are mined using the room-and-pillar method. The oldest underground gypsum mine in Germany, located in Obrigheim (Baden-Württemberg), has been in operation continuously for over a century and presently produces ~0.3 Mt/y. The largest underground gypsum mine is located in Hüttenheim, Bavaria. Production there has been ongoing since 1957 and reached 0.4 Mt/y after an increase in 1992. In both cases, the pre-processing of the raw material, including crushing, takes place underground (Henning 2025).

In Lower Saxony, due to the high quality and specific applications of the raw material, underground mining is also carried out. However, this type of exploitation is complementary to opencast mining (Henning 2025).

In Germany, steps are being taken to increase the exploitation of gypsum from natural deposits in order to secure its long-term supply. Given the growing public resistance to opencast mining, underground mining is becoming an increasingly popular alternative. In Bavaria, for example, mining is planned in the Alterheimer Mulde deposit, where between 0.3 and 1 Mt/y will be exploited using the room-and-pillar method. Similarly, the reactivation of an underground mine is planned in Haßmersheim (Baden-Württemberg), with an annual production of 0.6 Mt, which is enough for ~60 years. In both projects, gypsum pre-processing, including crushing, will be carried out underground to further reduce environmental impact (Henning 2025).

7. Selected gypsum deposits in Poland suitable for underground mining

Among the documented gypsum deposits in Poland, two were selected for detailed consideration in this study. These are the Winiary deposit, located near the currently exploited

Leszcze deposit, and the Siedliska deposit, situated within the Carpathian Foredeep. They belong to a broader set of undeveloped deposits, which makes them particularly suitable for underground gypsum exploitation.

The Winiary deposit is the largest documented gypsum deposit in Poland (Figure 5). Its anticipated economic (balance) resources are estimated to exceed 45 Mt. Moreover, geological premises suggest that the resource may be larger (Radomska and Knapczyk 1993).

On the other hand, the Siedliska deposit contains relatively small balance resources (Figure 6), estimated at 3.9 Mt, but meeting the criteria for opencast mining (Nowak 1993). However, due to the tilted nature of the strata, the resources located below the overburden, thicker than 15 m, are classified as sub-balance, that is, sub-balance resources (Figure 6). They amount to ~4.7 Mt and are well suited for underground exploitation.

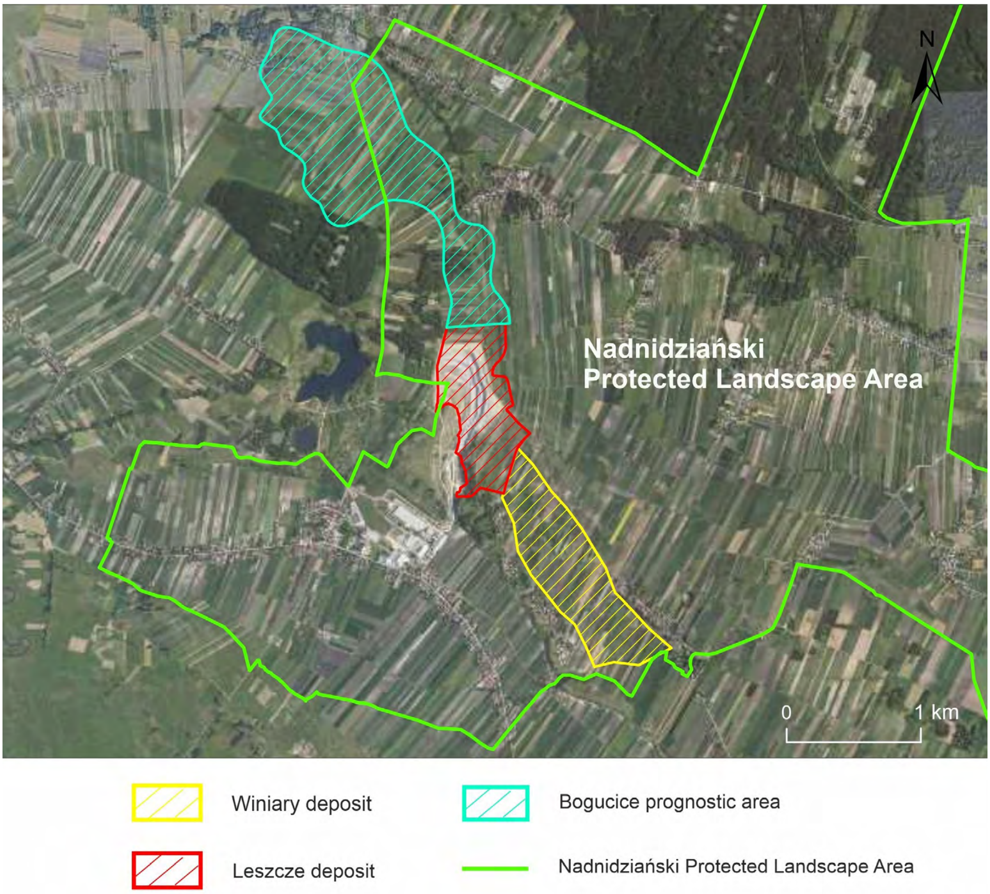

Fig. 5. Winiary gypsum deposit against the background of other gypsum deposits and protected natural area (based on Kwiatkowska 2025)

Rys. 5. Złoże gipsu Winiary na tle innych złóż gipsu oraz granic Nadnidziańskiego Parku Krajobrazowego

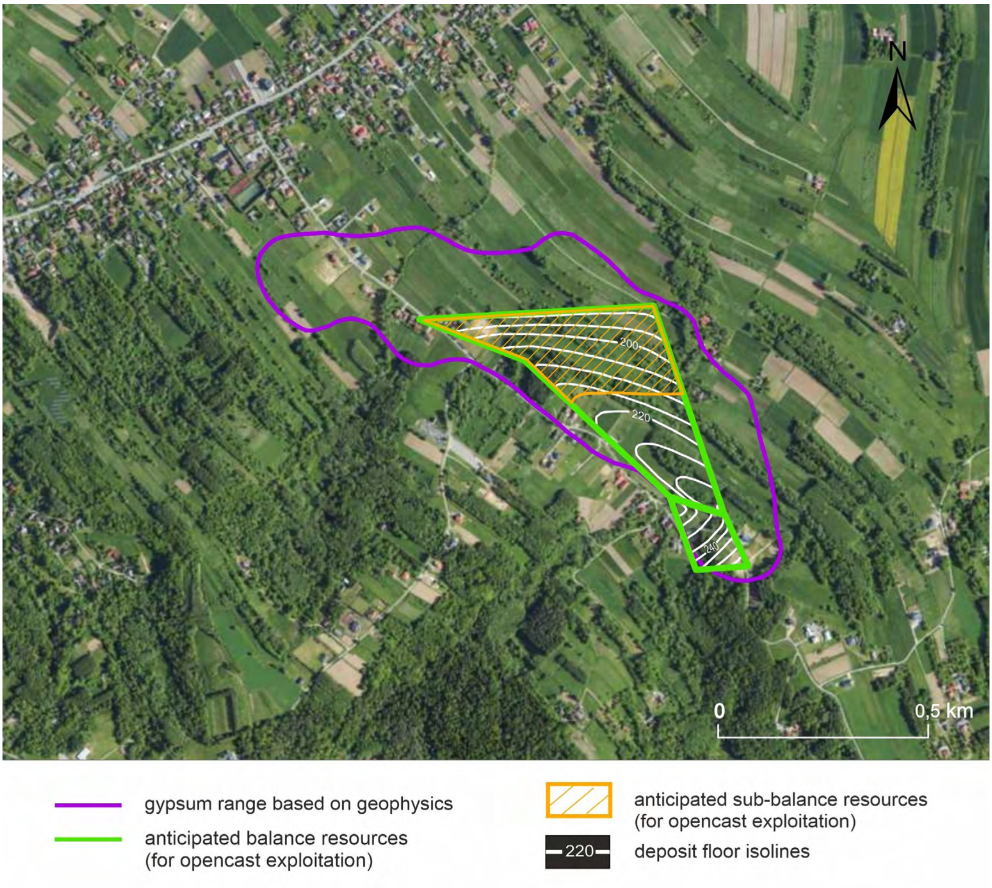

Fig. 6. Extent of the Siedliska gypsum deposit (based on Kwiatkowska 2025)

Rys. 6. Złoże gipsu Siedliska

Geophysical investigations indicate the potential for further documentation of additional gypsum resources suitable for underground mining. Preliminary estimates suggest that their total amount exceeds 10 Mt. This is evidenced by a comparison of the basic geological parameters of the characterized Winiary and Siedliska gypsum deposits (Table 5).

In the context of environmental constraints, underground mining is a favorable alternative to opencast methods. The selected gypsum deposits (i.e., Winiary and Siedliska) are characterized by significant seam thickness and relatively shallow occurrence, with an average overburden thickness of 18 to 20 m (Table 5). Moreover, they are characterized by simple geology without post-depositional deformations; hence, their underground exploitation will be relatively inexpensive and technically straightforward.

Table 5. Basic geological and qualitative parameters of the Siedliska and Winiary gypsum deposits (based on Nowak 1993; Radomska and Knapczyk 1993)

Tabela 5. Podstawowe parametry geologiczne i jakościowe złóż gipsu Siedliska i Winiary

Deposit name	Geological resources (Mt)		Average overburden thickness (m)		Average thickness of gypsum seam (m)		Average content of $CaSO_4$ (%)	
	balance	sub-balance	balance	sub-balance	balance	sub-balance	balance	sub-balance
Siedliska	3.951	4.743	8.0	19.4	24.3	28.7	84.54	n.d.
Winiary	46.496	6.161	5.4	18.0	27.8	34.3	87.02	89.71

n.d. – no data.

Gypsum ore can be transported by haul trucks or conveyor belts. To minimize the environmental impact of both exploitation and pre-processing (e.g., crushing and grinding), these processes can be performed underground. This method is currently used in several operating underground gypsum mines in Germany. The room-and-pillar mining system should be considered the best, as confirmed by experience from the above-mentioned German mines, where resource recovery rates are at the level of 50% or higher (Henning 2025).

Conclusions

As a result of the ongoing energy transition and the gradual phasing out of fossil fuel combustion, particularly hard coal and lignite, the supply of synthetic gypsum is expected to decline sharply over the next two decades. According to current projections, Poland's energy sector will achieve full decarbonization by ~2040, and Germany will reach this milestone by 2038. Currently, synthetic gypsum constitutes a dominant part of the gypsum raw material market in both countries, accounting for 60–75% of the total supply. To meet the future demand of the gypsum processing industry, it will be necessary to ensure a stable supply of raw material from the exploitation of primary (natural) deposits.

Poland has large documented gypsum resources, as well as poorly explored, prospective areas. However, the development of opencast mining is significantly limited by environmental considerations. Many areas where gypsum deposits occur are of high natural value and are subject to various forms of legal protection. These are landscape parks, protected landscape areas, and Natura 2000 areas. Therefore, underground mining, such as through the room-and-pillar method, appears as a viable alternative. This method is already being successfully used in several gypsum mines in Germany.

The simple geology of Polish gypsum deposits favors their underground exploitation. These deposits have often been classified as uneconomic or sub-balance for opencast mining due to thick overburden layers. On the contrary, these same deposits may be highly suitable for underground exploitation. This method allows for the pre-processing of gypsum ore underground, which additionally protects the natural environment. Using the example of the Winiary and Siedliska gypsum deposits, this study shows that they could play a key role in the situation of synthetic gypsum shortage caused by the decarbonization of the Polish coal-based energy sector.

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AVAILABILITY OF DOMESTIC GYPSUM RESOURCES VERSUS THE PREDICTED DECLINE IN SYNTHETIC GYPSUM PRODUCTION

Keywords

resource availability, gypsum deposits, opencast mining,
underground mining, environmental impact, energy transition

Abstract

The ongoing decarbonization of the Polish energy sector will lead to a substantial decline in synthetic gypsum production, currently constituting 60–75% of the domestic gypsum supply. Synthetic gypsum, generated as a by-product of flue gas desulfurization (FGD) in coal- and lignite-fired power plants, is directly linked to fossil fuel combustion. Based on energy transition scenarios and projected reductions in hard coal and lignite use, synthetic gypsum production in Poland is expected to decrease from approximately 2.5–2.6 Mt in 2024 to about 1.9 Mt in 2030, 1.2 Mt in 2035, and 0.6 Mt in 2040. Assuming an annual demand of ~4 Mt and a stable natural gypsum output of ~1 Mt, a significant supply deficit is anticipated after 2025. The study evaluates documented and prospective gypsum deposits in Poland, taking into account geological conditions, resource categories, environmental constraints, and land-use restrictions. Although total geological resources are substantial, many deposits are located within Natura 2000 sites or other protected areas, limiting the feasibility of opencast mining. As an alternative, underground mining using the room-and-pillar method is proposed. This approach reduces surface disturbance and enables underground pre-processing, minimizing environmental impact. The Winiary and Siedliska deposits are identified as particularly suitable for such exploitation due to favorable geological parameters. Underground development of selected deposits may therefore constitute a strategic response to the projected shortage of synthetic gypsum in Poland.

ANALIZA DOSTĘPNOŚCI KRAJOWYCH ŹRÓDEŁ GIPSU W KONTEKŚCIE PROGNOZOWANYCH ZMIAN PODAŻY GIPSU SYNTETYCZNEGO

Słowa kluczowe

dostępność zasobów, złoża gipsu, górnictwo odkrywkowe, górnictwo podziemne,
wpływ na środowisko, transformacja energetyczna

Streszczenie

Trwająca dekarbonizacja polskiego sektora energetycznego doprowadzi do znacznego spadku produkcji gipsu syntetycznego, który obecnie stanowi 60–75% krajowej podaży gipsu. Gips syntetyczny powstaje jako produkt uboczny odsiarczania spalin (IOS) w elektrowniach opalanych węglem kamiennym i brunatnym. W oparciu o scenariusze transformacji energetycznej i prognozowane ograniczenie zużycia węgla kamiennego i brunatnego przewiduje się, że produkcja gipsu syntetycznego w Polsce spadnie z około 2,5–2,6 mln ton w 2024 r. do około 1,9 mln ton w 2030 r., 1,2 mln ton w 2035 r. i 0,6 mln ton w 2040 r. Zakładając roczne zapotrzebowanie na poziomie około 4 mln ton i stabilną produkcję gipsu naturalnego na poziomie około 1 mln ton, po 2025 r. przewiduje się znaczny deficyt podaży tego surowca. W artykule dokonano oceny udokumentowanych i perspektywicznych złóż gipsu w Polsce, uwzględniając warunki geologiczne, kategorie zasobów, ograniczenia środowiskowe i ograniczenia wynikające z użytkowania gruntów. Chociaż całkowite krajowe zasoby geologiczne są znaczne, wiele złóż znajduje się w granicach terenów chronionych, co ogranicza możliwość eksploatacji odkrywkowej. Jako alternatywę zaproponowano wydobycie metodą podziemną systemem komorowo-filarowym z umiejscowieniem wstępnego etapu przeróbki kopaliny w wyrobiskach. Pozwoli to na redukcję wpływu wydobycia na powierzchnię terenu i ograniczenie wpływu na środowisko. Zaproponowane w artykule złoża Winiary i Siedliska, ze względu na korzystne parametry geologiczne, są odpowiednie do takiej eksploatacji. Podziemne zagospodarowanie wybranych złóż może więc stanowić strategiczną odpowiedź na prognozowany niedobór gipsu w Polsce.