GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2025 Volume 41 Issue 2 Pages 97–119

DOI: 10.24425/gsm.2025.154543

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The influence of injection well location on CO_2 storage capacity for the Jeżów structure (central Poland)

Introduction

Underground storage of carbon dioxide (Carbon Capture and Storage – CCS) is considered today as a technology that allows for the reduction of significant amounts of this gas emissions into the atmosphere on a scale of millions of tonnes per year. Preceded by the capture of CO_2 from large industrial emitters, the implementation of this technology is becoming increasingly urgent on the global path to zero net emissions. EU policy aimed at reducing CO_2 emissions encourages governments to use this technology on a large scale. Hence, since the end of the 20th century, numerous research projects and increasingly

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numerous examples of commercial CO_2 storage have been carried out. Underground storage of CO_2 is considered both on land and under the seabed, in deep saline aquifers, and depleted oil and gas reservoirs. In this respect, one of the crucial aspects is the assessment of storage capacity and the possibility of injecting CO_2 into identified, selected underground geological structures. The results of this analysis will determine the use of underground space for the sequestration of this gas. The changing prices of carbon dioxide emission allowances additionally emphasize the need to search for alternative solutions, such as CCS. The impact of these factors is particularly felt by countries with a high share of fossil fuels in the energy sector, which increases their interest in low-emission technologies (Komorowska and Surma 2024).

The topic of underground CO_2 storage is currently a point of interest to a large group of scientists, practitioners, and government institutions. The bibliometric analysis of research trends by Wang (Wang et al. 2024) indicates a significant increase in the number of scientific publications devoted to this topic after 2009. CO_2 storage in deep saline aquifers is considered the most promising CCS option today (Ma et al. 2022; Rasool et al. 2023; Lin et al. 2024). In recent years, several articles have been published presenting the various aspects of CCS technology holistically. Zhao et al. (Zhao et al. 2024) presented a comprehensive description of theoretical research of marine CO_2 geological storage and characterized the challenges and prospects facing the large-scale implementation of this technology. Rasool et al. (Rasool et al. 2023) conducted a comparative analysis of different underground CO_2 storage locations. Kumar et al. (Kumar et al. 2020) characterized CO_2 sequestration in deep aquifers in detail and discussed the storage mechanisms from the point of view of safety and storage capacity. Other review articles discuss the research status and prospects of CCS, highlight the potential of CO_2 storage (Lin et al. 2024), develop more efficient and safe storage techniques (Bashir et al. 2024), establish advanced scientific and technological infrastructures for CCS (Ma et al. 2022), and review experimental studies, modeling, and field studies related to underground CO_2 storage (Kalam et al. 2021).

Over the last 30 years, numerous CCS research and demonstration projects have been carried out worldwide, some currently under implementation. Kalam et al. (Kalam et al. 2021) and Ajayi et al. (Ajayi et al. 2019) reviewed CCS projects presenting their research objectives. The state of advancement and general characteristics of the projects were also given by Zhao et al. (Zhao et al. 2024) focusing on subseabed storage projects, Lin et al. (Lin et al. 2024), emphasizing the need to implement demonstration projects of the entire geological CO_2 storage process, and Ma et al. (Ma et al. 2022) classifying various storage projects.

The issues of assessing the storage capacity and CO_2 injection efficiency presented in the article concern the influence of various geological and deposit factors on injection and storage (Iglauer 2018; Wei et al. 2022). Wei et al. (Wei et al. 2022) emphasize that the estimation of CO_2 storage capacity is associated with numerous inconsistencies and uncertainties resulting from different technical assumptions and storage mechanisms. Vafaie et al. (Vafaie et al. 2023) point out that CO_2 injection experiments alone cannot capture the complex dynamics of CO_2 flow underground. Still, they provide essential information that will impact the efficiency of geological CO_2 storage.

Capillary caprock pressure and fracturing pressure are indicated as significant factors limiting CO_2 storage capacity. Eigbe et al. (Eigbe et al. 2023) point out that accurate estimation of injection pressure, flow rate, and depth are critical elements of CO_2 sequestration that should be carefully analyzed at the initial stage of work. Abdoulghafour et al. (Abdoulghafour et al. 2020) emphasize the essential role of capillary caprock pressure, which influences the amount of CO_2 that can be injected. CO_2 modeling conducted using a single well in 30 locations (Luboń and Tarkowski 2021) showed that the caprock capillary pressure values significantly affect the amount of CO_2 that can be injected underground. Also crucial in this respect is the critical analysis of existing analytical and numerical mathematical models used to estimate the maximum injection pressure (Hajiabadi et al. 2021). It is emphasized that the CO_2 sequestration capacity should be assessed based on the reservoir layers' actual geological conditions, the sealing caprock's properties, and the CO_2 injection rate (Tarkowski and Uliasz-Misiak 2021; Ang et al. 2022; Uliasz-Misiak and Misiak 2024).

Optimizing the number and location of CO_2 injection wells has recently been the subject of research presented in several articles. Maurand and Barrere (Maurand and Barrere 2014) proposed a methodology to estimate the optimal number and location of CO_2 injection wells. Cihan et al. (Cihan et al. 2015) indicate that selecting the best well locations and injection flow rates will be crucial to maximizing the amount of CO_2 stored and minimizing brine extraction. Additionally, the dipping and heterogeneity of the reservoir will affect the optimal injection rate. Studies aimed at obtaining the optimal CO_2 storage well performance, taking into account its position on the structure, for wells located along the Norwegian Continental Shelf (Allen et al. 2017) showed that the achievable storage capacity will depend on engineering constraints, length of injection period, and pressure management. Studies on the location of wells and their operating conditions for CO_2 sequestration in deep aquifers (Jun et al. 2019) allowed for the optimization of their location and fluid injection rate. The results of numerical simulations of CO_2 storage for the Choszczno-Suliszewo structure in NW Poland (Urych et al. 2022) showed the pressure increase observed during injection simulations and its impact on storage. Simulations conducted using a single well for 30 different locations (Luboń and Tarkowski 2021) showed that different capillary pressure values for CO_2 and H_2 injection significantly affect the amount of gas that can be injected into the structure, and maps of dynamic CO_2 storage capacity can be a helpful tool in determining the best locations for injecting well. The simulation of CO_2 injection into the Konary structure with 50 different injection well locations (Luboń 2020a, 2022) allowed to determine the dynamic CO_2 storage capacity for the considered locations. The results showed that fracturing pressure significantly influences underground carbon dioxide storage's dynamic capacity and safety. Including capillary caprock pressure in the modeling reduced the dynamic capacity by about 60%, and the highest dynamic CO_2 storage capacity was obtained by locating the well away from the top of the anticline structure.

Interesting results regarding the efficiency assessment of CO_2 geological storage were provided by the monographic study Luboń (Luboń 2020b). It shows the dynamic CO_2 storage capacity for the Suliszewo, Konary, and Sierpc structures, CO_2 storage efficiency factors, optimization of the location of the CO_2 injection well into the structure, and the permissible increase in capillary caprock pressure.

The research aims to determine the influence of the injection well location on the CO_2 storage capacity for the Lower Jurassic reservoir of the Drzewica Formation of the Jeżów geological anticlinal structure. This structure has a good geological and reservoir recognition of the Jurassic formations. Geophysical data and two deep wells provided the necessary data to build a geological model for the considered reservoir formation. Existing and processed by the authors, geological and reservoir data were used to build a geological model of the Drzewica Formation layers of the Jeżów structure. The results of CO_2 injection simulations obtained for each of the 36 analyzed injection well locations were aimed at estimating the dynamic CO_2 storage capacity, showing the variability of CO_2 storage capacity depending on the location of the injection well on the structure, and then developing a map of the dynamic CO_2 storage capacity. The obtained results may help determine the location of the optimal injection well for storing this gas in the future. In combination with the favorable location of the Jeżów structure close to significant CO_2 emitters, they may be an incentive to use it for CO_2 storage.

1. Geological structures for CO_2 storage in Poland and characteristics of the Jeżów anticline

The subject of underground CO_2 storage has been developing dynamically in Poland since the beginning of the 21st century. The results of the work carried out in this area include several monographic studies (Tarkowski 2005, 2010; Uliasz-Misiak 2008; Tarkowski et al. 2014a; Luboń 2020a) and numerous scientific articles (Tarkowski and Uliasz-Misiak 2006; Marek et al. 2011; Luboń 2016, 2020a, 2022; Luboń and Tarkowski 2021). The studies conducted so far have allowed to identify several potential reservoir levels for CO_2 storage in the Mesozoic formations of the Polish Lowlands. They occur in the Lower Cretaceous, Lower Jurassic, and Lower and Upper Triassic formations. Numerous structures that meet the geological conditions for CO_2 storage have been described, from the Marginal Trough, the Szczecin-Łódź Trough, and the Pomeranian-Kujawy Swell (Tarkowski 2010). The implementation of the Polish National Programme entitled Assessment of formations and structures suitable for safe CO_2 geological storage including the monitoring plans, carried out in 2008–2012 as part of a consortium of scientific institutions under the management of PIG-PIB made a significant contribution to this researches (Feldman-Olszewska et al. 2012; Michna and Papiernik 2012; Wójcicki 2012b; Šliaupa et al. 2013).

The best reservoir properties for CO_2 storage were identified in the Lower Jurassic lithostratigraphic Drzewica Formation of the Pliensbachian occurring under cover of the clayey-mudstone Ciechocinek Formation of the Lower Toarcian. In the formation mentioned above, 11 structures suitable for CO_2 storage were recognized (Tarkowski 2010). The theoretical CO_2 storage capacity of these structures has been estimated (Tarkowski 2008; Uliasz-Misiak 2008; Tarkowski et al. 2009b), and for the Konary, Suliszewo, and Sierpc structures geological models have been built, which allowed for the dynamic CO_2 storage capacity assessment (Luboń 2020a, b, 2022; Urych et al. 2022).

One of Poland's most interesting structures for underground CO_2 storage is the Jeżów structure, located in central Poland. It was initially characterized, and in ranking structures for CO_2 storage, it is one of the leaders (Tarkowski 2010). It is a salt cushion with two reservoir levels suitable for CO_2 storage. One occurs in the Lower Jurassic (Drzewica Formation), and one in the Lower Triassic.

The Jeżów anticline (salt pillow) occurs in the SE part of the Kujawy Swell. It was identified by reflection seismic and two deep boreholes: Jeżów IG-1 (depth 3062.0 m) and Rawa Mazowiecka 1 (depth 5,458.5 m). Within the Lower Jurassic formations reservoir level suitable for CO_2 storage are sandstones of the Drzewica Formation. Clay-mudstone formations of the Ciechocinek Formation separate these levels with an average thickness of 95 m (Tarkowski 2010). Geological data regarding the characteristics of the reservoir of the Drzewica Formation layers considered for CO_2 storage are presented in Table 1 and Figure 1.

Table 1. Geological characteristics of the Jeżów anticline along with geological and reservoir data used to build the geological model (prepared by the authors based on (Tarkowski et al. 2009a; Tarkowski 2010; Wójcicki 2012a))

Tabela 1. Charakterystyka geologiczna antykliny Jeżowa oraz dane geologiczno-złożowe wykorzystane do zbudowania modelu geologicznego

Depth of the reservoir (Drzewica Formation) and its thickness	Jeżów IG-1: 984–1,169 m (185 m)
Anticline surface	122 km^2
Permeability of reservoir rocks	2–1,229 mD
Porosity of reservoir rocks	1.6–25.9 %
Reservoir pressure	7.9–10 MPa
Reservoir temperature	34.3–38.1°C
Reservoir water salinity	hydrogen-carbonate-sodium brines 6 g/dcm^3
Reservoir lithology	sandstones with claystone-mudstone interbeddings
Caprock lithology (Ciechocinek Formation)	claystones and mudstones
Faults	found in the oldest layers of the Zechstein-Mesozoic complex

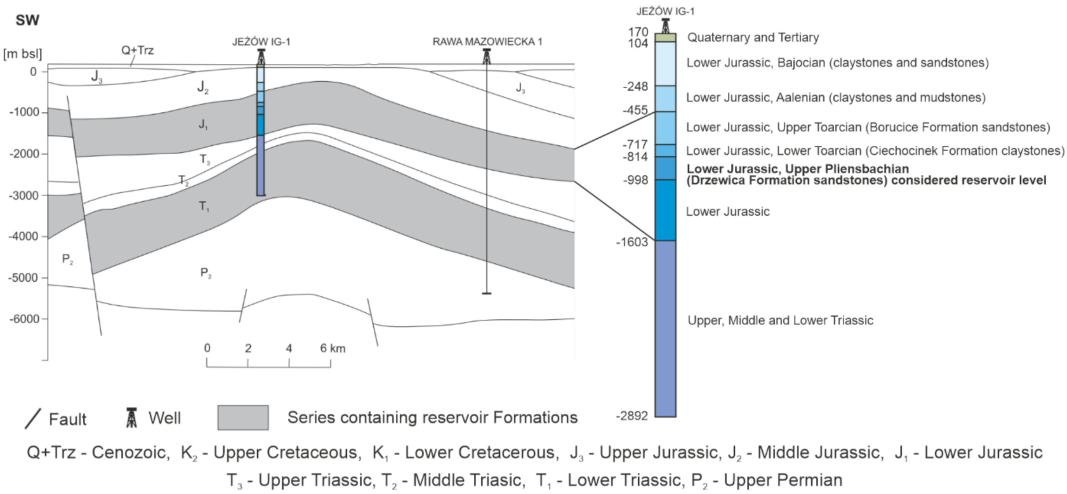

Fig. 1. Geological cross-section through the Jeżów anticline (salt pillow) (based on: Tarkowski 2010)

Rys. 1. Przekrój geologiczny przez antyklinę (poduszkę solną) struktury Jeżów

2. Methodology

The research methodology for assessing the impact of the injection well location on the CO_2 storage capacity for the reservoir (Drzewica Formation) for the Jeżów anticline included the following stages of work:

- Analysis of geological data essential for building a spatial numerical model of the layers considered for CO_2 storage, including analysis of porosity and permeability,
- Determination of main assumptions for CO_2 storage simulations (fracturing and capillary caprock pressure),
- Simulation of CO_2 injection for 36 injection well locations using PetraSim TOUGH2 software in two stages (test injection and target injection),
- Estimation of the dynamic CO_2 storage capacity for the considered injection well locations,
- Construction of a CO_2 dynamic storage capacity map covering 36 injection well locations.

2.1. Analysis of geological data essential for building a spatial numerical model

The basis for building a numerical model of the Jeżów structure was the construction of a static model of the structure covering the Lower Jurassic formations – the reservoir of the

Drzewica Formation. For this purpose, the profile of the Jeżów IG-1 well, structural maps, and geological cross-sections through the structure were used. Present-day 3D static geomodels built for Research & Development purposes in petroleum exploration, geothermic or energy storage fields vary in scale from regional to local (Papiernik 2014, 2017; Wygrala 2014; Papiernik and Michna 2019; Hałaj et al. 2022). The geological models used in the research comprise four main phases of modeling, starting from database building through structural modeling, facies modeling, and petrophysical modeling (Zakrevsky 2011; Wachowicz-Pyzik et al. 2015; Papiernik and Michna 2019; Hałaj et al. 2022).

The input geological model of the Jeżów Anticline is based on the Northern segment of the regional CCS model, termed the Bełchatów region model, which was created to meet goals of the National Program of CO_2 storage, realized in 2008–2012 (for details: Wójcicki 2012a). This structural framework hosted parametric models, including lithology, porosity, and shale volume permeability models.

Based on the regional model, the local update was performed in the Jeżów anticline. The update included a fundamental increase in horizontal resolution from 500 m to ~170 m and vertical resolution from ~30 to 90 layers (Figure 2). It was constructed using the multiscale structural and parametric modeling workflows (Papiernik et al. 2015, 2016; Papiernik 2017; Papiernik and Michna 2019). This allows for high-quality local geomodels to be obtained, even in regions poorly controlled with data.

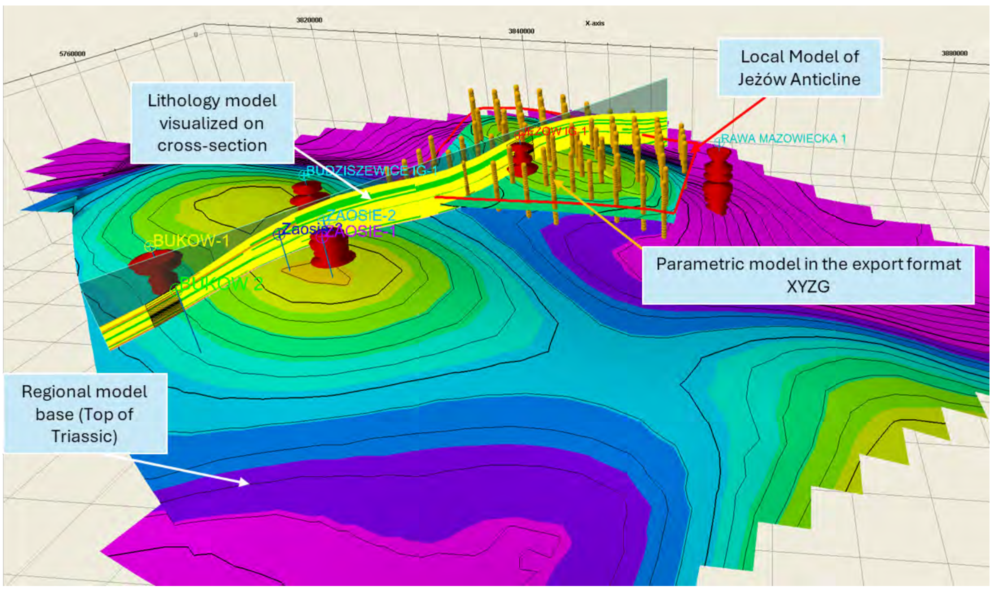

Fig. 2. Regional (Budziszewice–Jeżów) and Local (Jeżów) structural models visualized together with examples of parametric modeling and its export products

Rys. 2. Wizualizacja modeli strukturalnych regionalnych (Budziszewice–Jeżów) i lokalnych (Jeżów) wraz z przykładami modelowania parametrycznego i jego produktów eksportowych

The basic workflows and input data used by authors to create 3D models were calculated in Petrel with the use of the Corner Point Griding [CPG] method, which gives a direct framework for dynamic modeling with the use of SLB's Eclipse^{TM} software. The model presented in the paper was made with the TOUGH2 simulator. Similarly to Feflow simulator (Hałaj et al. 2022), there is no direct exchange format of models between software packages. To gain basic interoperability between the results of structural modelings, they were exported as ZMAP+ 2D- grids (shown as yellow points on Figure 2) and then imported to the PetraSim graphical interface for the TOUGH2 simulator. Figure 3 shows the model of the Jeżów structure built in the PetraSim graphical interface with the marked exemplary placing of the injection well and isoline of –850 m of the Drzewica Formation top, constituting the structure boundary (spill point). This model was designed to fully encompass the spill point within its entire extent.

The model is discretized into the computational grid, which density is higher in the area of the spill point, as well as in the area of the exemplary injection well. The model has an irregular, dome-like structure, and its construction indicates that it represents an underground geological formation such as an anticline (a type of structural trap) and is suitable for CO_2 storage.

The analysis of geophysical profiling performed for the Jeżów IG-1 well allowed for determining the porosity and permeability of rocks, showed on Figure 4. This profile shows a clear variation in both porosity (gray color) and permeability (black color) throughout the entire length of Drzewica Formation.

The best reservoir properties were observed at a depth of approximately 1,065–1,120 m, where porosity exceeds 20%, and permeability surpasses 500 mD, with some localized values approaching 5,000 mD. Sections with lower porosity and low permeability may act as barriers to fluid flow, which is crucial when assessing CO_2 storage capacity. Therefore, the profile has been divided into 10 distinct layers, with calculated average porosity and permeability values, as shown in Figure 3 and Table 2, to better represent the variability in

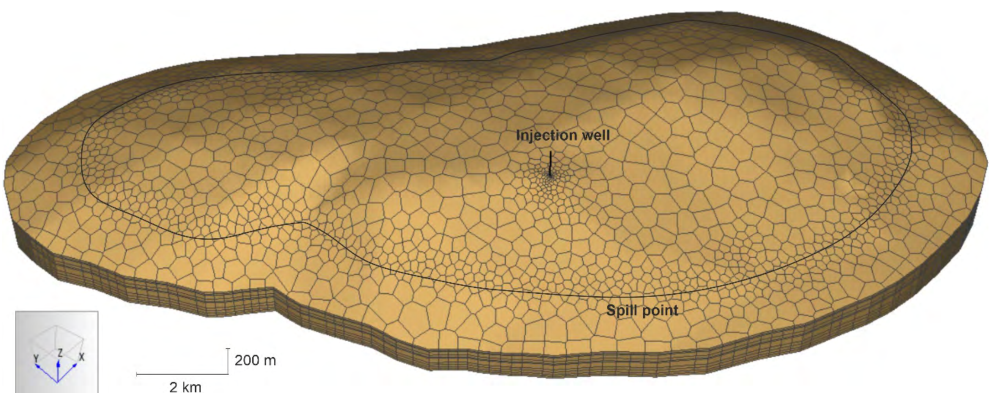

Fig. 3. The model of the Jeżów structure presented in the PetraSim software

Rys. 3. Model struktury Jeżów zaprezentowany w programie PetraSim porosity and permeability across different depth intervals. This division allows for a more detailed analysis of the reservoir properties, helping to identify zones with the highest storage potential and those that may act as barriers to fluid migration and potential pressure buildup. Such segmentation is essential for evaluating the reservoir's suitability for CO_2 storage and optimizing fluid flow simulations.

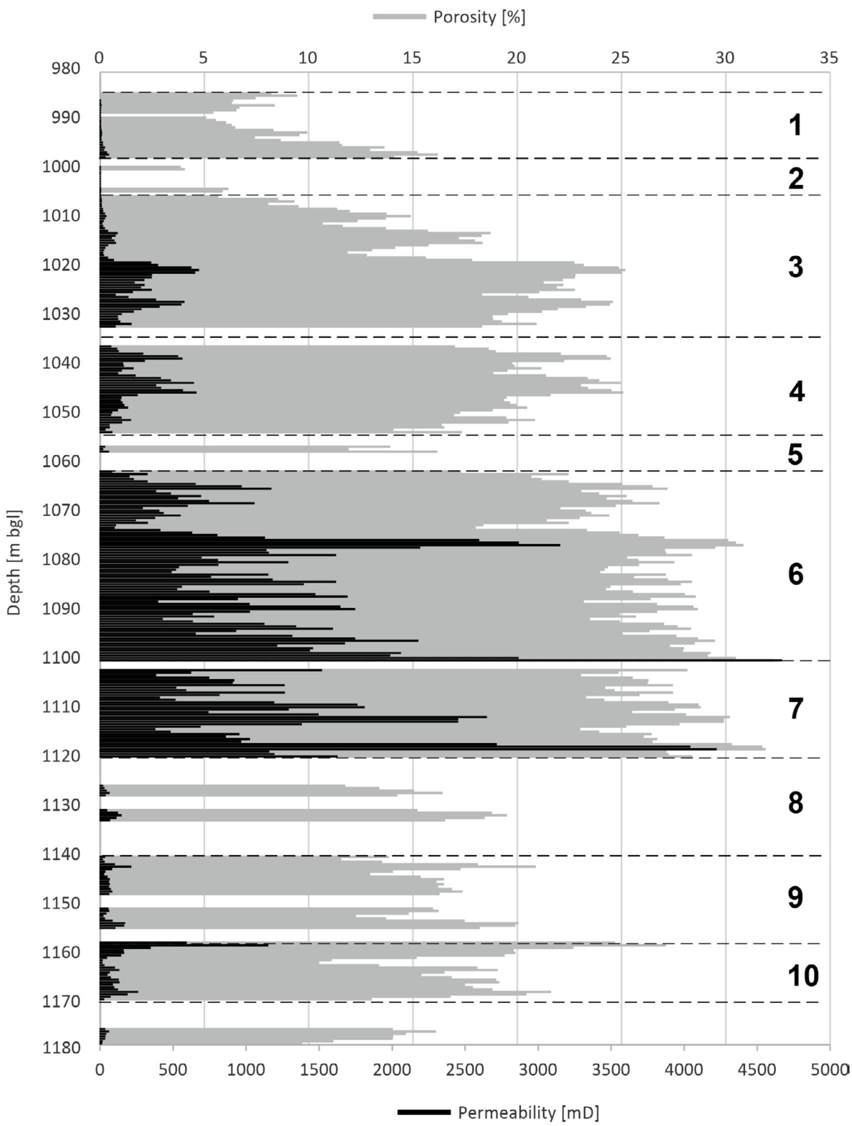

Fig. 4. Porosity and permeability profile of the reservoir in Drzewica Formation in the Jeżów IG-1 well (based on: Wójcicki 2012a)

Rys. 4. Profil porowatości oraz przepuszczalności poziomu zbiornikowego warstw komorowskich w otworze Jeżów IG-1

Table 2. Detailed data on average porosity and permeability for each of the ten selected layers

Tabela 2. Szczegółowe dane dotyczące średniej porowatości oraz przepuszczalności dla każdej z 10 wydzielonych warstw

Layer no	Average porosity (%)	Average permeability (mD)	Thickness (m)
1	8.6	12	13.5
2	1.6	2	8
3	16.6	170	28.5
4	18.8	222	19.5
5	3.7	12	8
6	25.9	1,071	38.5
7	24.8	1,229	19.5
8	4.0	17	20
9	13.4	58	15
10	14.9	143	14.5

Layers 6 and 7 exhibit the highest porosity (25.9% and 24.8%) and permeability (1071 mD and 1229 mD), making them the most favorable zones for CO_2 storage due to their very good storage capacity and fluid flow potential. Layer 6 is also the thickest (38.5 m), further enhancing its storage potential. In contrast, layers 2, 5, and 8 have very low porosity (1.6–4.0%) and permeability (2–17 mD), indicating that they may act as sealing units, restricting fluid movement and helping to contain injected CO_2 within the reservoir. On the other hand, these layers can also act as barriers that may lead to excessive pressure buildup within the reservoir.

2.2. Determination of main assumptions for CO_2 storage simulation

As a result of CO_2 injection into the structure, the pressure increases. The allowable pressure increase in the Jeżów structure was calculated similarly to calculating allowable pressures and stresses for underground gas storage facilities. It was calculated using Kirch's formula for the increase in pore pressure caused by fluid injection from a well into the reservoir, presented in the article by Carnegie et al. (Carnegie et al. 2002). The fracturing pressure calculation scheme for several Polish structures is presented in the appendix of the article by Tarkowski et al. (Tarkowski et al. 2024). The tensile strength of rocks was assumed at 6.45 MPa – the same level as the average value obtained during testing of typical reservoir rock samples from the underground gas storage facility "Swarzów" (Woźniak and Zawisza 2011).

In addition to fracturing pressure, attention was also paid to capillary caprock pressure. As a result of CO_2 injection and buoyancy forces lifting the injected carbon dioxide in the reservoir formation, the pressure increases and can exceed the capillary pressure of the caprock. After exceeding it at the boundary of reservoir rocks with the caprock, the injected CO_2 can break through the capillaries of the overlying seal, which can lead to its leakage. Capillary pressure can be defined using the Young-Laplace equation (Cavanagh and Wildgust 2011; Tokunaga and Wan 2013; Iglauer 2018). The values of the surface tension between CO_2 and brine – γ and the wettability angle – θ were assumed depending on the depth, based on the formulas given by Iglauer (Iglauer 2018). The assessment of capillary pressure in caprocks requires an analysis of their petrophysical properties, such as pore sizes, which influence the sealing capacity (Labus et al. 2015). The characteristic pore radius of the caprock pore space in Poland was determined by Tarkowski and Wdowin (Tarkowski and Wdowin 2011) and Tarkowski et al. (Tarkowski et al. 2014b) and is in the range of 0.01–0.1 μm. For further calculations, the value of 0.1 μm was assumed for safety reasons.

2.3. Simulation of injection and estimation of the CO_2 storage capacity

PetraSim TOUGH2 software (Pruess 2005; RockWare 2022) was used to simulate CO_2 injection into the Jeżów geological structure. A simulation of CO_2 injection was carried out using one vertical well for 36 different locations to estimate the dynamic storage capacity. It was assumed that carbon dioxide would be injected into the interval with the best permeability and porosity within the considered reservoir level, selected layers no. 6 and 7. It was assumed that the amount of CO_2 that could be injected into the chosen structure would be maximized at a pressure not exceeding the fracturing pressure calculated for each of the considered CO_2 injection wells and at a pressure not exceeding the capillary caprock pressure in the top part of the structure. It was also assumed that CO_2 would not migrate beyond the designated contour (spill point) of the structure and that the CO_2 saturation of rocks would not reach 10% in this location.

The free-phase CO_2 plume, even if it moves and disperses within the aquifer – either due to buoyancy-driven upward migration or the flow of water through the pores of the rock forming the structure – is effectively trapped within the structure. This is because the water flow is extremely slow, on the order of 10^{-3} to 10^{-2} m/year (Bachu and Adams 2003). Therefore, in the simulations of carbon dioxide injection into selected geological structure, groundwater flow was not included.

CO_2 injection for each of the analyzed wells was divided into:

- stage I – test injection (first year),
- stage II – target injection (next 30 years),

for a total of 31 years. In both stages, it was assumed that the efficiency of CO_2 injection into the structure would be constant throughout a given stage (1 year and the remaining 30 years).

2.4. CO_2 dynamic storage capacity map of Jeżów anticline

To create a dynamic CO_2 storage capacity map of the Jeżów structure, a simulation of CO_2 injection from a single vertical well was carried out for 36 different locations. The capacity isolines were created manually based on 36-point data of CO_2 storage capacity obtained from the simulation of CO_2 injection into the structure at the location of the well. The linear method was used to draw the isolines, approximating the values based on the distance between the points. It was assumed that the difference between the drawn capacity isolines, i.e., the capacity interval of the color scale on the map legend, is 11.5 million tonnes of CO_2. Finally, the drawing was checked for consistency with the point data to better reflect the distribution of the actual values.

3. Results

The results of CO_2 storage capacity for each of the 36 different injection well locations are presented in Table 3 and Figure 5. The location of some wells close to each other resulted from the need to determine the boundary beyond which the location of the well would pose a risk of CO_2 leakage beyond the designated contour (spill point). Carbon dioxide was injected into the Jeżów structure in the interval with the best permeability and porosity to avoid excessive pressure increase that could exceed the fracturing pressure or capillary caprock pressure. Carbon dioxide injection for each of the analyzed wells was divided into two stages for the same reason. However, the flow rate is constant throughout a given stage (1 year and the remaining 30 years) due to the probable need to receive constant amounts of CO_2 from the emitter over a more extended period.

Table 3 presents the dynamic CO_2 storage capacity for individual injection well locations in the Jeżów structure. Each well is characterized by its storage capacity in million tonnes and the limitation associated with its operation. The limitations can be divided into three categories: in 19 locations, the risk comes from exceeding the allowable pressures; in 9 locations, it is due to leakage at pressures within the allowable limits; and in 8 locations, both factors contribute to the limitation. The table includes 36 well locations, with capacities ranging from 94.36 to 147.37 million tonnes of CO_2. The most common limitation is due to pressure constraints.

Based on the estimated capacity for 36 different injection well locations presented in Table 3, a map of CO_2 storage capacity was developed for the considered structure, presented in Figure 5.

The Figure 5 provides a spatial representation of the CO_2 storage capacity distribution in the Jeżów structure. It is a contour map where different colors correspond to varying CO_2 storage capacities, as indicated by the color scale on the right. Warmer colors, such as orange and red, represent areas with higher storage capacity, while cooler colors, including green and blue, indicate lower capacity.

Table 3. Dynamic capacity of the Jeżów structure for individual injection well locations

Tabela 3. Pojemność dynamiczna struktury Jeżów dla poszczególnych lokalizacji otworu zatłaczającego

Well number	Capacity (mln tonnes)	Capacity limitation
1	110.64	pressure
2	111.21	pressure
3	110.45	leakage
4	137.62	pressure and leakage
5	120.48	pressure
6	107.89	pressure
7	94.36	leakage
8	125.60	pressure and leakage
9	130.99	pressure
10	134.12	leakage
11	130.05	pressure
12	119.92	leakage
13	124.08	pressure and leakage
14	143.58	leakage
15	142.73	pressure and leakage
16	138.95	pressure and leakage
17	139.80	pressure
18	129.38	leakage
19	132.89	pressure and leakage
20	124.27	pressure
21	136.67	pressure
22	130.90	pressure
23	133.27	pressure
24	135.63	pressure
25	134.12	leakage
26	147.37	pressure and leakage
27	96.25	leakage
28	114.05	pressure and leakage
29	117.08	pressure
30	134.12	leakage
31	139.80	leakage
32	144.15	pressure and leakage
33	132.79	pressure
34	129.38	pressure
35	126.83	pressure
36	130.61	pressure

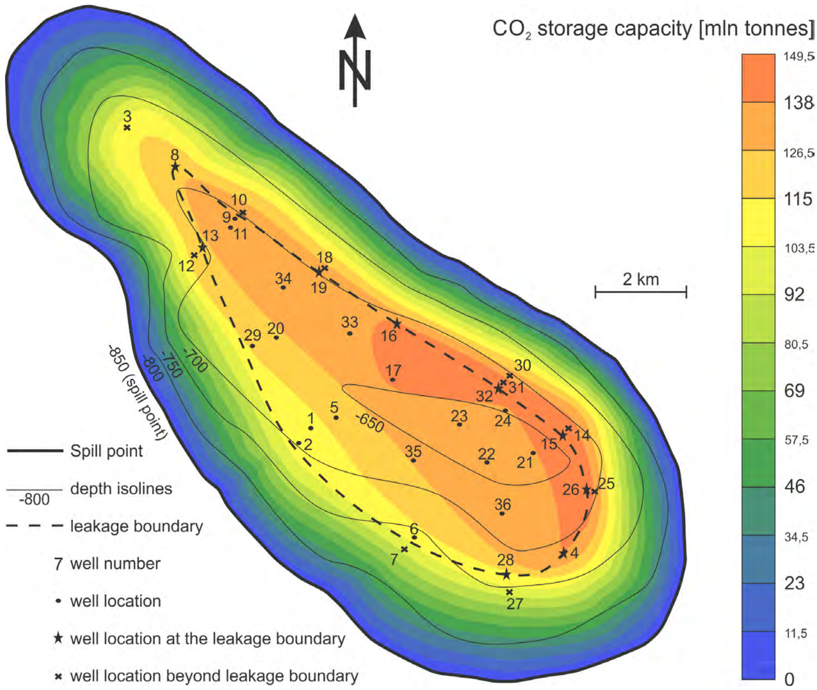

Fig. 5. Map of CO_2 capacity in the Jeżów structure obtained based on capacities collected in the marked and tested injection well locations

Rys. 5. Mapa pojemności CO_2 w strukturze Jeżów otrzymana na postawie pojemności otrzymanych w zaznaczonych i przetestowanych lokalizacjach otworu zatłaczającego

Depth isolines, shown as thin solid black lines, indicate depth variations in meters, ranging from –800 to –650 meters. A dashed black line marks the leakage boundary, identifying the area where CO_2 leakage constraints are expected. The solid black line represents the spill point, which denotes the critical depth where CO_2 could potentially migrate out of the structure.

Various symbols indicate well locations and their specific characteristics. Black dots represent general well locations, while stars signify wells situated at the leakage boundary. Crosses indicate wells that are located beyond the leakage boundary. The spatial distribution of these wells suggests that those near or beyond the leakage boundary may face operational constraints due to potential CO_2 migration risks.

The obtained CO_2 storage capacity oscillates from about 94.36 million tonnes to 147.37 million tonnes. The highest capacity (147.37 million tonnes) was obtained for well number 26, for which the capacity limitation results from the risk of exceeding the capillary caprock pressure and leakage. The smallest capacity was found for well number 7 (capacity 94.36 million tonnes of CO_2), and its limitation results from the fact that the CO_2 injection simulation showed a risk of leakage before the pressure reaches the allowable pressure.

In general, the capacity decreases radially from the top of the structure towards its boundaries along its extent. The highest CO_2 storage capacities are visible on the NE and E slopes of the structure. They were recorded for well locations numbered 15, 26, and 32. Interestingly, the highest storage capacities were also observed in well locations beyond the leak boundary (14, 25, 30, 31).

The dashed black line on the map shows the CO_2 leakage boundary, which was determined based on the circumstances that influence storage capacity, such as the risk of leakage without exceeding the allowable capillary caprock pressure. Numerous wells on or near this boundary show different capacities. Wells located in the area inside this boundary usually have higher capacities. The exception is the NE and E part of the structure, where the well located outside this boundary (well number 14 with a capacity of 143.58 million tonnes of CO_2) showed a higher capacity than the well on the boundary (number 15 – 142.73 million tonnes of CO_2).

4. Discussion

The Jeżów structure is one of the recognized and studied structures in Poland that has a geological model of a CO_2 storage reservoir developed based on seismic and well data. As part of the author's previous research (Luboń 2022), models were built, and CO_2 storage capacity maps were developed for the Konary, Sierpc, and Suliszewo structures, which allowed for the analysis of the dynamic CO_2 storage potential. The maps developed, as a result, enabled the visualization of areas with different CO_2 storage efficiency, which allowed the identification of optimal storage zones for each of the considered structures. The CO_2 storage capacity maps also show significant differences in capacity, depending on the injection well location (Luboń 2020a).

The presented results indicate spatial variability of CO_2 storage potential in the area of the analyzed Jeżów structure (anticline), which results from constraints related to both pressure (fracturing and capillary) and the risk of gas leakage, affecting the efficiency and safety of the storage process. Areas with the highest CO_2 storage potential suggest that the appropriate placement of injection wells is crucial for maximizing storage capacity, optimizing the use of the structure, and minimizing the risk of gas leakage. Locations distant from the top of the structure and in areas with a greater inclination of geological layers provide more favorable conditions for the migration of injected CO_2 towards the top of the structure while reducing the risk of leakage and excessive pressure increase in the top part of the near-well zone, which allows for more efficient and safer storage of this gas.

A comparison with the Konary structure, as shown in Luboń's article (Luboń 2020a), reveals key differences. In both cases, the highest CO_2 storage capacities were found along the structural slope. In the case of the Jeżów structure, similar to the Konary structure, the highest CO_2 storage capacities were found on the slope of the structure. However, in the case of the Jeżów structure, increased capacity values were also observed at the top of the structure. In contrast, in Konary, CO_2 storage capacity values were reduced at this location. The differences in the maximum storage capacities (approximately 15 million tonnes of CO_2 for Konary and almost 150 million tonnes for Jeżów) indicate that the structures under consideration differ significantly in capacity, which indicates the requirement for an individual approach to planning their use for safe and effective CO_2 storage.

The estimated CO_2 storage capacity is significant, average 127 million tonnes, from a single well. The Jeżów structure allows injecting of an average of over 4 million tonnes of CO_2 per year from a single well over 30 years, corresponding to the typical operational lifespan of a large carbon dioxide emitter. It is, therefore, a promising option for long-term CO_2 sequestration activities, supporting Poland's emission reduction goals. The anticline is located in central Poland, which makes it conveniently located in terms of logistics for numerous large CO_2 emitters, and therefore it may constitute an interesting location. The energy company Veolia Energia Łódź is located 50 km from this structure, enabling relatively cost-effective and fast CO_2 transport. Within a radius of 50 to 100 km, there are other large industrial plants, such as Elektrociepłownia Żerań in Warsaw, Enea Wytwarzanie (Świerże Górne) and PKN Orlen (plant in Płock). The proximity of these emitters to the Jeżów structure makes it a potentially strategic location for long-term CO_2 storage, which enables the reduction of transport costs and allows for increased operational efficiency of CO_2 sequestration.

The authors' results largely coincide with those of Jun et al. (Jun et al. 2019) and confirm the importance of pressure management and well layout optimization for increasing CO_2 storage capacity and safety. In both cases, higher capacity and more effective CO_2 retention are associated with appropriate well location selection and pressure control, especially in heterogeneous geological environments. It should also be emphasized that the analysis of optimal well layout and operating conditions for different types and configurations of wells used in CO_2 sequestration (e.g., single vertical, two vertical, horizontal, or with additional wells for brine extraction) can be a valuable tool to optimize CO_2 storage capacity. The results of Maurand and Barrere's research (Maurand and Barrere 2014) based on simulation and kriging interpolation show the possibility of determining the optimal locations and number of wells, which allows for optimizing the storage efficiency while minimizing the risk of excessive pressure increase and CO_2 leakage. In this case, similarly to the authors' results, excessive pressure increase can disrupt the integrity of the caprocks. Therefore, optimizing the amount of CO_2 injected is necessary, minimizing the pressure increase due to gas injection into the structure. Optimizing the location and control of injection wells to maximize CO_2 retention and more stable storage, as discussed by Stopa et al. (Stopa et al. 2016) and exemplified in this study, enhances the long-term safety of CO_2 storage. The authors' results confirm the observations of Okwen, Yang, and Frailey (Okwen et al. 2014), who stated that anticline-type geological structures can significantly increase CO_2 storage efficiency by limiting lateral gas flow. Similar to the present paper's results, where the well's location on the steep side of the structure provided the highest CO_2 storage capacity. Similarly, Allen et al. (Allen et al. 2017) confirm that well location and pressure management play a key role in maximizing storage capacity and minimizing the risk of CO_2 leakage. Cihan, Birkholzer, and Bianchi (Cihan et al. 2015), in addition to optimal well placement, also propose using brine extraction to manage pressure during CO_2 sequestration.

International case studies demonstrate that well location influences plume migration, injectivity, and leakage risks (Li et al. 2024; Worden 2024). At Sleipner (Norway), optimal well placement in a high-permeability reservoir allowed for efficient CO_2 dispersion and minimal pressure buildup. In contrast, Snøhvit (Norway) faced excessive pressurization due to low-permeability sandstone, necessitating a shift in injection location. Tomakomai (Japan) successfully utilized a dual-reservoir strategy, adjusting injection depth based on reservoir conditions to maximize efficiency (Li et al. 2024). The In Salah Project (Algeria) highlighted the risks of placing injection wells near pre-existing faults, leading to caprock deformation and surface uplift, increasing leakage risks. Similarly, at Gorgon (Australia), efforts to manage aquifer pressure through water extraction wells were hindered by sand production and clogging, limiting CO_2 injectivity. In contrast, the Decatur Project (USA) demonstrated the benefits of well placement in a high-porosity saline aquifer, ensuring stable injection rates and effective pressure dissipation (Worden 2024).

Conclusions

A geological model dedicated to CO_2 storage was built for the Lower Jurassic layers of the Jeżów structure. CO_2 injection simulations were performed using 36 injection well locations. Considering the CO_2 storage capacity map, the dynamic CO_2 storage capacity was presented for the selected injection well locations.

Spatial variability of the CO_2 storage potential in the Jeżów structure was noted. This results from pressure-related constraints (both fracturing and capillary), which affect the efficiency and safety of the storage process. Stated that the CO_2 storage capacity of the considered structure varies depending on the location of the injection well, from 94.36 to 147.37 million tonnes of CO_2. It is the largest in the NE part of the structure, resulting from the favorable arrangement of reservoir layers and overburden rocks. Particularly favorable conditions for CO_2 migration towards the structure roof are provided by well locations distant from the top of the structure and areas with a greater inclination of geological layers.

The obtained results allow for more effective and safe planning of the CO_2 storage and emphasize the importance of optimal placement of injection wells for maximizing capacity, effective use of the structure, and reducing the risk of gas leakage.

The results proved the Jeżów structure's suitability for CO_2 storage and its high position in the ranking of structures intended for storing this gas in Poland. They indicate the need for an individual approach to assessing the dynamic storage capacity of CO_2 for each considered geological structure planned for safe storage of carbon dioxide.

This work was supported by the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (research subvention). A part of the article written by B. Papiernik was carried out and financed as part of the statutory work of the Department of Energy Resources, No. 16.16.140.315/05.

The article, which is the result of collaboration between K. Luboń and B. Papiernik, was also developed during the research internship of K. Luboń at the Department of Energy Resources, AGH University of Science and Technology.

The Authors have no conflict of interest to declare.

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THE INFLUENCE OF INJECTION WELL LOCATION ON CO2 STORAGE CAPACITY FOR THE JEŻÓW STRUCTURE (CENTRAL POLAND)

Keywords

CCS, CO_2 injection simulation, CO_2 stoage capacity, deep saline aquifers

Abstract

Underground carbon dioxide storage is considered a technology that can significantly reduce CO_2 emissions into the atmosphere. Following the capture of CO_2 from large industrial emitters, implementing this technology is becoming increasingly urgent on the global path to net zero emissions. This technology requires searching for appropriate structures that meet the requirements of underground CO_2 storage. The suitability of a geological structure for underground CO_2 storage stems from its dynamic capacity, which ensures the injection of the largest possible and safe amount of gas. Its determination requires each time a simulation of CO_2 injection based on a reliable geological model of the structure.

A geological model of the Jeżów structure dedicated to CO_2 storage in the Lower Jurassic layers was built, and injection simulations were conducted for 36 different injection well locations. The dynamic CO_2 storage capacity was presented for the considered injection well locations using the CO_2 storage capacity map. Spatial variability of the CO_2 storage potential was noted. It results from pressure-related constraints (both fracturing and capillary) and varies in the case of the Jeżów structure, depending on the injection well location, from 94.36 to 147.37 million tonnes of CO_2.

The obtained result is influenced by the geological and reservoir parameters of the reservoir layers and the caprock, their arrangement, the distance of the injection well from the top of the structure, and the inclination of the layers. The presented results allow for more effective and safe planning of CO_2 storage, emphasizing the importance of optimal injection well layout for maximizing capacity, effectively using the structure, and reducing the risk of gas leakage.

WPŁYW POŁOŻENIA OTWORU ZATŁACZAJĄCEGO NA POJEMNOŚĆ SKŁADOWANIA CO_2 DLA STRUKTURY JEŻÓW (ŚRODKOWA POLSKA)

Słowa kluczowe

CCS, głębokie poziomy wodonośne, symulacje zatłaczania CO_2, pojemność składowania CO_2

Streszczenie

Podziemne składowanie dwutlenku węgla jest uważane za technologię pozwalającą na redukcję znaczących ilości emisji tego gazu do atmosfery. Poprzedzone wychwyceniem CO_2 u dużych przemysłowych emitentów, wdrożenie tej technologii staje się coraz bardziej pilne na globalnej drodze do zerowej emisji netto. Wymaga to poszukiwań odpowiednich struktur spełniających wymagania podziemnego składowania CO_2. Przydatność struktury geologicznej wynika z jej pojemności dynamicznej zapewniającej przyjęcie jak największej ilości zatłoczonego gazu. Jej określenie wymaga przeprowadzenia każdorazowo symulacji zatłaczania CO_2 w oparciu o wiarygodny model geologiczny struktury.

Zbudowano model geologiczny struktury Jeżów dedykowany do składowania CO_2 w warstwach jury dolnej oraz przeprowadzono symulacje zatłaczania dla 36 różnych lokalizacji otworu zatłaczającego. Z wykorzystaniem mapy pojemności składowania CO_2 przedstawiono dynamiczną pojemność składowania CO_2 dla rozważanych lokalizacji otworu zatłaczającego. Odnotowano przestrzenną zmienność wielkości potencjału magazynowania CO_2. Wynika ona z ograniczeń związanych z ciśnieniem (zarówno szczelinowania, jak i kapilarnego nadkładu) i zmienia się ona w przypadku struktury Jeżów, w zależności od lokalizacji otworu zatłaczającego, od 94,36 do 147,37 mln ton CO_2. Na otrzymany wynik mają wpływ zarówno parametry geologiczno-złożowe warstw zbiornikowych oraz nadkładu, ich ułożenie, oddalenie otworu zatłaczającego od szczytu struktury, jak i nachylenie warstw. Przedstawione rezultaty pozwalają na bardziej efektywne i bezpieczne planowanie składowania tego gazu, podkreślają znaczenie optymalnego rozmieszczenia otworów zatłaczających dla maksymalizacji pojemności oraz efektywnego wykorzystania struktury i ograniczenia ryzyka wycieku gazu.