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CO_2 storage capacity of geological structures located within Polish Lowlands' Mesozoic formations

Introduction

Carbon dioxide capturing and storage within an orogen requires recognition of deep geological structures able to hold needed gas amount safely, assuring permanent retention as well. Suggested Council Directive on CO_2 geological storage, issued on 23 January 2008 (Chapter 2. Sink selection and permission of prospecting), presents general hints on sink selection and emphasizes necessity of directed actions to be undertaken to avoid leakage – essential risk that could weigh upon human health and environment. According to the *Annex 1* of the Directive, the geological structure usage as an underground sink should be defined by description and evaluation of potential carbon dioxide storage complex and its environs.

One of the most important leading components is selecting geological structures suitable for underground carbon dioxide storage and estimating their storage capacity on the base of existing data. This is to stress that the need to choose prospective geological formations and geological structures suitable as underground sinks to store carbon dioxide that would be captured during power generation and industrial processes, remains an urgent and current issue for EU countries. It is essential to choose 10–12 geological structures suitable for carbon dioxide storage for conducting CCS technology pilot projects within the *EU Flagship Programme;* allotting 1–2 projects to Poland.

Issues of recognition of structures and areas, suitable for carbon dioxide geological storage, have been considered since the 4th EU FP (the JOULE project), through the 5th EU FP (the GESTCO project), up to the 6th EU FP (The EU GeoCapacity Project). European

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countries express diverse interests on the subject, due to their more or less advantageous geological conditions. The EU GeoCapacity project realization (2006–2008) (MEERI PAS contributes as a partner) will allow to define the carbon dioxide storage ability and capacities of the selected structures within brine aquifers, oil and gas deposits and deep, unexploited coal beds in a unified way for most of the EU countries (Willscher et al.).

On the European scale, Poland (similarily to Germany, France, Denmark) represents exceptionally favorable conditions for underground carbon dioxide storage. In Poland this arises from existence of thick (several kilometers of thickness) Permo-Mesozoic sedimentary rock complexes, with elevated (anticline) structures, combined with salinar tectonics (salt pillars, salt pillows, salt banks). The chosen structures to store carbon dioxide underground are combined with tectonics. Similar conditions occur in other north – western countries (Germany, Denmark), lying within an area of Permo-Mesozoic basin of Central and NW Europe.

In Poland underground carbon dioxide storage is weighed within: deep brine aquifers, hydrocarbon reservoirs (gas and oil) and deep unexploited coal beds (Tarkowski 2005; Tarkowski and Uliasz-Misiak 2005, 2006). As far as exhausted hydrocarbon reservoirs are concerned carbon dioxide sequestration additionally might be combined with enhanced oil (CO2-EOR) and gas recovery (EGR) operations. In deep coal strata it might be combined with intensification of methane production (ECBM).

The paper aims to present a list of Polish Lowlands' geological structures in deep brine Mesozoic aquifers, that fulfill criteria of carbon dioxide geological storage issued in the *The best practice...* (2006), as well as estimation of their predicted carbon dioxide storage capacity (volumetric and dissolution based ones). The presented structure register is the first so complete inventory of such structures in Poland, combined with carbon dioxide storage capacity estimation, calculated on the basis of earlier detailed recognition of geological and reservoir parameters.

1. Geological structures suitable for underground carbon dioxide storage in Poland

Research on recognition of underground carbon dioxide storage possibilities has been executed in Poland. Realization of several scientific projects allowed to collect indispensable data to define prospective carbon dioxide storage areas and, at the same time, to estimate carbon dioxide storage potential of the subject areas, to begin geological structure selection, to analyze geological – reservoir data and to estimate capacity of underground carbon dioxide storage (Tarkowski 2005; Tarkowski, Uliasz-Misiak 2005, 2006; Uliasz-Misiak 2007, 2008).

The works were executed within research projects like the 6^{th} EU FP (The EU Geo-Capacity Project) and works financed by the State. Preliminary results allowed to determine possibilities of carbon dioxide storage within deep brine aquifers as well as within hydrocarbon deposits in Poland (Tarkowski, Uliasz-Misiak 2005). Mesozoic (Lower Cretaceous, Lower Jurassic, Lower Triassic) deep brine aquifers were chosen as suitable to store carbon dioxide, and within them several structures were defined as suitable for that purpose. An analysis of 330 natural gas and oil deposits in Poland allowed to choose 4 suitable oil ones (Barnówko-Mostno-Buszewo, Cychry, Kamień Pomorski, Nosówka) and 19 gas ones (Barnówko-Mostno-Buszewo, Bogdaj-Uciechów, Borzęcin, Brońsko, Kościan S, Paproć, Radlin, Wilków, Załęcze, Żuchlów, Husów-Albigowa-Krasne, Jarosław, Jodłówka, Kielanówka-Rzeszów, Mirocin, Pilzno-Południe, Przemyśl, Tarnów-Jura, Zalesie), placed within Polish Lowlands, Carpathians or Carpathian Foreland (Tarkowski, Uliasz-Misiak 2005; Uliasz-Misiak 2007).

Due to small carbon dioxide storage capacity of hydrocarbon deposits in Poland further works focused on recognition of geological structures within deep Mesozoic brine aquifers of Polish Lowlands. Works executed within frames of the EU GeoCapacity project allowed

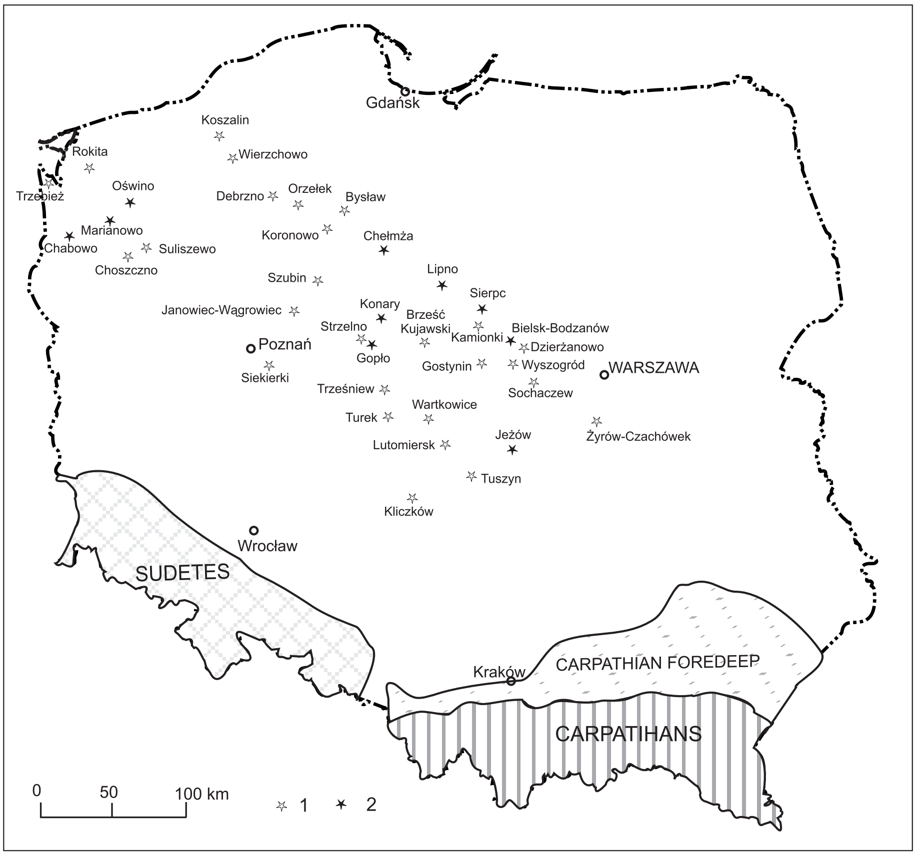

Fig. 1. Location of geological structures suitable for underground carbon dioxide storage
1 – single structure location, 2 – double structure location

Rys. 1. Lokalizacja struktur geologicznych do podziemnego składowania dwutlenku węgla
1 – lokalizacja z jedną strukturą, 2 – lokalizacja z dwiema strukturami

the MEERI PAS to define minutely brine Mesozoic aquifers chosen before, considering Upper Triassic level, to define 18 geological structures for carbon dioxide geological storage, including their characteristics, capacity and storage estimation, and case-study results for the Dzierżanowo/Warszawa structure.

Part of the earlier defined structures did not meet requirements of an underground carbon dioxide sink, displayed in the rules accepted by the EU GeoCapacity project Board, which excluded them from further consideration. The register of structures chosen in brine aquifers of Polish Lowlands' Mesozoic by the MEERI PAS increased to 27 items, within frames of the project for the Ministry of Environment – *An interactive atlas of carbon dioxide geological sequestration possibilities in Poland,* realized by the *Przedsiębiorstwo Badań Geofizycznych* (PBG) company. For these structures the MEERI PAS carbon dioxide storage capacity (volumetric and dissolution based ones) were calculated, injection points defined and structures' contour outlines presented.

This paper presents for the first time a list of 48 geological structures combined with 37 locations, chosen within Mesozoic brine aquifers of Polish Lowlands, and estimated carbon dioxide storage capacity (dissolution and volumetric ones).

1.1. Selecting a structure

Selecting optimal structures that suit CO_2 underground storage involves many factors like: geology, geothermal and hydrodynamic conditions, emission source location, economic and legal issues, etc. Selection of locations to store CO_2 underground is performed basing on geological and reservoir criteria, regarding carbon dioxide specific properties as well. Let us name the basic ones: deposition depth, thickness, rock porosity and permeability, overburden and water mineralization.

These criteria act as preliminary keys to select structures that not only reveal proper carbon dioxide storage capacity but also guarantee safe injection process execution. The paper used structure selection criteria issued in: *The best practice, for the storage of CO_2 in saline aquifers* (2006). A tectonic structure suitable to store carbon dioxide within a brine level is understood as an anticline structure covering one brine aquifer characterized with reservoir and overburden rocks' specific geological – deposit conditionings (here: Lower Cretaceous, Lower Jurassic, Lower or Upper Triassic).

Data on tectonic structures occurring within Mesozoic deep brine aquifers of Polish Lowlands were analyzed. 48 tectonic structures to store carbon dioxide underground (eleven of them enclose two reservoir horizons within the same location) were selected (Fig. 1):

- 17 in a Lower Cretaceous level (Bielsk-Bodzanów-K, Bysław, Chełmża-K, Dzierżanowo, Gopło-K, Kamionki-K, Lipno-K, Oświno-K, Sierpc-K, Sochaczew, Strzelno, Trześniew, Turek, Tuszyn, Wartkowice, Wyszogród, Żyrów-Czachówek);
- 18 – Lower Jurassic (Bielsk-Bodzanów-J, Brześć Kujawski, Chabowo-J, Chełmża-J, Choszczno, Gopło-J, Gostynin, Janowiec, Jeżów-J, Kamionki-J, Konary-J, Lipno-J, Lutomiersk, Marianowo-J, Oświno-J, Sierpc-J, Suliszewo, Trzebież);

— 13 in a Lower and in an Upper Triassic (Chabowo-T, Debrzno, Jeżów-T, Kliczków, Konary-T, Koronowo, Koszalin, Marianowo-T, Orzełek, Rokita, Siekierki, Szubin, Wierzchowo).

Selected geological structures form anticline structures, sometimes salt pillows (Gostynin, Jeżów, Szubin), salt pillars (Kamionki, Wartkowice), or tectonic grabens (Kliczków, Siekierki).

Selection process involved geological and reservoir key criteria to define storage location like: total storage capacity (dissolution based one and volumetric one), reservoir level properties (depth, effective thickness, porosity, permeability, water mineralization), overburden properties (faults and overburden thickness). Minimum stored carbon dioxide amount was assumed at 60 Mt, which corresponds with 30 year emission of a plant producing 2 Mt of CO_2 per year. Capillary pressure was not considered due to no data available.

Only these structures were considered which were recognized with at least one bore hole (in most cases there were more of them, up to 14). Range values of analyzed properties of individual reservoir and overburden rocks followed *The best practice for the storage of CO_2 in saline aquifers* (2006). Most of the considered geological criteria, used to select carbon dioxide underground storage location of the analyzed structures, occur within a favorable index range (vide tab. 1 in *The best practice... 2006),* in some cases values occur within a caution index range, rarely within a negative one.

In 45 structures reservoir to store carbon dioxide occurs below –800 m, only in the 3 anticline's top occurs slightly above. Effective thickness of the reservoir in 46 structures is greater than 50 m, only in case of the 2 structures it comes up to the edge value. Porosity over 20% occurs in case of 22 structures, 26 do not exceed the caution criterion (10%). Criterion of permeability over 300 mD is met by 33 structures, in case of 11 it occurs within a caution range, in 4 of them it does not reach 100 mD.

Water mineralization over 100 g/dm^3 occurs in 25 structures, in case of other 15 ones it occurs within a caution range, in case of another 8 ones it fails the criterion. Waters occurring in the aquifer are always salty or saline, never potable. Strata foreseen to hold CO_2 generally are not faulty – 21, faults in 16 structures fade within reservoir, in two cases faults pass into overburden rocks, 9 structures lack data.

State of tectonic engagement of the structure area is poorly recognized in many cases. Overburden pack rock thickness is sufficient to ensure tightness. In case of all four considered reservoirs (K1 J1, T3 and T1) several dozen meters' thick package of impermeable or poorly permeable rocks covered with a thick pack of poorly permeable rocks occurs directly above the reservoir.

1.2. Carbon dioxide underground storage capacity of the selected structures

Capacity of an underground carbon dioxide sink is a key factor impacting on the geological structure storage usability. A carbon dioxide storage capacity means the carbon dioxide amount that could be injected into the structure safely, with no environmental side effects (Tarkowski 2005; Tarkowski and Stopa 2007; Uliasz-Misiak 2008).

Within deep brine aquifers carbon dioxide will be trapped by three mechanisms: dissolution in reservoir liquids, mineral fixation by geochemical reactions with reservoir fluids and rocks, and carbon dioxide hydrodynamic trapping (Bachu and Adams 2003). Storage capacity in all kinds of geological structures is determined first of all by: structure size, porosity (understood as volume of pores in a rock, part of reservoir that could be filled in by gas), as well as assumed PVT properties.

Volumetric storage capacity and storage capacity resulting from carbon dioxide dissolution in reservoir fluids were estimated (Figs 2–4). Volumetric storage capacity was calculated basing on available data on the selected tectonic structures: surface, efficient thickness, porosity. Carbon dioxide density in reservoir conditions was evaluated using tables (Span and Wagner 1996). Carbon dioxide storage efficiency coefficient was assumed at 20%.

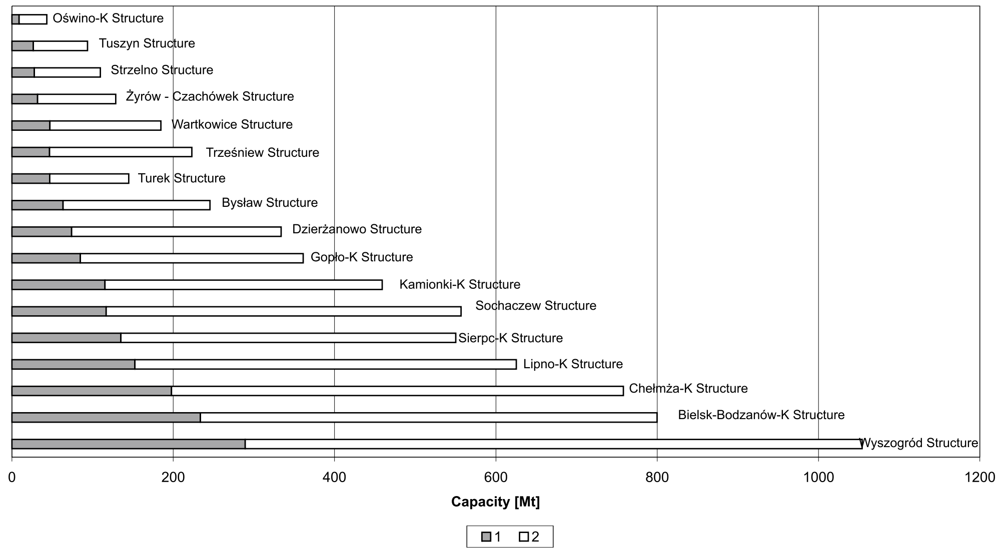

Fig. 2. Capacity of carbon dioxide underground storage within structures occurring in Lower Cretaceous formations of the Polish Lowlands
1 – dissolution based capacity, 2 – volumetric CO_2 capacity

Rys. 2. Pojemność podziemnego składowania CO_2 struktur zlokalizowanych w utworach dolnej kredy Niżu Polskiego
1 – pojemność z rozpuszczania, 2 – wolumetryczna pojemność składowania CO_2

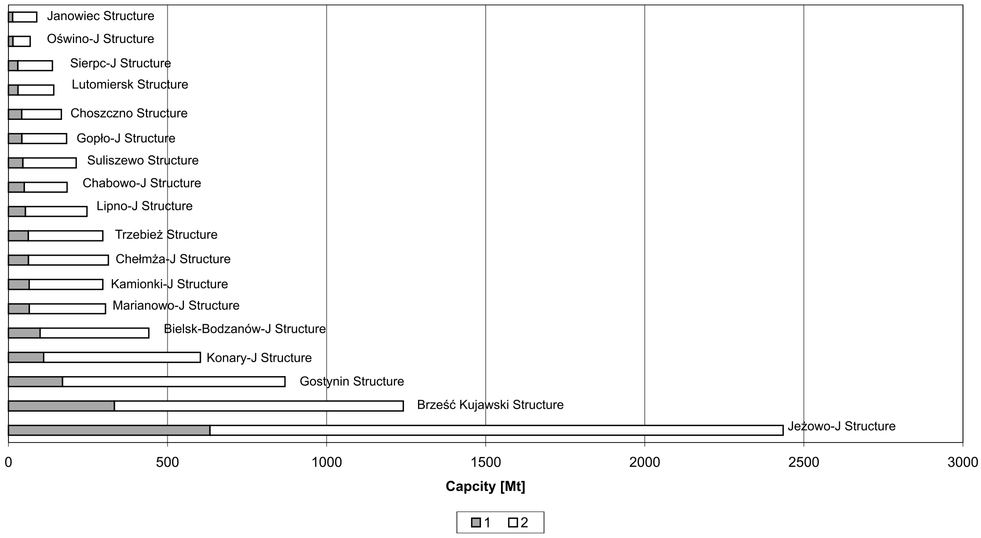

Fig. 3. Capacity of carbon dioxide underground storage within structures occurring in Lower Jurassic formations of the Polish Lowlands
1 – dissolution based capacity, 2 – volumetric CO_2 capacity

Rys. 3. Pojemność podziemnego składowania CO_2 struktur zlokalizowanych w utworach dolnej jury Niżu Polskiego
1 – pojemność z rozpuszczania, 2 – wolumetryczna pojemność składowania CO_2

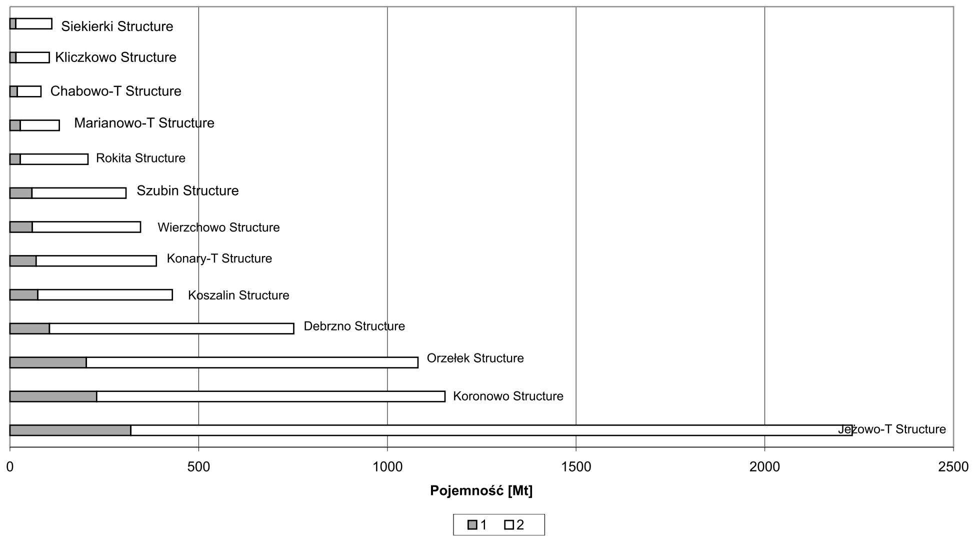

Fig. 4. Capacity of carbon dioxide underground storage within structures occurring in Lower and Upper Triassic formations of the Polish Lowlands
1 – dissolution based capacity, 2 – volumetric CO_2 capacity

Rys. 4. Pojemność podziemnego składowania CO_2 struktur zlokalizowanych w utworach dolnego i górnego triasu Niżu Polskiego
1 – pojemność z rozpuszczania, 2 – wolumetryczna pojemność składowania CO_2

Volumetric storage capacity was calculated using methodology proposed in the EU GeoCapacity project. It is expressed by the following formula:

$$M_{CO_2 s} = A \cdot h \cdot \varphi \cdot \rho_{CO_2} \cdot C_{efs}$$

where:

$M_{CO_2 s}$ – carbon dioxide storage capacity within a geological structure,
A – surface,
h – effective thickness,
φ – porosity,
ρ_{CO_2} – carbon dioxide density in reservoir conditions,
C_{efs} – carbon dioxide storage efficiency coefficient.

Carbon dioxide solubility in reservoir fluids is a function of pressure, temperature and fluid mineralization. Amount of carbon dioxide dissolvable in brine increases as pressure increases and/or temperature drops. Carbon dioxide storage capacity resulting from gas dissolution in reservoir fluids was estimated using the on-line calculator (*Sequestration Calculators*) available at MID-CARBON web pages, allowing to calculate carbon dioxide amount that could dissolve in fluids of an individual structure.

Total estimated carbon dioxide storage capacity of the considered tectonic structures within brine Mesozoic aquifers of Polish Lowlands comes to 22 342 Mt, involving:

— Lower Cretaceous – 6 671 Mt (1 698 Mt dissolution based and 4 973 Mt volumetric),
— Lower Jurassic – 8 259 Mt (1 918 Mt and 6 341 Mt),
— Lower and Upper Triassic – 7 412 Mt (l 236 Mt and 6 176 Mt), respectively.

2. Discussion

Presented results of capacity estimation of selected structures within Mesozoic formations of Polish Lowlands to store carbon dioxide underground indicate a very large capacity of the considered geological objects. Total capacity of the 48 structures corresponds with 70 year emission of carbon dioxide in Poland (referring to emission of the year 2004).

The selected structures are placed in central and NW part of Polish Lowlands, and could hold carbon dioxide sinks for numerous, large carbon dioxide emitters located not farther than 80–100 km, often below 50 km. Large carbon dioxide emitter layout in Poland (Tarkowski, Uliasz-Misiak 2005, 2007) and structure location both reveal that the suggested structures allow underground storing of carbon dioxide captured at many carbon dioxide emitting plants, excluding Upper Silesia, Carpathians, Carpathian Foredeep, SW and NE parts of Poland.

Comparison of the total carbon dioxide storage capacity of structures occurring in Mesozoic brine aquifers of Polish Lowlands, that comes to 22 342 Mt, with applicable carbon dioxide storage capacity estimated for all of hydrocarbon reservoirs in Poland (Uliasz--Misiak 2007), coming to 685 Mt (natural gas) and 15.7 Mt (oil), reveals that capacity of the first one constitutes 96.3 % of joint carbon dioxide storage capacity of the considered locations, while capacity involving natural gas reservoirs constitutes 3%, oil reservoir combined capacity – 0.7%. These proportions would be even more favorable for structures defined within brine aquifers if considering only these hydrocarbon reservoirs (natural gas and oil) that were selected as carbon dioxide sinks in Poland (Tarkowski, Uliasz-Misiak 2005; Uliasz-Misiak 2007). Location of the selected structures within Mesozoic brine aquifers does not overlap with occurrence range of natural gas and oil reservoirs chosen as underground carbon dioxide sinks.

Location selection of the future carbon dioxide sinks must meet several requirements such as capacity, injectivity and safety of underground storage process, as well as proper location referring to carbon dioxide industrial capture installation distribution. That is why further research on displaying detailed geological conditions is necessary, considering selection of future underground carbon dioxide sink set up at prospective locations.

The MEERI PAS executes further works on detailed recognition of the selected structures, some of them (like the Dzierżanowo one) are featured within a case study on carbon dioxide capture and storage, worked out in the EU GeoCapacity project. Further work on the subject is being realized by the MEERI PAS as a part of its own activities and a state Program: *National Program on recognition of formations and structures suitable for safe geological carbon dioxide storage, combined with site monitoring,* which is coordinated by the Polish Geological Institute (PIG), while MEERI PAS is a consortium member.

Presented research results constitute a response to the queries by the Ministry of Environment, Ministry of Economy, and the industry concerning possibilities of storing carbon dioxide underground in Poland. Presented recognition of geological structures capable of storing carbon dioxide underground reveals that our country possesses favorable conditions for carbon dioxide underground storage.

Large capacity and a lot of defined structures shall allow their use in CCS technology demonstration projects to be run within the EU *Flagship Programme* in Poland. Facing the necessity to cut back carbon dioxide emission in Poland, emission trading system and international commitments of our country to reduce carbon dioxide emission level, geological conditions favorable for carbon dioxide underground storage should be milked by authorities and industrial carbon dioxide emitters.

Conclusions

Several years' research results on recognition of geological structures in Mesozoic brine aquifers (Lower Cretaceous, Lower Jurassic, Lower and Upper Triassic) of Polish

Lowlands were presented. 48 structures suitable for underground carbon dioxide storage, were selected. Eleven of them enclose two reservoirs within the same location.

Basing on the methodology being used in the EU GeoCapacity Project (volumetric and dissolution) capacity calculations of selected structures were performed. Total capacity of the defined structures comes to about 22 342 Mt (including: dissolution based 4852 Mt and volumetric 17 490 Mt), considering structure capacity size diversity, varying from several dozen up to 2000 Mt of carbon dioxide. The number of preliminary defined structures suitable for underground carbon dioxide storage puts Poland amongst these European countries that possess significant capabilities to neutralize carbon dioxide underground.

The presented, estimated values of CO_2 storage volume for selected geological structures – due to applied estimation manner and used data reliability – set up rather an approximation approach and depict more qualitative attitude than quantitative one. Further detailed research should focus on the defined structures, albeit the results might alter (reduce) the structures` read storage capacity, or even prove uselessness of some of them for CO_2 storage needs.

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POJEMNOŚĆ PODZIEMNEGO SKŁADOWANA CO_2 DLA STRUKTUR GEOLOGICZNYCH W UTWORACH MEZOZOIKU NIŻU POLSKIEGO

Słowa kluczowe

Podziemne składowanie CO_2, głębokie solankowe poziomy, struktury geologiczne, pojemność składowania CO_2, Polska

Streszczenie

Przedstawiono wyniki badań dotyczące rozpoznania struktur geologicznych do składowania CO_2 w mezozoicznych solankowych poziomach (dolnej kredy, dolnej jury oraz dolnego i górnego triasu) Niżu Polskiego. Na podstawie kryteriów przedstawionych w *Best practice for the storage of CO_2 in saline aquifers* wskazano 37 lokalizacji, w których wytypowano 48 struktur do podziemnego składowania dwutlenku węgla. Jedenaście z nich obejmuje dwa poziomy zbiornikowe w obrębie tej samej lokalizacji. Obliczeń pojemności wytypowanych struktur (wolumetrycznej i z rozpuszczania) dokonano w ujednoliconej metodyce, przyjętej w projekcie EU GeoCapacity. Całkowita pojemność opisanych struktur wynosi 22 342 Mt (w tym: pojemność wolumetryczna 17 490 Mt, pojemność z rozpuszczania 4852 Mt), przy zróżnicowaniu wielkości pojemności od kilkudziesięciu do przeszło dwa tysiące Mt dwutlenku węgla. Oszacowana pojemność odpowiada 70-letniej emisji tego gazu w Polsce.

CO_2 STORAGE CAPACITY OF GEOLOGICAL STRUCTURES LOCATED WITHIN POLISH LOWLANDS' MESOZOIC FORMATIONS

Key words

Underground CO_2 storage, deep brine aquifers, storage capacity, geological structures, Poland

Abstract

The paper presents results on recognition of geological structures for CO_2 storage within Mesozoic brine aquifers (Lower Cretaceous, Lower Jurassic, Lower and Upper Triassic) of Polish Lowlands. Basing on criteria issued in: *The best practice for CO_2 storage of in saline aquifers*, 37 locations were chosen, combined with 48 structures suitable for underground carbon dioxide storage needs. Eleven of them contain two reservoir horizons within the same location. Capacity calculations for chosen structures (volumetric one and dissolution based one) were executed using a unified methodology, accepted by the EU GeoCapacity project Board. Total capacity of these structures comes to 22 342 Mt (that is: volumetric 17 490 Mt, dissolution based 4852 Mt), considering capacities from several dozen up to over 2 000 Mt of carbon dioxide. The defined capacity equals Poland's carbon dioxide emission for 70 years.