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CO_2 emissions and geological storage possibilities in the Czech Republic

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Abstract. A study focused on CO_2 capture and storage potential of the Czech Republic was performed within the CASTOR and EU GeoCapacity European R&D projects. The first part of the study focuses on country-wide greenhouse gases emissions, their development and related national policies. A comprehensive inventory of big industrial CO_2 emission point sources follows based on both data from the National Allocation Plan and monitoring and reporting results for the EU Emission Trading Scheme. The second part deals with the national geological settings of the Czech Republic. Big sedimentary basins were evaluated regarding their suitability and potential for geological storage of CO_2 and several tens of promising structures were selected, representing all the three main types of storage structures – deep saline aquifers, hydrocarbon fields and unmined coal seams. The first rough assessment of storage capacities of the selected structures was made, resulting into a total figure of ca 3300 Mt CO_2, which can be regarded the first estimation of the country-wide CO_2 storage potential. Deep saline aquifers, representing almost 87 % of this capacity, are the most important structures from the quantitative point of view.

Key words: Greenhouse gases, carbon dioxide, CO_2 capture and storage, , ,CO_2 emissions, CO_2 storage capacity.

1. Introduction

The Czech Republic counts among countries with high level of CO_2 emissions in terms of per capita and per GDP unit values. This is the reason why various options of their reduction are placed on the agenda. Among these options, CO_2 capture and storage (CCS) seems to be one of the most effective, especially in relation to big stationary sources like power plants, refineries, steel mills or cement factories. To be able to assess the territorial CCS potential of the country, a detailed study focused on big CO_2 emission sources (exceeding 100 kt CO_2 / year) was performed, accompanied by a review of the national geology resulting into selection of geological structures potentially suitable for geological storage of CO_2.

2. Greenhouse gas emissions in the Czech Republic

Protection of the climate system of the Earth is a top-priority environmental issue in the Czech Republic (CR). It is included in the Resolution No. 187/2004 of the Government of the CR (National Program to Abate the Climate Change Impacts in the Czech Republic) and also in the Actualized State Environmental Policy of the CR (2004). The Czech Republic has committed itself to reduce its greenhouse gas (GHG) emissions by 8 % from the base year (the emissions in 1990 for CO_2, CH_4 and N_2O, but 1995 for F-gases) in the first commitment period (2008 – 2012) of the Kyoto Protocol. It is believed, that the CR will be able to fulfill this goal without serious problems.

Moreover, in 2001 a national target was declared by the Czech government in the State Environmental Policy to reduce GHG emissions in 2005 even by 20 % compared with the year 1990. From GHG emission data for period 1990 – 2004 it is evident that this target will be met (see Fig. 1). Much more ambitious targets are incorporated in the National Program to Abate the Climate Change Impacts in the Czech Republic - to reduce CO_2 emissions per capita by 30 % until 2020, compared to 2000; to reduce total aggregate CO_2 emissions by 25 % in 2020, compared to 2000; and to keep at the commenced trend to 2030. Considering these ambitions, it is clear that development and application of new advanced technologies (including CO_2 capture and geological storage) are highly desirable.

Greenhouse gas (GHG) emission inventories in the CR are compiled according to the standard IPCC methodology and the results are submitted annually to the United Nations Framework Convention on Climate Change Secretariat (UN FCCC) in standard formats. The Czech Hydrometeorological Institute (CHMI) is responsible for GHG inventory preparation on the territory of the CR. Result of these inventories is shown in Fig. 1. In 2006, the total aggregated emissions (including removals from the LULUCF sector) reduction was almost 23.9 % compared to 1990. It is evident that CO_2 represents a thumping majority (85.9 %) of all GHG emissions, while contributions of CH_4, N_2O and F-gases are 8.3 %, 5.1 % and 0.7 %, respectively (CHMI, 2006; CHMI, 2007, CHMI, 2008; Fott, Vácha 2005).

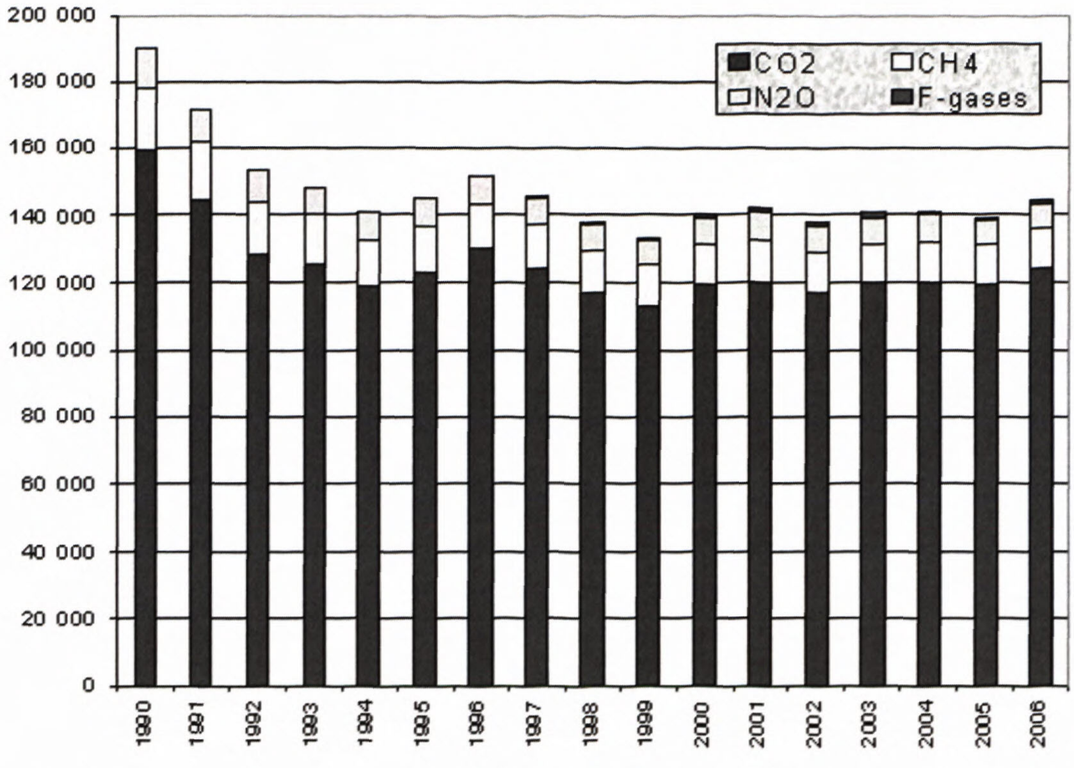

Fig. 1 Total aggregated greenhouse gases emissions in the CR in 1990 – 2006 [kilotonnes CO_2 equivalent]

Recently, a new source of data on individual CO_2 emission sources has appeared. It contains data collected for the purposes of the European Union Emissions Trading Scheme – EU ETS. All major CO_2 emitters (stationary point sources) are included in this scheme. In addition, all facilities under EU ETS are obligated to regularly monitor and report their CO_2 emissions

Since 1990, the emissions reduction in the CR was much higher than in the EU, especially due to the industry restructuring in the first period of the 1990s. On the other hand, further reduction after 1995 was supported by the implemented policies and measures (mainly oriented to energy efficiency, usage of natural gas and biomass, etc. – see below). A comparison of GHG emissions development in the EU and the CR is shown in Figure 2.

A number of measures have been implemented in the CR, leading to a decrease in GHG emissions. These include measures limited to certain specific subject or sector (e. g. the State program for energy savings and use of renewable energy sources, etc.), as well as framework measures (e.g. the National Program to Mitigate Climate Change). The majority of these measures were primarily oriented towards energy efficiency and/or air quality (clean air) and the GHG/CO_2 emissions reduction was a side effect only. The EU Emission Trading System (EU ETS), established recently, represents the fist measure oriented primarily on greenhouse gas emissions reduction. At the same time it must be stated that the emissions reduction achieved in the energy and industrial sectors are – to a significant extent - negated by the increase of CO_2 emissions generated by transport.

Notwithstanding the achieved emissions reduction since 1990, some relative indicators show high GHG emission figures for the CR, e. g. emissions per capita or per GDP unit (see Figure 3). It is mainly due to the wide use of brown coal, the relatively low energy efficiency and the relatively low GDP level. This is another reason why it is very important to reduce GHG emissions in the CR.

3. CO_2 emissions from individual facilities covered by EU ETS

For the 1st period of EU ETS (2005-2007), about 97 mill. allowances were annually allocated by NAP I (First national allocation plan) among Czech facilities (installations) which are taking part in EU ETS. In general, amount of allowances allocated per year were above the real amount of monitored, verified and reported emissions in years 2005 (82.5 mill. t.) and 2006 (83.7 mill. t.) and it will probably be the same case in 2007. For the 2nd period of EU ETS (2008-2012), about 86.8 mill. allowances will be annually allocated by NAP II (Second national allocation plan).

There are a few reasons of difference between reality and NAP I:

– The amount of allocated allowances includes also bonuses for "early actions" and other bonuses which increase the number of allowances in comparison to historical emissions;

– Real emissions are positively affected by intentional saving measures (usage of biomass, natural gas etc.) in order to sell surplus allowances;

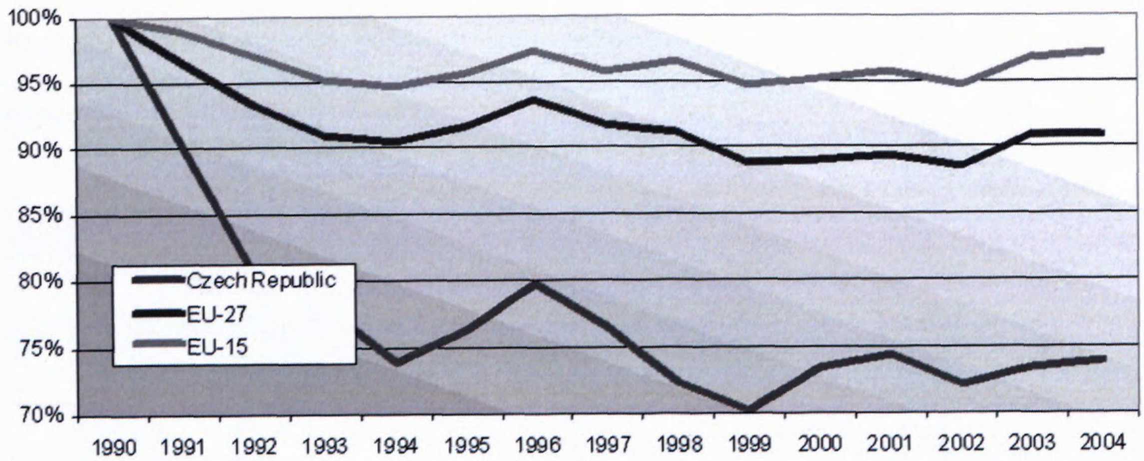

Fig. 2 Comparison of GHG emissions development in Czech Republic and in the EU

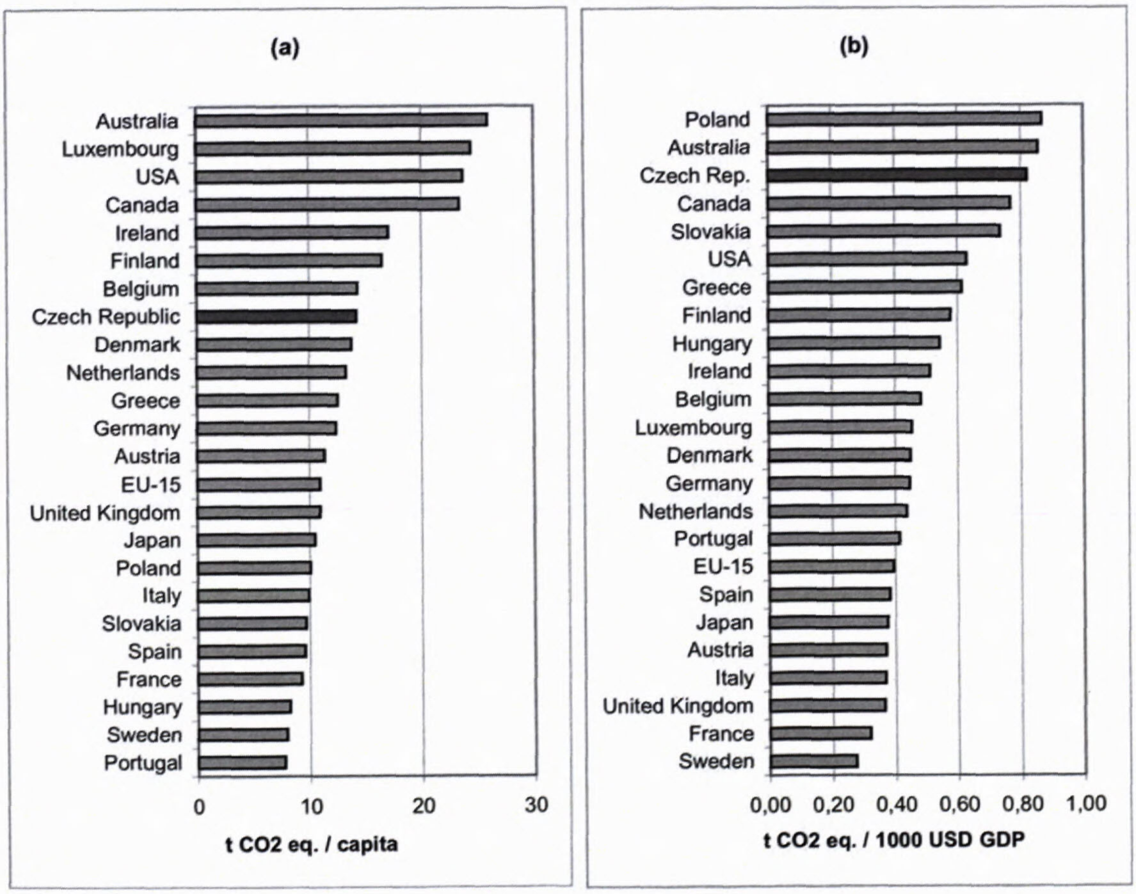

Fig. 3 Comparison of GHG emissions per capita (a) and per GDP unit /recalculated according to purchasing power parity/ (b) in 2003

Allowances are allocated for three-year period, which reflects the expectation of gradual economic growth and real emissions were monitored only for the first year of this period;

– Real emissions were probably generally underestimated and/or data used in NAP preparation were overestimated.

In the following paragraphs we use two approaches of representing CO_2 emissions from individual facilities:

I Emissions approximated by amount of allocated allowances per year by NAP for the period 2005 – 2007;

II Emissions expressed as really monitored, verified and reported in 2005.

Approach I: Emissions approximated by allocated allowances

According to the Czech national GHG inventory (CHMI, 2006), annual CO_2 emissions from the whole area of the Czech Republic were approximately 127 million in 2004. More than 76 % of it (97 mill. t) are covered by stationary industrial point sources. To obtain information about geographical distribution of CO_2 emissions, an inventory of emission point sources bigger than 100 000 t CO_2 per year has been created. These sources are responsible for 91 mill. t of annual CO_2 emissions which represents 71.7 % of total Czech CO_2 emissions and 93.8 % of emissions from stationary point sources (see Tab.1).

Tab. 1 Overview of CO_2 emissions in the Czech Republic (Approach I

Type of emissions	mill. t / yr
Total CO_2 emissions from the whole area of the Czech Republic	127
CO_2 emissions from sources covered by EU Emission Trading System (NAP)	97
CO_2 emissions from facilities emitting more than 100 kt CO_2 per year	91
CO_2 emissions from facilities emitting more than 500 kt CO_2 per year	80
CO_2 emissions from facilities emitting more than 1 Mt CO_2 per year	68

Data sources for establishing CO_2 emissions from individual stationary sources were in this case (Approach I):

- First National Allocation Plan of the Czech Republic (for the EU Emission Trading Scheme);
- National Integrated Pollution Register of the Czech Republic (under IPPC Directive).

Both data sources are open to public. The First National Allocation Plan (NAP I) has been prepared by the Ministry of Environment, in cooperation with the Ministry of Industry and Trade, based on the data obtained by the Czech Hydrometeorological Institute. The Integrated Pollution Register (IRZ) has been set up by the Ministry of Environment and is run by the Czech Environmental Information Agency (CENIA).

Emission data from the National Allocation Plan (NAP) should represent a suitable assessment of CO_2 emissions for the period of 2005 – 2007 because the allocation of emission allowances is based both on historical emission data (since 1999) and expected progress of national economy in future. According to the NAP, 87 major point sources producing more than 100 kt of CO_2 per year have been identified. 19 of them are power plants, 31 heating facilities, 12 energy producers for manufacturing industry, 8 metallurgical plants, 10 cement & lime works, 3 refineries and 4 other facilities. 22 of the above mentioned facilities emit more than 1 Mt CO_2 per year and 18 of them between 500 – 1 000 kt per year. These two groups represent almost 82 % of national CO_2 emissions from stationary industrial point sources. The share of individual industry sectors in total CO_2 emissions of the country is shown in Tab. 2.

Geographical distribution of Czech stationary industrial point sources is shown in Fig. 4. It is obvious that the sources are concentrated especially in the NW and NE part of the country.

The concentration of CO_2 in exhaust gases is usually lower than 20 % because the combustion processes are performed in the air atmosphere (21 % O_2, 79 % N_2).

Tab. 2 Share of industry sectors in total CO_2 emissions

Sector	Emissions [t/yr]	Share [%]	Number of facilities
Power	55 243 423	60,8	25
Heat	10 335 207	11,4	27
Chemicals (other)	5 373 587	5,9	7
Refineries	1 317 766	1,5	3
Iron and Steel	12 597 603	13,9	7
Paper and pulp	778 672	0,9	3
Cement	2 974 603	3,3	5
Other*	2 186 609	2,4	10
Total	**90 807 470**	**100.0**	**87**

* lime, glass, coke production, natural gas compress station

Nevertheless, two exceptions could be identified (= "good opportunities for carbon capture") where the CO_2 concentration is much higher. These sources are marked as "Early opportunities" in the map in Fig.4.

The first case is the ammonia production at Chemopetrol, a.s., Litvínov. The process includes production of hydrogen by gasification of residual fuel oil by steam oxygen mixture. Gasification is followed by the shift reaction: $CO + H_2O = CO_2 + H_2$. CO_2 is separated from H_2 by low temperature absorption (RECTISOL), H_2 is used for ammonia synthesis by reaction with N_2. The assumed amount of CO_2 produced is about 700 kt per year. This source seems to be very perspective for CO_2 a pilot capture and storage application.

The second case is the Sokolovská uhelná, a.s. plant in Vřesová, consisting of two sources: (i) classical heating plant emitting about 60 % of total CO_2 amount and (ii) steam-gas cycle power plant, emitting the remaining 40 % of CO_2, based on gasification of brown coal by steam–oxygen mixture. Even in this case about 700 kt CO_2 per year are captured by the RECTISOL process and after that released to the atmosphere.

Approach II: Real CO_2 emissions from facilities covered by EU ETS in 2005

CO_2 emissions from individual facilities (installations) covered by EU ETS are monitored and reported according to Decree of the Ministry of Environment No. 696/2004 that represents the Czech implementation of the Decision of European Commission No. 2004/156/EC which is generally called "Monitoring and Reporting Guidelines". Monitoring is based mostly on calculations from consumption of individual fuels (or material) and from relevant emissions factors (Fott et al., 2006). Before submission to the "competent authority" (Ministry of Environment) the report on monitoring has to be verified pursuant to Act No. 695/2004 Coll. that is Czech implementation of Directive 2003/87/EC generally called as "Directive on EU ETS".

Similar emission statistics as presented for Approach I are given in Tables 3 and 4.

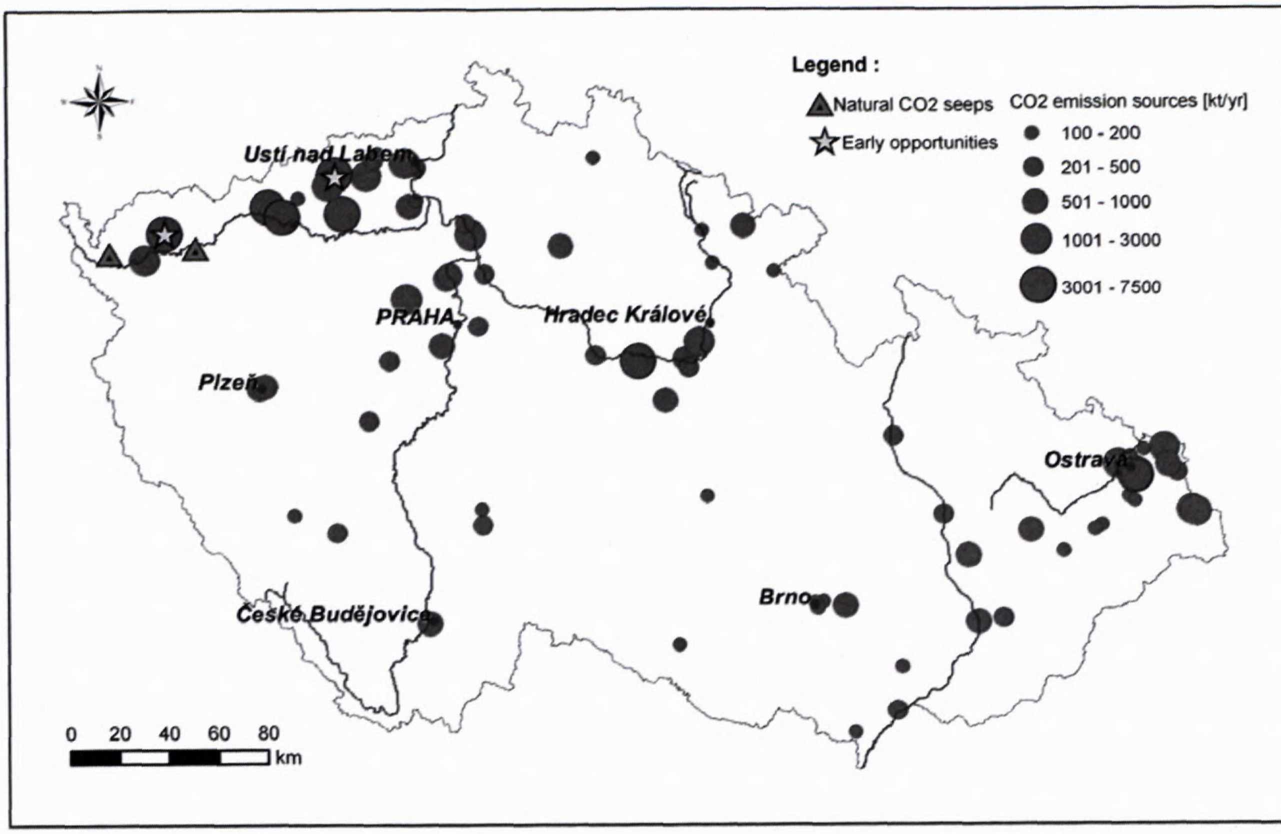

Fig. 4 Map of CO_2 emission sources in the Czech Republic (pointspurces emitting more than 100 kt CO2/year)

Tab. 3 – Overview of CO_2 emissions in the Czech Republic (Approach II)

Type of emissions	mill. t / yr
Total CO_2 emissions from the whole area of the Czech Republic, National Inventory	127
CO_2 emissions from sources covered by EU Emission Trading System (2005)	82
CO_2 emissions from facilities emitting more than 100 kt CO_2 per year	77
CO_2 emissions from facilities emitting more than 500 kt CO_2 per year	65
CO_2 emissions from facilities emitting more than 1 Mt CO_2 per year	60

Tab. 4 – Share of industrial sectors in CO_2 emissions covered by ETS (Approach II)

Sector	Emissions [t/yr]	Share [%]	Number of facilities
Power	49 145 177	63,0	25
Heat	8 849 058	11,3	27
Chemicals (other)	4 540 421	5,8	7
Refineries	969 327	1,2	3
Iron and Steel	9 866 977	12,6	7
Paper and pulp	454 158	0,6	3
Cement	2 553 038	3,3	5
Other*	1 652 271	2,1	10
Total	**78 030 427**	**100.0**	**87**

* lime, glass, coke production, natural gas compress station

4. General geology – sedimentary basins

The territory of the Czech Republic belongs to the Bohemian Massif (western part) and the Carpathians (eastern part). A significant part of the area is formed of crystalline rocks. Nevertheless, several major sedimentary formations, representing potentially suitable CO_2 storage areas, can be found (Mísař et al., 1983; Picha et al., 2006):

Tertiary:

- Vienna Basin (Czech part) is located in SE part of the Czech Republic. The age of the sediments is Miocene (from Eggenburg to Pontian). This basin is the oldest oil and gas industry area in the CR.
- Carpathian Foredeep (Czech part) is a narrow basin oriented SW – NE, limited from SE by the Carpathian Flysch Zone. The sediments are of Miocene origin (Ottnangian? - Karpathian – Badenian). Some oil & gas structures can be found here.
- Carpathian Flysch Zone is located at the Czech – Slovak border. It is composed of folded Carpathian nappes (mainly Tertiary sandstones and claystones). The basement of the napes is formed by Miocene sediments of the Carpathian Foredeep. Below them, Mesozoic and Palaeozoic sediments can be found. In some parts, however, the pre-Tertiary basement of the nappes is formed by crystalline rocks. All the autochthonous sediment formations, as well as the weathered parts of the crystalline complexes represent important oil & gas and aquifer structures.

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• Sub-Krusne hory Mountains Basins comprise 3 basins - Cheb, Sokolov and North Bohemian Basin. The sediments are of Eocene, Oligocene and lower Miocene age. The basement of these basins is composed of Carboniferous and Cretaceous sediments. Active brown coal open pits are located in the Sokolov Basin and in the North Bohemian Basin. In general, the basins are too shallow and do not include structures suitable for storage of CO_2.

Tertiary and Cretaceous:

• South Bohemian Basins comprise 2 basins - Budejovice and Trebon - in the south of the CR. Their sediments are of Cretaceous and Miocene origin. Small brown coal open pits were located in the Budejovice Basin (no more active). The basins are too shallow for CO_2 storage purposes.

Cretaceous:

• Bohemian Cretaceous Basin is one of the largest basins in the CR. It is located in the middle of the Bohemian Massif. The sediments are of Cenomanian – Santonian age. This basin is an important groundwater reservoir and as such it is not suitable for CO_2 storage. The basement of the basin is partly built of Permian-Carboniferous sediments (see below) with interesting aquifer structures and coal measures.

Permian-Carboniferous:

• Lower Silesian Basin (Czech part) is located in the north of the CR. The sediments are of Lower Carboniferous (Tournaisian) – Upper Permian age. Coal mining activity was stopped here in the early 1970s. The basin contains an interesting aquifer structure for potential CO_2 storage.

• Central Bohemian Basins represent a chain of typical limnic basins, located along the line Plzeň – Prague - Mladá Boleslav. Coal mines were located mainly in the Plzeň Basin, the Rakovník Basin and the Kladno Basin. The last coal mine in this area was closed in 2003 (in the Kladno Basin). The sediments are of Upper Carboniferous (Westphalian) – Lower Permian origin. The Permian-Carboniferous sediments continue from Central Bohemia to the Lower Silesian Basin under the Cretaceous sediments of the Bohemian Cretaceous Basin. Several promising aquifers as well as coal-bearing structures are located within this stratigraphic unit.

Carboniferous:

• Upper Silesian Basin (Czech part) is located in the NE of the CR. Its sediments originate from Tournaisian – Westphalian. There are two typical coal layer complexes in the Czech part of the Upper Silesian Basin: Ostrava layers and Karvina layers. Nowadays, this basin is the only pit coal producing area in the CR. This area has a big potential for enhanced coal-bed methane recovery. The Carboniferous filling of Upper Silesian Basin is mostly covered by Neogene sediments and Carpathian flysch.

The general assessment of the sedimentary basins described above shows that all the three generally recognized options for geological storage of CO_2 (deep saline aquifers, hydrocarbon fields and unmined coal seams) are available on the Czech territory.

5. Storage options

5.1. Aquifers

5.1.1. General description

Regarding aquifers, the attention was aimed at vertically closed structures with sufficient sealing and significant pore volume capacity. Altogether, 22 potentially suitable structures were identified, 17 of them in the Carpathians (eastern part of the country) and 5 in sedimentary basins of the Bohemian Massif. Due to the long-term hydrocarbon exploration, the knowledge of Carpathian structures and their properties is much better than that one of the Bohemian Massif aquifers.

The geographical distribution of the structures considered is shown in Fig. 5.

The Carpathian aquifers are situated in the Carpathian Foredeep (Vlkoš – Lobodice, Mušov, Drnholec, Iváň, Vlasatice) and in the Flysch Zone (Koryčany, Osvětimany – Stupava, Zdounky, Bařice, Rusava, Kozlovice – Lhotka, Frýdlant nad Ostravicí, Vyšní Lhoty – Morávka, Mikulov, Nosislav – Nikolčice, Kobeřice, Kobylí). Promising structures were selected on the base of a former study aimed at identification of aquifers suitable for underground natural gas storage sites (Müller et al., 2000).

Reservoir rocks of the Foredeep aquifers are Lower Miocene sandstones while the seal consists of Upper Miocene claystones. In the Flysch Zone, aquifers are situated mainly in Miocene sandstones except for the structures of Kobylí (Paleocene and Miocene sandstones), Mikulov (Jurassic limestones) and 3 structures in the North (Kozlovice – Lhotka, Frýdlant nad Ostravicí, Vyšní Lhoty – Morávka) where Upper Carboniferous and Miocene sandstones appear. Carpathian Flysch nappes (with claystone layers) form structure sealing in all cases.

The Bohemian Massif aquifers (Žatec, Roudnice, Mnichovo Hradiště, Nová Paka, Police) are situated in Permian-Carboniferous Central Bohemian and Lower Silesian basins, partly covered by thick sediments of the Bohemian Cretaceous Basin. Reservoir rocks are mainly Upper Carboniferous (Stephanian) sandstones and arcoses while the seal is usually formed by overlying Lower Permian (Autunian) claystones. The structures are quite complicated and information about their properties is lacking in large areas. Therefore, the delineation of the aquifers is not so precise as of those ones in the Carpathians and the calculated storage capacities must be considered as rough estimates only. On the other hand, the geographical position of Bohemian aquifers (close to the biggest CO_2 emission sources) is very suitable from the CO_2 storage point of view.

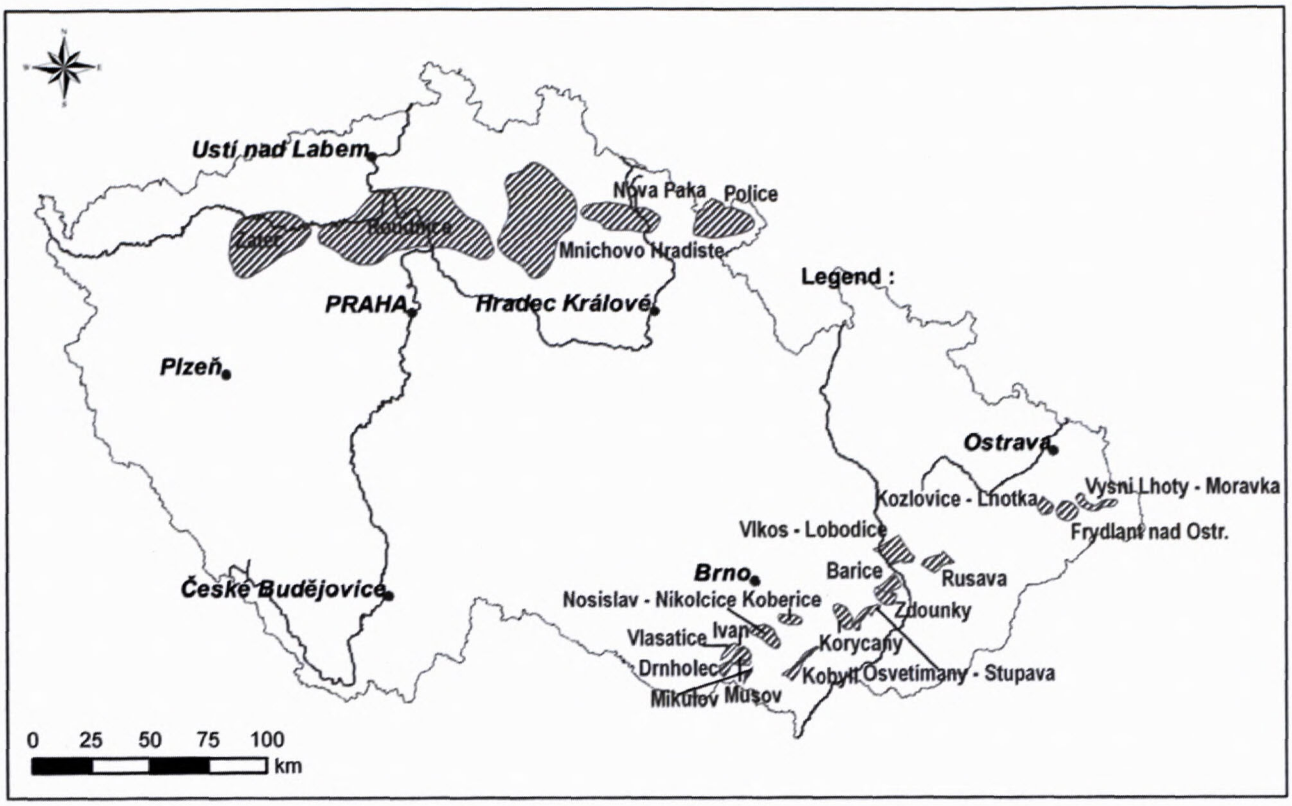

Fig. 5 Geographical distribution of aquifers suitable for geological storage of CO2 in the Czech Republic

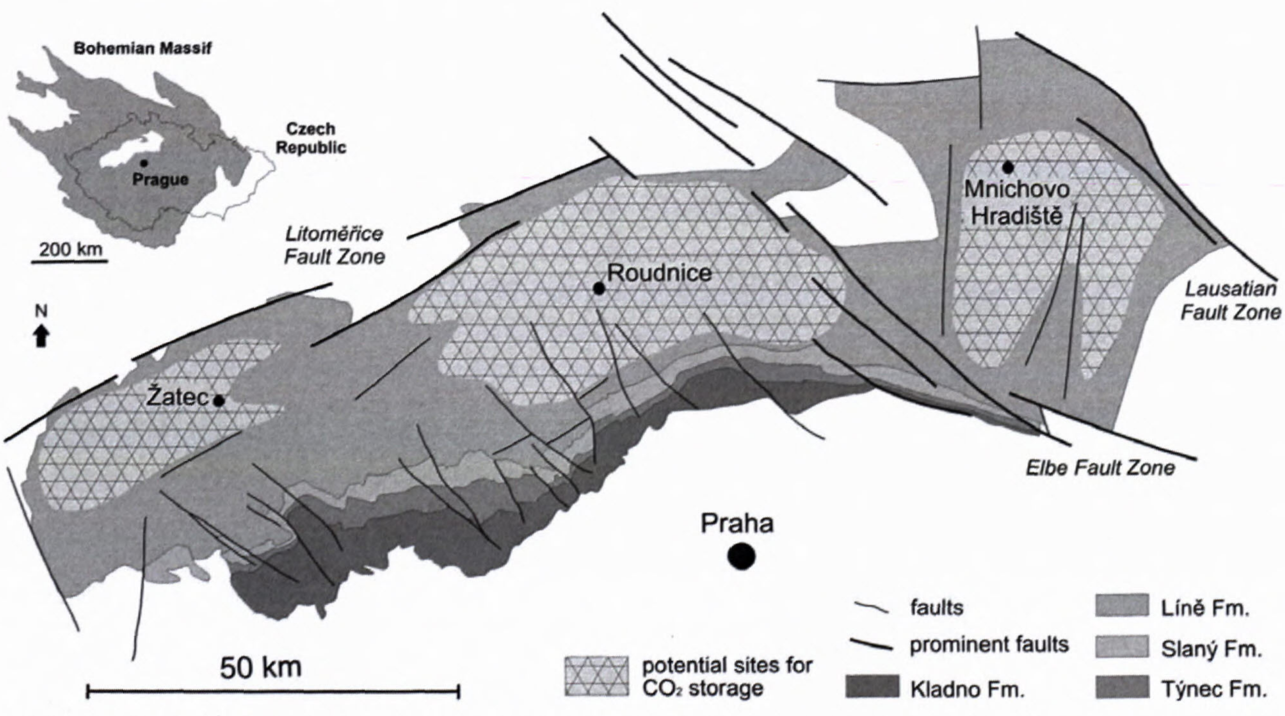

Fig. 6 Simplified and uncovered (Cretaceous, Tertiary) geological map of the Central Bohemian basins (Žatec, Roudnice, Mnichovo Hradiště) with potential sites for CO2 storage

5.1.2. Estimated storage capacity

The storage capacity calculations were based on the volumetric approach. Structure area, average thickness and average porosity were used for pore volume determination, according to the formula (e. g. Brook et al., 2003; Bachu et al., 2007; Bachu, 2008):

$$M_{CO2} = S * t * p * \rho_{CO2} * (1 - S_w) * RF,$$

where M_{CO2} is the effective CO_2 storage capacity, S – area, t – average thickness of aquifer layers, p – average porosity of aquifer layers, ρ_{CO2} – CO_2 density under aquifer conditions (depends on pressure and temperature), S_w – irreducible water saturation, RF – recovery factor (capacity coefficient)

Porosity values used for the calculations were derived from well-log data available. In the Carpathians, the porosity ranges from 5 to 20 %, while in the Bohemian Massif it is considerably lower (up to 6 %, considering the complex structure of the layers). The average CO_2 density value of 630 kg/m^3 (corresponding to the typical pressure and temperature conditions of the aquifers) was used for all structures. The recovery factor used for calculation of the effective storage volume was 6 % for Bohemian regional aquifers and 40 % for Carpathian structures.

The list and main parameters of the aquifers considered is shown in Table 5. The total storage capacity has been assessed at about 2863 Mt CO_2. This means that aquifer structures represent the most important CO_2 storage option in the Czech Republic.

5.2. Hydrocarbon fields

5.2.1. Exploration and production history, stratigraphy, distribution, Ultimate Recovery

Hydrocarbon exploration history in the CR started in 1900 when the first well called "Helena" was finished. This well was located in the Carpathian Flysch Zone (Bohuslavice nad Vláří) and reached a depth of 450 m with some gas shows. In the Vienna Basin (near Hodonín), another well was drilled in the same year (final depth 217 m, gas and oil shows recognized). The first really positive well was finished near Slavkov (Carpathian Flysch Zone) in 1908 and produced gas from 500 m depth for a local sugar factory until 1920. The first oil reservoir was opened in 1920 in the Vienna Basin (near Hodonín). The first production well produced oil from 313 - 338 m depth and the daily production of the field was about 80 t in 1925 (Bednaříková et al., 1984).

At present, there are more than 40 oil and gas producing fields in the CR, registered by Czech Geological Survey - Geofond. All of them are located in the eastern part of the CR, in the Carpathians (Vienna Basin, Carpathian Foredeep, Carpathian Flysch Zone). From the stratigraphic point of view, Miocene sediments represent the reservoir rocks in all these areas. In the Carpathian Flysch Zone, oil & gas can be found in Mesozoic and Paleozoic sediments as well. In some cases, hydrocarbon reservoirs are situated in weathered crystalline complexes.

Some of the reservoirs are depleted, especially the shallow structures in the Vienna Basin. Deeper structures in the Vienna Basin are still producing, as e.g. the fields Hrušky (oil and gas), Týnec (oil), Lanžhot (oil), Poddvorov (oil and gas), Vracov (oil), Lužice (oil), Poštorná (oil) and Prušánky (oil and gas). Most of the structures in the Vienna Basin represent tectonic traps.

Most of the gas reservoirs located in the Carpathian Foredeep are depleted and some of them have been transformed into natural gas underground storage sites (e.g. Dolní Dunajovice).

Nowadays, the most important producing oil and gas reservoirs are located in the Carpathian Flysch Zone. The majority of Czech oil production is coming from the Dambořice – Uhřice and Žarošice fields (tectonic traps in combination with elevation). Production layers are sediments building the basement of Flysch nappes, i.e. Jurassic and Paleozoic. There are also some small gas fields in Miocene sediments (Ždánice area) and small oil reservoirs in the crystalline basement (Ždánice, Lubná - Kostelany) there. In 2004, the Janovice gas structure (Miocene – tectonic trap) in the northern part of the Flysch Zone was reopened.

The fields Dambořice – Uhřice and Žarošice produced both together 267 thousand m^3 of oil in the year 2006, it is about 86 % of the cumulative oil production of the Czech Republic (311 th. m^3 in 2006). The main gas producing field (except CBM production from Upper Silesian Basin) is now the Kloboučky field located in Ždánice area, Carpathian Flysch Zone, with production about 20 millions m^3 in the year 2006 (cumulative national gas production including CBM in 2006 was 222 mill. m^3). Domestic production of crude oil and natural gas in the Czech Republic represents only 3 %, resp. 2 % of the domestic consumption (oil - 9,067 th. m^3, gas - 9,804 mill. m^3 in 2006; Czech Statistical Office, 2008).

5.2.2. EOR possibilities

The first EOR attempts (using various media) in the CR were performed in the 1960s and 1970s. The most important was the water-flooding into oil reservoirs of the Hrusky field. During the years 1964 – 1974 more then 1 million m^3 of water has been injected. The EOR effect has been calculated at about 12 %. Nowadays, the Dambořice – Uhřice oil & gas field is being transformed into a natural gas storage and natural gas injection helps to increase the oil production. Unfortunately, the domestic operator (MND) does not publish more detailed information.

Nevertheless, many of the partly depleted oil fields in the Vienna Basin and the Carpathian Flysch Zone are suitable for CO_2-EOR. Their operator shows interest in using this technology in future but, until now, no suitable source of CO_2 has been available.

5.2.3. Estimated storage capacity

For the calculation of the CO_2 storage capacity of oil and gas reservoirs, 6 major hydrocarbon fields were considered. 4 of them are situated in the Carpathian Flysch Zone (Lubná –Kostelany, Ždánice, Dambořice – Uhřice, Žarošice) while the 2 remaining belong to the Vienna Basin (Hrušky and Poddvorov). The size of other reservoirs is too small and their storage capacity can be regarded as negligible.

The storage capacity calculations were based on the volumetric approach. The basic assumption is that the theoretical capacity for CO_2 storage in hydrocarbon reservoirs equals to the volume previously occupied by the produced oil and gas (Gozalpour et al., 2005, Bachu et al., 2007). To determine this volume, the Ultimate

Tab. 5 – Selected aquifers of the Czech Republic and their basic parameters

Structure name	Stratigraphic unit	Lithology	Depth of structure top [m]	CO_2 storage capacity [Mt]
Kobeřice	Miocene	sandstone	1 300	43.1
Nosislav - Nikolčice	Miocene	sandstone	945	82.7
Vlasatice	Miocene	sandstone	930	4.3
Mušov	Miocene	sandstone	880	12.1
Iváň	Miocene	sandstone	825	81.6
Drnholec	Jurassic	limestone	880	5.3
Mikulov	Miocene	sandstone	1 005	31.0
Kobylí	Paleocene - Miocene	sandstone	1 100	317.5
Zdounky	Miocene	sandstone	1 115	17.1
Bařice	Miocene	sandstone	1 115	56.4
Vlkoš - Lobodice	Miocene	sandstone	800	270.6
Rusava	Miocene	sandstone	1 055	66.0
Kozlovice - Lhotka	Upper Carboniferous - Miocene	sandstone	815	48.9
Frýdlant nad Ostravicí	Upper Carboniferous - Miocene	sandstone	925	62.7
Vyšní Lhoty - Morávka	Upper Carboniferous - Miocene	sandstone	965	35.0
Koryčany	Miocene	sandstone	1 365	10.6
Osvětimany - Stupava	Miocene	sandstone	1 585	34.0
Žatec	Upper Carboniferous	sandstone (arcose)	950	450.0
Roudnice	Upper Carboniferous	sandstone (arcose)	830	872.0
Mnichovo Hradiště	Upper Carboniferous	sandstone (arcose)	1 100	274.0
Nová Paka	Upper Carboniferous	sandstone (arcose)	900	50.0
Police	Upper Carboniferous	sandstone (arcose)	1 200	38.0
Total				**2 862.9**

Tab. 6 – Major hydrocarbon fields of the Czech Republic and their basic parameters

Field name	Stratigraphic unit	Lithology	Depth [m]	Ultimate Recovery – oil [mill m^3]	Ultimate Recovery – gas [mill m^3]	CO_2 storage capacity [Mt]
Hrušky	Miocene – Badenian	sandstone	1 320	1.82	2 099	14.1
Poddvorov	Miocene – Sarmatian	sandstone	930	0.48	850	5.3
Lubná –Kostelany	Cambrian	granite	1 300	0.14	208	1.4
Ždánice	Cambrian & Miocene	granite, sandstone	750	0.76	628	4.1
Dambořice – Uhřice	Carboniferous & Jurassic	sandstone, carbonates	1 900	2.39	491	4.5
Žarošice	Jurassic	carbonates	1 680	0.84	453	3.3
Total				**6.43**	**4 729**	**32.7**

Recovery /UR/ figures (i.e. previous production + proven recoverable reserves), both for oil and for gas, were used. In the case of oil, the 1:1 ratio was used to convert the volume of UR oil into reservoir pore volume ready to store CO_2. In the case of natural gas, the Bg factor (ratio between gas volume under surface conditions and its volume under reservoir conditions) was used to calculate the original pore volume occupied by natural gas in the reservoir. The average value of Bg = 0.0095 (kindly recommended by RWE-Transgas, the domestic natural gas storage operator) was used for the calculations. To convert the calculated pore volume into CO_2 storage capacity, the average CO_2 density value of 630 kg/m^3 (corresponding to the typical pressure and temperature conditions of the reservoirs) was used for all structures.

The list and main parameters of the structures considered is shown in Table 6. The total storage capacity of the 6 major fields has been assessed at about 32.7 Mt CO_2. This means that hydrocarbon structures do not play a significant role as potential CO_2 storage site but, on the other hand, they represent an interesting potential from the EOR point of view.

The geographical distribution of the oil & gas fields considered is shown in Fig. 6.

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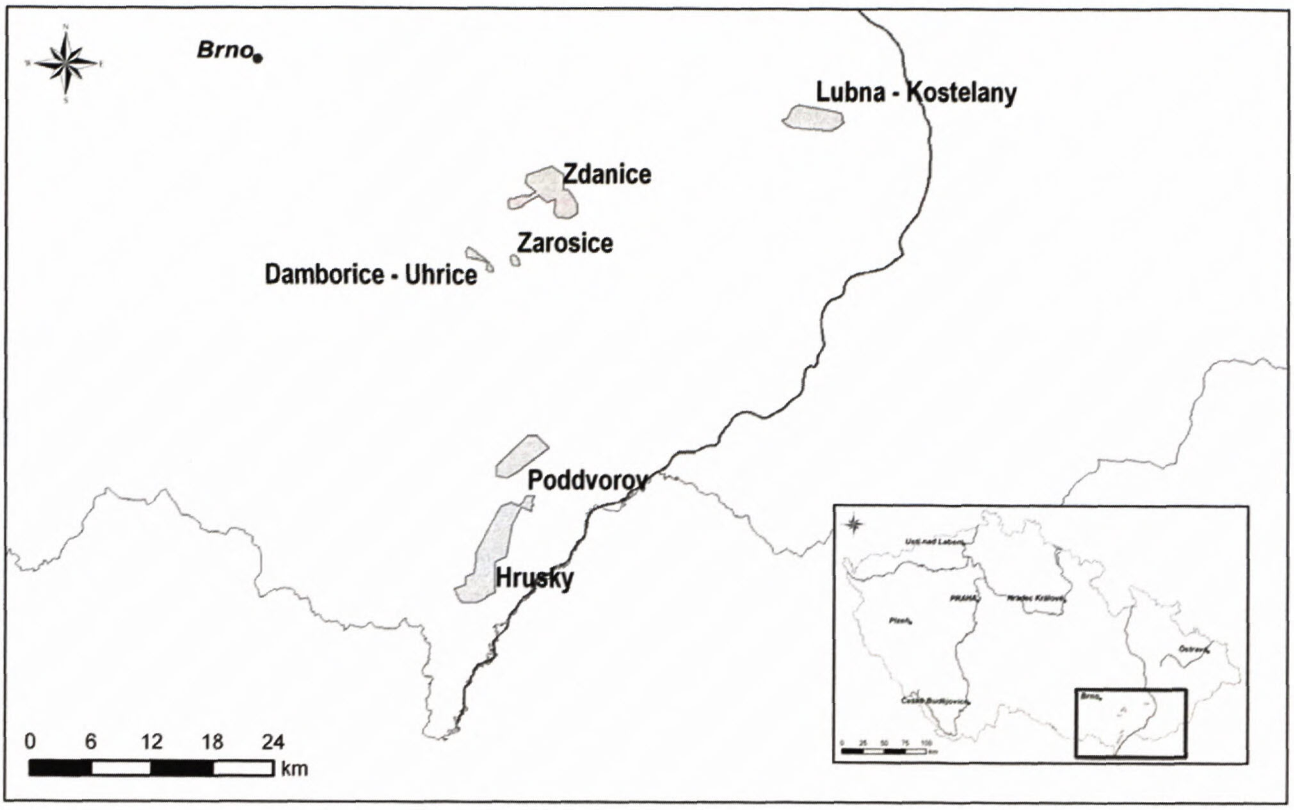

Fig. 7 Location of major hydrocarbon fields of the Czech Republic

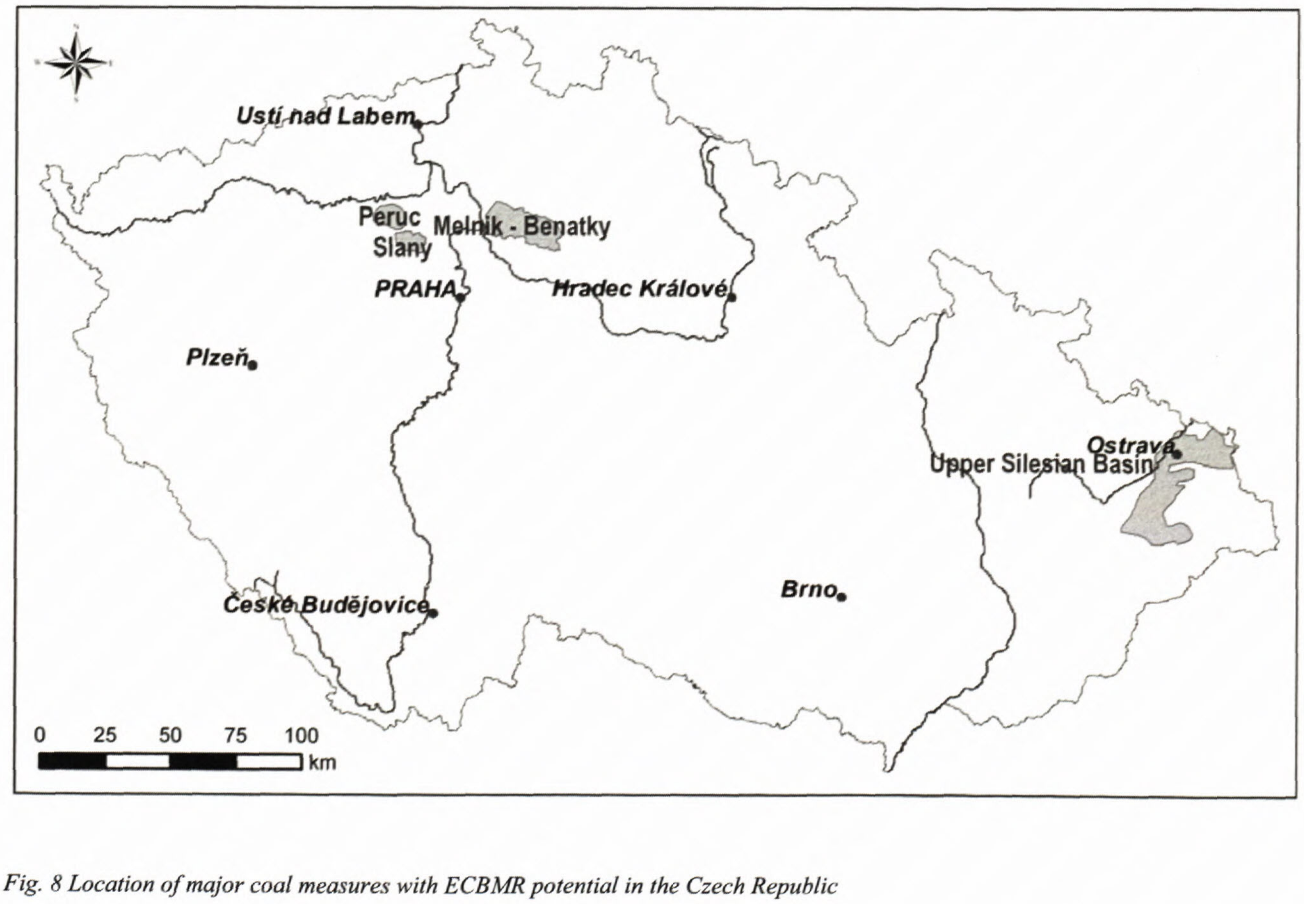

Fig. 8 Location of major coal measures with ECBMR potential in the Czech Republic

Tab. 7 Major coal measures with ECBMR potential in the Czech Republic and their basic parameters

Name	Stratigraphy	Depth of structure top [m]	Total PGIP* [mill. m^3]	CO_2 storage capacity [Mt]
Upper Silesian Basin	Carboniferous - Namurian	600	100 000	380,0
Slaný	Carboniferous – Westphalian C	900	1 778	6.8
Peruc	Carboniferous – Westphalian C	1200	2 840	10.8
Mělník - Benátky	Carboniferous – Westphalian C	600	2 670	10.1
Total				**407,7**

*PGIP = producible gas in place

5.3. Coal measures

History of coal mining in the CR is very rich but the majority of Czech pit coal collieries has been recently closed. At present, pit coal collieries are located in the Upper Silesian Basin only. For the purposes of CO_2 storage, however, the unmined pit coal measures are interesting, especially due to the enhanced coal bed methane recovery (ECBMR) possibilities. Such structures can be found in large parts of the Upper Silesian Basin and in Permian-Carboniferous Central Bohemian Basins (see Fig. 7).

Upper Silesian Basin (USB) is a large and complex paralic – limnic sedimentary structure stretching from NE part of Czechia far into Poland. In the northern part of the Czech portion of USB, extensive coal mining activity has been carried out while the southern and south-eastern parts (deeper and partly covered by Carpathian Flysch) remained unmined. Coal layers are of Namurian and Westphalian age; the overlying Miocene sediments as well as the Flysch nappes can be considered as seals. For the purposes of this study, the basin was handled as one structure. The estimation for the whole area of the Czech part of USB is at minimum 100 milliards (US billions) m^3 CBM (Durica et al, 2006). To be able to refine the first rough CO_2 storage capacity estimate and assess the ECBMR potential, it will be necessary to divide the basin into several parts according to geological conditions. This work is planned to be done within follow-up research projects.

The Central Bohemian structures (Slaný, Peruc, Mělník – Benátky) represent typical limnic coal basins. Substantial coal layers are of Westphalian age and the seal is composed of claystones (Westphalian to Stephanian sedimentation). All of these 3 structures were subject of geophysical and geological exploration in the 1970s and 1980s (e.g. Žbánek et al. 1978, 1988 & 1991). However, the plans to open new pit coal collieries in these areas have not become reality.

The storage volume calculations were based on the assessments of total producible gas in place (PGIP) that were made within the framework of coal bed methane studies between 1990 – 2003 (EPA report, 1992; Bódi et al., 1992; Hemza, 2000; Ďurica & Müller, 2003; Ďurica et al. 2006), using the formula:

$$Q = M * p * k * c$$

/where Q = PGIP (m^3), M = pure coal mass (t), p = real methane content (m^3 per tonne of coal), k = recovery factor, c = completion factor/. A simple exchange ratio 1:2/i.e. 1 molecule of CH_4 is replaced by 2 molecules of CO_2, suggested e.g. by van Bergen & Wildenborg (2002)/ and so called CO_2 normal condition density was used for the rough estimations of CO_2 storage capacities.

The list and main parameters of the structures considered are shown in Table 7. The total storage capacity of the selected unmined coal measures has been assessed at about 408 Mt CO_2. This volume represents an interesting storage potential, especially if the ECBMR possibilities are taken into account.

6. First estimate of country-wide storage capacity

Based on the results described in Chapter 5, the first rough estimate of CO_2 storage capacity in geological structures of the CR was made (see Tab. 8).

Compared with the CO_2 emission data (82 Mt/yr from stationary industrial point sources, see Tab. 3) and taking into account the 1.3 capture loss coefficient, the selected geological structures would hold all industrial CO_2 emissions of the country produced during 30.9 years (provided the emission level of 2005-7 will not change).

Tab. 8 Overview of CO_2 storage options in the Czech Republic

Structure type	Total CO_2 storage capacity [Mt]
Aquifers	2 862.9
Hydrocarbon fields	32.7
Coal measures	407,7
Total	**3 303.3**

7. Conclusions

Despite the fact that protection of the climate system of the Earth is a top-priority environmental issue in the Czech Republic, the public awareness of the CO_2 capture and storage (CCS) technology is generally low. Until now, the research pioneers (especially the Czech Geological Survey and a few others) were able to start building the awareness of CCS as a viable climate change mitigation option among environmental policy decision makers (Ministry of Environment, etc.) and the geological research community. This long-term effort is, however, at its beginning and much work has still to be done.

The first estimate of country-wide CO_2 storage capacity, compiled within this study, is one of the most important steps on this way. The calculated volume of ca. 3300 Mt CO_2 shows that geological structures are able to hold the entire volume of the CO_2 industrial emissions for more than 3 decades. Another positive conclusion of the study is that prospective storage structures could be found relatively close to the biggest CO_2 emission sources (e.g. aquifers of the Central Bohemian Basins, see chapter 5.1).

Aquifers represent an overwhelming majority (86.7 %) of the storage capacity but in some cases (especially in the Bohemian Massif) the level of knowledge of the structures is quite low and additional data would be needed before a CO_2 storage project might be started. The share of coal measures (12.3 %) and hydrocarbon fields (1.0 %) in the total storage capacity is quite low. These options, however, are interesting from the economical point of view because they might be connected with enhanced hydrocarbon recovery.

The Czech National Program to Abate the Climate Change Impacts in the Czech Republic declares ambitious emission reduction targets, exceeding the Kyoto protocol commitments - to reduce CO_2 emissions per capita by 30 % until 2020 compared to 2000, to reduce total aggregate CO_2 emissions by 25 % in 2020 compared to 2000 and to keep at the commenced trend to 2030. Considering these ambitions, it is clear that development and application of new advanced technologies, including CO_2 capture and geological storage, is inevitable. To prepare a reliable ground for political decisions, further research in the area of geological storage of CO_2 is needed, incl. selection of the most prospective sites, case studies and potentially a pilot project.

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