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EU GeoCapacity

Assessing European Capacity for Geological Storage of Carbon Dioxide

Instrument type: Specific Targeted Research Project

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D16
WP2 Report
Storage capacity

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Abstract

This document is deliverable D16 WP2 Report Storage Capacity and provides a description of the work carried out in WP2. It also provides a summary of capacity estimates for deep saline aquifers, hydrocarbon fields and coal beds for each country and brief descriptions of the methodology used and assumptions made. Geological descriptions and further details and background information for the storage capacity estimates in the GeoCapacity GIS database appear from the technical reports of WP2 and WP3.
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1 INTRODUCTION

The focus of the GeoCapacity project is GIS mapping of CO₂ point sources, infrastructure and geological storage in Europe. The main objective is to assess the European capacity for geological storage of CO₂ in deep saline aquifers, oil and gas structures and coal beds. Other priorities are further development of methods for capacity assessment, economic modelling and site selection as well as international cooperation, especially with China. The results of GeoCapacity include 25 countries and comprise most European sedimentary basins suitable for geological storage of CO₂.

The Work in GeoCapacity has been structured in 7 work packages:

- WP1: Inventory of emissions and infrastructure, GIS
- WP2: Storage capacity
- WP3: Economic use of CO₂
- WP4: Standards and site selection criteria
- WP5: Economic evaluations
- WP6: International cooperation
- WP7: Project management

This document is deliverable D16 WP2 Report Storage Capacity and provides a description of the work carried out in WP2. It also provides a summary of capacity estimates for deep saline aquifers, hydrocarbon fields and coal beds for each country and brief descriptions of the methodology used and assumptions made. Geological descriptions and further details and background information for the storage capacity estimates in the GeoCapacity GIS database appear from the following more technical reports:

- Deliverable D11/D12 Geological information and storage capacity of deep saline aquifers
- Deliverable D17 Assessment of the capacity for the use of CO2 in hydrocarbon fields
- Deliverable D18 Assessment of potential for CO2 usage in coal fields
- Deliverable D19 GeoCapacity economic use of CO2 in hydrocarbon fields
- Deliverable D20 Calculation of amount of CO2 that could be stored in coal beds

The participating countries have been divided into three geographical groups facilitating regional cooperation. The groups comprise new countries and countries previously participating in the CASTOR project and work initiated in CASTOR has been continued and further detailed in GeoCapacity. A fourth group consists of countries previously part of the GESTCO project and they have been updating, supplementing and detailing their country profiles in the GeoCapacity project. The groups are:

- NORTH EAST GROUP
  - Slovakia
  - Estonia
  - Latvia
  - Lithuania
  - Poland
  - Czech Republic
• CENTRAL EAST GROUP
  o Hungary
  o Romania
  o Bulgaria
  o Albania (covered by Greece)
  o FYROM (covered by Greece)

• SOUTH GROUP
  o Croatia
  o Spain
  o Italy
  o Slovenia
  o Bosnia-Herzegovina (Covered by Croatia)

• COUNTRY UPDATES
  o Germany (also covering Luxemburg)
  o The Netherlands
  o France
  o Greece
  o United Kingdom
  o Denmark

Thus, the GeoCapacity GIS is a comprehensive database of European storage capacity. However, the GIS do not necessarily represent all available storage capacity in each country. It rather represents the extent of work and level of detail which has been possible within the available economic frame of the project. On the other hand, not all storage capacity in the database may necessarily be equally exploitable. As a supplement to the capacity estimates in the database, we have therefore also provided more conservative estimates for each country in this report.

Norway and Belgium was part of the GESTCO project, but has not been updated in GeoCapacity. The data from the GESTCO project for these two countries has, however, been included in the GeoCapacity database and a conservative estimate has been estimated from the database values using the same ratio between database and conservative estimates as for Denmark.
2 WP 2.1 NORTH EAST GROUP

2.1 Slovakia

The Slovak Republic is located in the central part of Europe and from the initial view does not belong to the huge producers of carbon dioxide (40 Mt - 2005). Anyway due to structure of energy sector and composition of economic base, portion of CO₂ per capita reaches an average value from the European scale. The area extension is about 49 000 km², population amount is 5, 4 mil. inhabitants. The country's installed electric capacity amounted to 8.2 GW (2007), of which 40 % is generated from thermal electricity production, 30 % from hydro and 29 % from nuclear power. The energy sector can be considered a heavy polluter of the environment. The issue of ensuring energy supply whilst maintaining and protecting the environment is also on the agenda of the Slovak Republic. The Slovak Republic has signed (1999) and ratified (2002) the Kyoto Protocol to the UN Framework Convention on Climate Change, therefore committing itself to reduce its greenhouse gases GHG-emissions until 2012 by 8% as compared with the 1990 value. Currently the Slovak Republic is around 25 % below the GHG-emissions limits.

2.1.1 Maps of regional storage potential

A map of regional storage potential strictly depends at the geological pattern of The Slovak Republic area. This is variegated from both, time scale and diversity lithological sets. From the previous investigation was clear that in terms of nowadays knowledge the older geological units representing Hercynian orogenic stage are almost inconvenient for CO₂ storage. Therefore our attention has been turned at the younger units, originated during Alpine orogenic stage, especially at the sedimentary members of Miocene and older units, which take a part substantial volume within Inner Carpathians sedimentary basins during transpression regime and its transition to transtension at the end of collision. This is the event of the East Slovakian basin (Transcarpathian basin) and Vienna basin as well (Čverčko & Smetana, 1973, Csontos et al., 1992, Keith et al., 1994). Above mentioned basins are known with small hydrocarbons occurrences that are typically exhausted and therefore can serve as potential storage site. The largest and the deepest basin is the Danube basin and this is as thermal extensional one classified Vass et al., (1990). Besides of these a Miocene basin hidden beneath cover of volcano sedimentary complex of tertiary rocks (mostly andesites and its products) has been investigated in the central part of Slovakia, the locality Bzovík. In the framework of this stage of works, evaluation of all available data sets have been carried out with concentration at the geophysical maps (Kubeš et al., 2001) and cross sections, results of deep boreholes and looking for physical and chemical properties of rocks from hydrocarbon exploitation which could be as a potential storage site considered (Konečný et al., 1970, Polák, M., 1978, Panáček et al., 1993)

Unfortunately we have recognized that there are too many gaps in the relevant knowledge of studying environment that could be utilized for assessment of basic features of probable storage site.

2.1.2 Capacity estimation in aquifers

Unfortunately, as we mentioned before, the significant part of parameters needed for capacity calculation was derived from similar localities, literature sources or from theoretical assumptions. Boundaries of complexes in question and their depths and thicknesses were often assessing from geophysical methods interpretation (gravity, seismic). Theoretical capacity including large uneconomic maybe not so realistic volumes: regional estimates without storage efficiency. We are in the bottom part of resource-reserve pyramid.
For capacity calculation has been used the volumetric approach with using formula Brook et al. (2003):

\[ M = S \times h \times p \times F \]

Where

- \( M \) : calculated capacity
- \( S \) : area
- \( h \) : thickness
- \( p \) : porosity
- \( F \) : sweep coeff.

The most important was to assess value of sweep coefficient, because this item by decisive fashion can influence final results. Ambiguities in volume of aquifer, density of gas are not so “dangerous”; assessment of porosities is more decisive. For that reason we have utilized two ways calculation - an optimistic view with sweep coefficient 30% (The East Slovakian Basin 40% due to better level of knowledge), and the pessimistic approach with unified sweep coefficient with value 4%. The result of the negative approach is a total capacity of 1716 Mt and the result of the positive approach is a total capacity of 13708 Mt.

### 2.1.3 Capacity estimation in hydrocarbon fields

The main oil and gas reservoirs occur in Badenian and Sarmatian sands and sandstones in the Vienna Basin (Bílek, K., 1974) and the East Slovakian Neogene Basin (Rudinec, 1989). The most known and exploited gas bearings are also in mentioned Neogene Basins. In the Vienna Basin is exploited 30% of cumulative gas from Badenian, Sarmatian and Pannonian sands and sandstones. In the biggest deposits methane content reaches from 94.3 to 99.4%. In the East Slovakian Neogene Basin is exploited 70% of Slovak gas domestic production. Reservoirs are located mainly in the Badenian and Sarmatian clastic and volcano-clastic sediment formations. Methane content in the main exploited deposits reaches from 79.8 to 98.7%. Proven gas deposits in the Badenian, Sarmatian and partly also in Pannonian sands and sandstones in the Danube Basin are of minor economic importance because of the small reserves and poor quality of gas (big proportion of CO₂ and N₂).

Oil and gas Miocene accumulations in Vienna basin occur in the depth interval of 150–2000 m, the most favourable are Badenian, Sarmatian and Pannonian sedimentary formations. Reservoir rocks are sandstones and conglomerates (2–30 m, exceptionally up to 60 m thick). Porosity of sandy layers ranges from 10 to 29%, permeability from 50–250 mD. Clays and claystones are the seal rocks. The Vienna Basin is an area of rather low heat flow. An average geothermal gradient in the depth interval 0–3 km is 2.8–3.0° C/1000 m. Anomalous pressure layers (up to 100% higher than hydrostatic pressure) have been observed in the central part of the Vienna Basin.

The East Slovakian Neogene Basin (ESNB) is hot. Geothermal gradient reaches value of 3.7°C/100 m in the north-western part, and to 5°C/100 m in the central, southern and eastern parts of the basin. This basin is the area with the highest heat flow values in Slovakia (from 82 to 113 mWm⁻², mean heat flow is 103 mWm⁻²). Overpressures (up to 90% higher than hydrostatic pressure) have been observed in ESNB. Average porosity of sandstones ranges from 8 to 30%.
Facultative oil indications in Danube basin have been observed during boring in Sarmatian. A few gas deposits are mainly in Badenian and Sarmatian clastic formations (sands, sandstones and conglomerates). There are also some natural reservoirs of nearly pure CO₂ (ca 83%) and nitrogen (e.g. Sered deposit).

Capacity for storage was calculated according to methodology given in the deliverable 24. The results are as follows:

Table 2.1: Capacity in hydrocarbon fields.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Number of objects</th>
<th>Capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vienna basin</td>
<td>14</td>
<td>73.7</td>
</tr>
<tr>
<td>East Slovakian basin</td>
<td>9</td>
<td>49.9</td>
</tr>
<tr>
<td>Danube basin</td>
<td>13</td>
<td>9.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>36</strong></td>
<td><strong>133.5</strong></td>
</tr>
</tbody>
</table>

From the above mentioned table is obvious that for carbon dioxide storage purposes is Danube basin unsuitable due to overly small capacities of objects under study.

### 2.1.4 Capacity estimation in coal fields

Slovak Republic coal fields are not appropriate for CO₂ storage because of shallow depth of coal seams (generally 400 m below surface), complicated shapes as a result of intensive tectonic activity, complicated hydrogeological conditions, low rank of coalification. For that reasons we didn’t calculate CO₂ capacities of Slovak coal fields.

### 2.1.5 Case studies

#### Case study No. 1: Locality Bzovík, the Middle Slovakian Neovolcanics

The example of possible storage site, hidden beneath volcano sedimentary cover from the Slovak republic territory has been presented in this contribution. Even in the most pessimistic estimation storage capacity, this object could be sufficient for CO₂ storage and its lifetime could be about 20 years what is in concordance with contemporary relations. Nowadays does not being place in the world, where annual amount of stored CO₂ remarkably exceeds limit of 1 Mt. It is obvious, that this initial consideration can be changed, after carrying out targeted additional investigation.

This object is a typical example of structure which from the first, initial estimation can be as suitable storage site considered. Many important data are missing that is a reason, why the calculation volume was carried out by volumetric approach with the simple formula given by Brook et al., 2003. In the other words, it is useless to estimate unknown needed parameter, controlled by effort to achieve maximum precise result. There are many proves from practice, that real construction, or calculation is facilitated only in these cases, when tangible results from drilling, or other works are available.

Beside of this only physical trapping was assumed, even though is obvious that due to carbonate composition of reservoir rocks a chemical trapping certainly will play substantial role by potential storage of CO₂ namely in increasing storage site capacity.
Table 2.2: Calculated storage capacity for case study Bzovik.

<table>
<thead>
<tr>
<th>Capacity Bzovik</th>
<th>Area (10^6 m²)</th>
<th>Thickness (m)</th>
<th>Porosity</th>
<th>CO₂ density (t/m³)</th>
<th>Sweep coef.</th>
<th>CO₂ storage capacity (mt)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>The first calcul.</td>
<td>146</td>
<td>200</td>
<td>0.15</td>
<td>0.63</td>
<td>0.30</td>
<td>828</td>
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<td>Case study -var1</td>
<td>170</td>
<td>300</td>
<td>0.08</td>
<td>0.63</td>
<td>0.10</td>
<td>257</td>
<td></td>
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<tr>
<td>Case study -var2</td>
<td>200</td>
<td>300</td>
<td>0.05</td>
<td>0.70</td>
<td>0.08</td>
<td>168</td>
<td></td>
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<tr>
<td>Case study -var3</td>
<td>150</td>
<td>200</td>
<td>0.04</td>
<td>0.68</td>
<td>0.06</td>
<td>49</td>
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<tr>
<td>Case study -var4</td>
<td>120</td>
<td>150</td>
<td>0.03</td>
<td>0.65</td>
<td>0.04</td>
<td>14</td>
<td>59x less than the 1st</td>
</tr>
</tbody>
</table>

This object is a typical example of structure which from the first, initial estimation can be as suitable storage site considered. Many important data are missing that is a reason, why the calculation volume was carried out by volumetric approach with the simple formula given by Brook et al., 2003. In the other words, it is useless to estimate unknown needed parameter, controlled by effort to achieve maximum precise result. There are many proves from practice, that real construction, or calculation is facilitated only in these cases, when tangible results from drilling, or other works are available.

Beside of this only physical trapping was assumed, even though is obvious that due to carbonate composition of reservoir rocks a chemical trapping certainly will play substantial role by potential storage of CO₂ namely in increasing storage site capacity.

It is necessary to emphasize, that chemical trapping was not taken into account however is clear that due to carbonate content of reservoir can influence storage capacity in positive direction. The location of the area regarding population is suitable; on the other hand, big sources of CO₂ are not available in the nearby vicinity of this area. The main branch of gas pipeline is about 15 km to the South of this region. But in the radius about 100 km we can find several big producers from paper, aluminium industry, as well as exchange gas distribution, which overall annual CO₂ production exceeds value 1,5 Mt. Nevertheless on the trace of pipeline is the compressor station very close to discussed area, the Velke Zlievce which emitted to the air annually about 520 000 t of carbon dioxide. From this point of view the locality in question can be a good potential target for possible CO₂ storage, on condition, that supplementary tangible geological works will be realized.

_The Case study No. 2 - The East Slovakia - Two sources vs. three storage sites_

The case study is focused at The East Slovakia territory, which represents almost one third of Slovak republic, from extension point of view. There are the biggest CO₂ sources in this area. The total CO₂ emission of 11 biggest plants represents 14.63 Mt CO₂/year 2007. It is almost one half of total Slovak republic CO₂ emissions.

Easternmost source is heating power plant Vojany, with annual CO₂ production more than 2.6 Mt, second one is the gas compressor station (transit pipeline) Velke Kapusany with production
0.45 Mt. On the other hand, there is several geological CO₂ storage possibilities observed in this area. Selection was strong affected by the fact, that in a close vicinity of CO₂ sources are three recently exploited gas deposits (Senné, Stretava and Ptruška). The sources distances from gas deposits Senné and Stretava (on the North) are from 5 to 11 km. The distance of the south-eastern gas deposit Ptruška from both sources is 8 and 13 km. These are relations which offer very good prognosis for CO₂ storage from this side.

Stretava gas and gasoline deposit is situated in the environment of Pliocene, Early and Late Sarmathian and Badenian sedimentary layers. Migrated hydrocarbons originated some accumulations in the upper part of tectonically shaped elevation. Major gas accumulations are located in both: lithological and tectonical traps as well. The most productive horizons are in depths 1 100 to 1 300 m. The common lithology is represented by various types of claystones and sandstone. There were recognized of several gas and water bearing horizons, which can serve in the future as space for potential CO₂ storage.

Gas and gasoline deposit Senne is located eastward from deposit Stretava. The geological situation in this part of area is complicated. There is the package of 3 000 m thick complex of Neogene sedimentary rock overburdens Mesozoic and Palaeogene units. Neogene is build by sandy-clay rocks of Karpatian, Badenian, Sarmathian, Pliocene and Pannonian. Deposit was created in the framework of anticlinal structure, tectonically delimited by Močarany-Topľany faults system. Hydrocarbons are accumulated mainly in Stretava Late Sarmathian Formation. Gas is accumulated in 6 thicker and mass of thin sandstone layers in depth from 1295–2133 m.

Ptruška gas and gasoline deposit is situated in SE part of Potisia Lowland, close to Slovakian-Ukrainian border. From geologic point of view, this area is a part of East Slovakian Neogene Basin. Surface of crystalline basement rises towards to Ukrainian border Neogene are Middle Badenian volcanoclastic sediments, Early Badenian clays and sandstones (Lastomir Fm.), Late Sarmathian Stretava Fm. (sands, sandstones, conglomerates and volcanics), Early Sarmathian (Ptruška Fm. – clay, claystone, tuff, sand). Pliocene and Pannonian are clayey, with thin coal layers. Tectonic activity formed anticline structure suitable for accumulation of migrated hydrocarbons. Gas bearing structures are in lithologically most favourable sediments in Late and Early Sarmathian, where are 20 gas-bearing horizons in depth interval 1200–2200 m.

Estimated CO₂ storage capacity all three deposits is 33.9 Mt of CO₂ (see Table 2.3).

Table 2.3: Estimated CO₂ storage capacity for all three ESNB deposits included in case study.

<table>
<thead>
<tr>
<th>Name of deposit</th>
<th>Main content</th>
<th>Avg, depth (m)</th>
<th>Stratigraphic unit</th>
<th>Lithology</th>
<th>Total estimated CO₂ storage capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretava</td>
<td>Gas</td>
<td>1200</td>
<td>Badenian, Sarmathian</td>
<td>claystone, sandstone, tuffites, conglomerates</td>
<td>14.5</td>
</tr>
<tr>
<td>Senne</td>
<td>Gas</td>
<td>1900</td>
<td>Late Badenian, Early Sarmathian, Late Sarmathian</td>
<td>claystone, sandstone, tuffites, conglomerates</td>
<td>15.2</td>
</tr>
<tr>
<td>Ptruksa</td>
<td>Gas</td>
<td>1805</td>
<td>Early Sarmathian, Late Sarmathian</td>
<td>claystone, sandstone, clay, tuffites, conglomerates</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>Total estimated storage capacity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>33.9</strong></td>
</tr>
</tbody>
</table>
As we mentioned before, total CO₂ production from both sources - Heating Power plant Vojany and Compressor Station-Branch 01 Velke Kapusany is 3.11 Mt CO₂ per year. Distance of both sources from deposits is from ca 3–13 km, what seemed to be very favourable. We suppose that part of CO₂ separated from emissions could be transported by existing pipelines to close deposits and injected into underground structures. CO₂ could be used as a medium in secondary enhancement of deposits recovery. (EGR). On the other hand, we have to realize, that Nafta a.s. has not activities like this in its program for the middle period. Anyway, in our opinion injection to three separate deposits could be more effective than into only one. Theoretically, when injected 1 Mt of CO₂ (like in Sleipner), deposits will be served as storage site full 30 years (if we neglected degree of recovery, water flooding...and so on).

2.1.6 Country summary

In the database is included big CO₂ producers with annual emissions more than 100 kt of this gas. The total annual emissions from large point sources are 22.77 Mt. This volume is valid for the period 2005–2007. The dominant producer is US STEEL Košice, s.r.o., where is hidden beside of iron and steel production a huge thermal power plant with installed output about 950 MW. Following producers are from the sector of energy production, refinery, gas transmission stations, cement mills and many heating plants. The amount 32 big sources produces almost 68 % overall annual Slovakian production.

Mutual geographical position of majority big sources and suitable geological structures for carbon dioxide storage is quite consistent what permits serious consideration about concrete storage sites evaluation. This is valid in the western and the eastern part of the region mainly. The sources situated in the northern part Slovakia are exception.

A storage sites classification according to perspective (from the low to the high degree) is as follows:

- Coal fields – this entity has been excluded from our consideration due to geological and technical problems:
  - Very complicated hydro-geological situations practically in all coal deposits. Water horizon is common in productive beds besides; there are frequent water outbreaks in exploited mines and occurrence of shifting sands. The all abandoned coal mines are perhaps flooded in this time.
  - the depths of coal horizons are very shallow and usually situated in the environment of heavy populated areas
  - Coal is developed in the young, Tertiary sedimentary basins with very complicated tectonic situation and broken by numerous faults. Coal is in low coalification stage, what moreover reduces storage capacity because of lower absorption of such types of coal.
- Hydrocarbon fields, the available data are the most credible, but relatively small volumes of reservoirs are suitable only for small local sources for prospective CO₂ storage.
- Aquifers, this group of suitable objects is characterized by the same features as in the majority other European countries; huge capacity and lack of reliable data. From this point of view the calculation is only from the bottom part of pyramid.
Table 2.4: CO₂ emissions and storage capacity estimates in Slovak Republic.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s) 2007 (Mt)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2005</td>
<td>23</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2005</td>
<td>46</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Theoretical</td>
<td>1716</td>
<td>13708</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Theoretical</td>
<td>-</td>
<td>134</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total storage capacity estimate</strong></td>
<td></td>
<td>1716</td>
<td>13842</td>
</tr>
</tbody>
</table>
Figure 2.1: Map of CO₂ emissions, infrastructure and storage capacity in Slovakia.
2.2 Estonia

2.2.1 Maps of regional storage potential
Estonia has no regional storage potential, explained by shallow sedimentary basin, absence of hydrocarbon and coal fields and low salinity of the aquifers, containing fresh water and somewhere mineral water up to 19–20 g/l, classified as brackish water.

2.2.2 Geological description, aquifers
Estonia lies on the southern slope of the Baltic shield, consisting of strongly metamorphosed Precambrian crystalline basement. The basement is unconformably overlain by a condensed (<800 m) Ediacaran and Lower Palaeozoic sedimentary cover represented by Cambrian, Ordovician, Silurian and Devonian rocks (Figure 2.2). The dominant structure in the basin is the Estonian Homocline which dips gently southwards at about 6 to 18 degree, decreasing in thickness from c.100 m in northern Estonia to some 500 m in the southern Estonia and reaches 784 m on the small south-western island of Ruhnu. In south-western Estonia the boundary between the Estonian Homocline and Baltic Synclise is indistinct, coinciding roughly with the -550 m contour line on top of the basement. In the southeast, the Estonian Homocline borders on the Võru Saddle. The Valmiera-Lokno Uplift in the Estonian-Latvian border zone is 20 to 30 km wide and 200 km long. It comprises the Valmiera and Smiltene (both in Latvia), Mõniste and Haanja (in Estonia), and Lokno (in Russia) uplifts. The Estonian Homocline is complicated by major and minor linear disturbances and fracture zones (Figure 2.2). Most of the flexures have low amplitude (<50 m) and correspond to the faults in the crystalline basement. A few similar structures in the central part of the Baltic Synclise (Latvia) show displacement of the basement surface up to 600 m (Suveizdis, 1979). The sedimentary cover is composed of siliciclastic (Ediacaran and Cambrian) and variously argillaceous carbonate rocks (Ordovician and Silurian). Mainly siliciclastic Devonian rocks with dolomitized carbonate interlayers occur only in southern Estonia (Figure 2.3).

Siliciclastic and carbonate Palaeozoic and Ediacaran rocks form porous, fissured and karstified mostly confined aquifers (Devonian, Silurian–Ordovician, Ordovician–Cambrian and Cambrian–Ediacaran), isolated from each other by regional aquitards (seals). The water from all these aquifers is used in Estonia for the water supply. At the southern Estonia mainly Devonian aquifers are applied (Perens & Valner, 1997). Usually average mineral content of the drinking water is about 0.3–0.4 g/l. The mineral water used for the bottling and marketing usually has mineral content of 2–3 g/l. The highest mineral content in the mineral waters found in the deep aquifers in the southern (575–595 m depth) and south-western Estonia (707–784 m depth in Ruhnu Island) is 15–19 g/l (Karise, 1997).

Owing to shallow sedimentary basin, low mineral content of the drinking water, absence of hydrocarbon and gas fields Estonia does not have CO₂ storage potential.
Figure 2.2: The top of the Precambrian basement (bottom of the sedimentary basin) is marked by contours. Flexures above the basement fault are indicated by yellow lines. Deep boreholes penetrating the crystalline basin are denoted by black circles. The section line (Figure 2.3) is shown by green.

Figure 2.3: The section along Valga-Letipea line is modified after Puura & Vaher, 1997. ♦ – seismic shot point, Q – Quaternary, D – Devonian, O – Ordovician, C – Cambrian, V – Vendian, PR – Palaeoproterozoic basement.

2.2.3 Capacity estimation in aquifers

Estonia has zero capacity potential in aquifers.
2.2.4 Capacity estimation in hydrocarbon fields
Estonia has no hydrocarbon fields and thereafter no potential in hydrocarbon fields.

2.2.5 Capacity estimation in coal fields
Estonia has no coal fields. Estonia has oil shale fields and mines. Their maximum depth is 30–65 m. Therefore oil shale mines could not be used for CO₂ storage.

2.2.6 Case studies
The Estonian-Latvian case study is only one crossing national borders study in EU GeoCapacity project. The CO₂ storage potential in Estonia is limited by a lack of hydrocarbon fields and favourable saline aquifers, whereas the potential for CO₂ storage in Latvia is greater. The viability of such a case is proved by successful application in the Latvian Inčukalns Underground Natural Gas Storage over the last 40 years, providing Estonia with natural gas when necessary.

The Estonian-Latvian case study is only one crossing national borders study in EU GeoCapacity project. The CO₂ storage potential in Estonia is limited by a lack of hydrocarbon fields and favourable saline aquifers, whereas the potential for CO₂ storage in Latvia is greater. The viability of such a case is proved by successful application in the Latvian Inčukalns Underground Natural Gas Storage over the last 40 years, providing Estonia with natural gas when necessary.

16 anticlinal structures in Cambrian aquifer were estimated as prospective for CO₂ storage in Latvia. Two anticlinal structures in Latvia Luku-Duku and South Kandava are offered for the case study by LEGMA. The top of the Cambrian aquifer is located at the depth of 1024–1053 m. Reservoir thickness in the structures is 28–45 m. The area of the reservoirs is 50 and 69 km². CO₂ capacity of the structures is 40.2 and 44 Mt of CO₂ (value in GeoCapacity database). Their total minimal capacity in Cambrian aquifer is about 84 Mt of CO₂. This will be enough for 8–10 years for storage of CO₂ emissions from the Eesti and Balti Power Stations.

CO₂ pipelines could be constructed along the available natural gas pipelines connecting Estonia and Latvia. The total distance to the structures using pipelines is about 650–800 km. Long distance factor and possible high price of using private land in Latvia can increase price of CO₂ storage making it uneconomic. Public acceptance in both countries is another critical factor for project implementation.
2.2.7 Country summary

In Table 2.5 below is given a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions). Storage capacity in aquifers and hydrocarbon in Estonia is equal to zero. Figure 2.5 show the data for Estonia included in the GeoCapacity database.

Only 9 sources of big CO₂ emissions (>100000 t/year) were registered in European Emission Trading Scheme (ETS) in 2005. These sources are situated at the north (near Tallinn) and northeast of Estonia (Figure 2.5) and produced altogether 11.5 Mt CO₂, that is 91% of the all emissions produced in Estonia by 42 enterprises registered in ETS, and 55% of total Estonian CO₂ emissions (20.9 Mt). The large emissions were produced mainly by power plants located close to the Estonian oil-shale deposit (north-eastern Estonia). All the large emissions and main part of the smaller emissions are produced in Energy Sector mainly using oil shale combustion. Power industry contributes 92% of the large emissions, 6% was produced by cement industry and 2% by chemical industry. The two largest Estonian power stations “Eesti” and “Balti” produced respectively 7.7 and 2.25 Mt of CO₂ in 2005, which is together 9.95 Mt of CO₂ (87% of the large industrial emissions in Estonia).

Table 2.5: CO₂ emissions and storage capacity estimates in Estonia.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2005</td>
<td>12</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2005</td>
<td>21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 2.5: Map of CO₂ emissions and infrastructure in Estonia and storage capacity in Latvia. Estonia does not have storage capacity on own territory, therefore only storage capacity in the neighbouring Latvia could be applied for storage of Estonian CO₂ emissions.
2.3 Latvia

2.3.1 Maps of regional storage potential

Only local structures in the Cambrian water-saturated sandstone are prospective for the establishment of CO2 storages. In one of such geological structures, an underground storage of natural gas was established already in 1968, the Inčukalns gas storage.

The main criteria for the determination of prospective objects are as follows: the existence of a local high identified based on the seismic data, the size and depth of the trap, reservoir properties and existence of reliable caprock. Based on those criteria, the prospective structures suitable for the establishment of underground storages of CO2 are as follows: Dobele, North Blidene, Blidene, Snepele, South Kandava, Degole, Luku-Duku, Kalvene, Vergale, Edole, North Kuldiga, Viesatu, Aizpute, Usma, Liepaja and North Ligatne (Figure 2.6).

The following structures were identified as belonging to the first group of prospective objects: Kaltene, Luku-Duku, N. Blidene, Blidene, Dobele and N. Ligatne. They are situated within the tectonically dislocated Saldus-Sloka-Inčukalns high and are represented by near-fault brachyanticline folds. Their area comprises 14–50 km², the amplitude exceeds 55–80 m; the effective thickness of the reservoir exceeds 30 m. The depth of the Cambrian reservoir in the Kaltene, Luku-Duku, N. Blidene and Dobele areas reaches ÷950–1050 m, while that of the N. Ligatne area - approximately 700 m.

Figure 2.6: Location of CO₂ sources over 100 000 t/ year (2005) emissions and anticlinal structures prospective for CO₂ storage in Latvia.

The second group is situated in the Western Latvia and is associated with the Liepaja-Kuldiga-Talsi high. The Snepele, Vergale, N. Kuldiga, Edole, Usma, Liepaja and Aizpute structures identified there are also represented by near-fault brachyanticlines. Their thickness varies from
10 km² to 26 km², the amplitude from 25 to 60 m, while the effective thickness exceeds 30 m. The depth of the reservoir within those structures varies from ±950 m to ±1050 m.

The third one was identified in the Central Latvia: Degole, Viesatu and S. Kandava structures. The Degole structure is represented by an asymmetrical brachyanticline folds without faulting. Viesatu structure is represented by a near-fault brachyanticline folds. The southern and northern flanks of the S. Kandava structure are complicated by faults. The area of those structures comprises 14–20 km², the amplitude ±50–70 m, the thickness of the reservoir varies from 25 m at the S. Kandava structure to 50–55 m at the Degole and Viesatu structures. The depth of the reservoir varies from 1000 to 1050 m.

2.3.2 Geological description, aquifers

Sandstone of the Cambrian aquifer is prospective for the storage of CO₂. The thickest reservoir in the Cambrian section occurs in Western and Central Latvia, corresponding to the Deimena Formation and Cirma strata (only N. Ligatne and Incukalns areas).

As regards the depth of occurrence and structural features, the Latvian territory is subdivided into three regions. In the Western and Central Latvia, within the Caledonian complex, faults, plicated and disjunctive deformations are widespread. The depth of the Cambrian reservoir there varies from 700 m in Central Latvia to 1700 m in SW Latvia. All the anticlinal structures, which are prospective for the establishment of CO₂ storages, are situated there.

NE Latvia is rather extensively dislocated, but the Cambrian reservoir lies at the depth 300–700 m there. Besides, the water-resisting properties of the Ordovician caprock considerably deteriorate in that direction; the thickness of the Cambrian reservoir is much smaller.

In Eastern Latvia, within the Latvian Saddle, the depth of the occurrence of the Cambrian deposits decreases from 900–800 m to 400 m. Besides, contrasting local highs are practically absent within the Latvian Saddle.

The Deimena Formation and Cirma strata are represented by sandstone, siltstone and clay. Sandstone prevails in the section, comprising up to 75–90%. Siltstone and clay comprise 10–30%; their thickness varies from 0.2 to 3–4 m, infrequently reaching 10 m. The sandstone is light grey and white, quartzose, fine-grained. The clastic skeleton of the sandstone is well sorted and comprises more than 90% of the deposits. Among the clastic material, quartz prevails (95–99%); the rest is represented by pelitised potassium feldspar, muscovite and biotite. The cement of the sandstone is clayey and quartzose-regeneration. In its top part, the cement is frequently kaolinitic, secondary carbonatic, infrequently gypsum-bearing. The Cambrian sandstone is weakly or medium cemented and is characterised by good filtering and volume properties. In most of the Latvian territory, the average effective porosity of the sandstone comprises 20–25%, while permeability reaches hundreds and thousands mD, mineralization of groundwater up to 120 g/l; water temperature 11°–25°. The depth is over 600 m in central Latvia, up to 1,100 m in western Latvia.

2.3.3 Capacity estimation in aquifers

The assessment of CO₂ storage capacity in deep saline aquifers in the Latvia is based on evaluation of 16 individual structural traps. The capacity estimates in the GeoCapacity database
for all 16 structures have been calculated according to the methodology described for deep saline aquifers in the GeoCapacity deliverable D24 “Storage capacity standards”, using the formula:

\[ M_{CO2t} = A \times h \times NG \times \phi \times \rho_{CO2r} \times S_{eff} \]

where:

- \( M_{CO2t} \): “trap” storage capacity
- \( A \): area of aquifer in trap
- \( h \): average height of aquifer in trap
- \( NG \): average net to gross ratio of aquifer in trap (best estimate)
- \( \phi \): average reservoir porosity of aquifer in trap (best estimate)
- \( \rho_{CO2r} \): \( CO_2 \) density at reservoir conditions (best estimate)
- \( S_{eff} \): storage efficiency factor (for trap volume)

The area of the structures was determined on the base of contour maps at the top of the reservoir formation. Thickness, porosity and net/gross were evaluated using data from exploration wells drilled (based on log data interpretation) on the structure or extrapolating information from wells on nearby structures. The \( CO_2 \) density varies with depth as a function of pressure and temperature.

Based on the “rule-of-thumb approach” described for open and semi-closed aquifers in GeoCapacity deliverable D24 Storage capacity standards, a storage efficiency factor of 40 % has been assumed corresponding to open high quality reservoirs.

Table 2.6 shows the results of the evaluation of trap volumes, as well as the theoretical, optimal and conservative estimates of the \( CO_2 \) volumes.

Table 2.6: Storage capacity estimation for local structures in Latvia.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Reservoir volume (by the closing isohypse) ((10^6 m^3))</th>
<th>Theoretical capacity ((Mt))</th>
<th>Capacity (optimistic values) ((Mt))</th>
<th>Capacity (conservative values) ((Mt))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aizpute</td>
<td>587</td>
<td>72.8</td>
<td>31</td>
<td>14</td>
</tr>
<tr>
<td>Bildene</td>
<td>2091</td>
<td>259.3</td>
<td>112</td>
<td>58</td>
</tr>
<tr>
<td>N.Blidene</td>
<td>2655</td>
<td>329.2</td>
<td>142</td>
<td>74</td>
</tr>
<tr>
<td>Degole</td>
<td>782</td>
<td>97.0</td>
<td>41</td>
<td>21</td>
</tr>
<tr>
<td>Dobele</td>
<td>2000</td>
<td>248.0</td>
<td>105</td>
<td>56</td>
</tr>
<tr>
<td>Edole</td>
<td>283</td>
<td>35.1</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>Kalvene</td>
<td>525</td>
<td>65.0</td>
<td>27</td>
<td>14</td>
</tr>
<tr>
<td>Liepaja</td>
<td>660.0</td>
<td>73.0</td>
<td>31</td>
<td>6</td>
</tr>
<tr>
<td>Luku-Duku</td>
<td>1440</td>
<td>179.0</td>
<td>75</td>
<td>40</td>
</tr>
<tr>
<td>N. Kuldiga</td>
<td>490</td>
<td>61.0</td>
<td>21</td>
<td>13</td>
</tr>
<tr>
<td>N. Ligatne</td>
<td>810</td>
<td>100.4</td>
<td>41</td>
<td>23</td>
</tr>
<tr>
<td>S.Kandava</td>
<td>1573</td>
<td>195.1</td>
<td>82</td>
<td>44</td>
</tr>
<tr>
<td>Snepele</td>
<td>602</td>
<td>74.6</td>
<td>31</td>
<td>17</td>
</tr>
<tr>
<td>Usma</td>
<td>180</td>
<td>9.0</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Vergale</td>
<td>194</td>
<td>24.1</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Viesatu</td>
<td>424</td>
<td>52.6</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>1875.2</td>
<td>790</td>
<td>404</td>
<td></td>
</tr>
</tbody>
</table>
2.3.4 Capacity estimation in hydrocarbon fields

There are no hydrocarbon fields prospective for CO₂ storage in Latvia.

A small oil deposit was discovered in 1963 in Western Latvia (Kuldīga area). The oil pool is associated with the top Cambrian sandstone. The minimum reserves are evaluated as 0.08 million cu. m, the maximum 0.31 million cu. m. There has been no evaluation of the volume of possible oil storage of CO₂ within the Kuldīga deposit. There are no hydrocarbon fields prospective for CO₂ storage in Latvia onshore. However, more than 10 anticlinal structures were identified in the Latvian offshore area, which are prospective for oil exploration. That is why the establishment of CO₂ storages in the oil fields under development is a possibility for the future.

2.3.5 Capacity estimation in coal fields

There are no hydrocarbon fields prospective for CO₂ storage in Latvia.

2.3.6 Case studies

Six CO₂ sources with the emissions exceeding 0.1 Mt per year existed in Latvia in 2005. The total emissions from those sources comprise 4.09 Mt. It should be mentioned that the Latvian government is considering the possibility of the construction of a new power plant in Western Latvia, which would use coal as fuel, where, based on the data from JSC “Latvenergo”, the CO₂ emissions would exceed 2 Mt per year. However, as regards the planned power plant, there is no design data for the evaluation of the efficiency of construction of a CO₂. That is why the object SJSC “Latvenergo, TEC-2” was selected for a case study (Figure 2.1). That object is the biggest source of CO₂ emissions in Latvia, 0.79 Mt per year.

Subsidiary of SJSC “Latvenergo” “Rigas Termoelektrostacija” TEC-2 is the biggest combined heat and power plant in Latvia. During the period of 1973–1992 four water heaters were launched, but in 1975–1979 there were put into operation four steam boilers and four steam turbines. Riga TEC-2 electric capacity is 330 MWel, but heating capacity – 1148 MWth. After the completion of Riga TEC-2 reconstruction in 2008, it has become the most modern combined heat and power plant in the Baltic region, enhancing the power independence of Latvia and efficiency and effectiveness of electricity generation to the maximum. After the reconstruction electricity generation in the cogeneration regime will increase from average 820 GWh/ p.a. to about 2200 GWh/p.a., thus supplying Latvia with additional 1400 GWh/p.a.

Anticipated activity description: the second stage of reconstruction of Riga TEC-2 includes the installation of the second combined cycle gas turbine (gas turbine, boiler, steam turbine), as well as construction of the gas compressor station, the water cooling system, various wastewater pump stations, the fire fighting pump station and other facilities. The anticipated electrical capacity is about 400 MWel and heat capacity, about 260 MWel. The basic fuel for electricity and heat generation is natural gas and reserve (emergency) fuel, heavy fuel oil [http://www.latvenergo.lv].

Three anticline structures - Dobele and Blidene/N.Blidene are considered potential storages. The locations of those structures are advantageous for the use as CO2 storages because of their proximity to pipelines. As regards the Dobele structure, high level of knowledge regarding it is a positive aspect. Twenty wells were drilled at that structure, which allows to evaluate the storage volume quite accurately and to eliminate drilling costs. The low level of knowledge regarding the Blidene and N.Blidene structures is a negative aspect.
Dobele structure

The Dobele structure situated in central Latvia, up 75 km to the west of the Riga city, where the CO₂ source – “TEC” – 2 is located. The Dobele local high is a well-expressed brachyanticlinal fold of the Caledonian structural complex, the southern flank of which is adjacent to a fault with the amplitude 300 m. The Cambrian reservoir is shielded by the clayey-carbonate Silurian deposits in the fault zone. The Silurian deposits are quite tight and would ensure the tightness of the reservoir within the structural trap. The hypsometrically closed area of the structure for the top of the Cambrian reservoir within the 1,070 m MSL contour line comprises 67 km², the height (amplitude) is almost 120 m (Figure 2.2). The top part of the Cambrian succession (the Deimena Formation) is considered a potential storage. Compared to the rest (Lower) Cambrian, it is characterised by a more uniform, predominantly sandstone, composition and better capacity-filtering properties. The top of the reservoir of the Dobele local high lies at the depth of 950 m MSL in the dome of the structure, and at up to 1,070 m MSL at the periphery of the flanks. The effective thickness of the reservoir is 52 m, the effective porosity is 22%, and the permeability varies from a few tens to hundreds mD, reaching 1000–1500 mD in some cores.

The Dobele structure situated at the distance of 80 km from “Rigas Termoelektrostacija” TEC-2. „Rigas Termoelektrostacija” TEC-2 is connected with the Dobele structure via an existing gas pipeline. The length of the gas pipeline is 110 km. The distance between the Dobele structure and the gas pipeline is 8 km. „Rigas Termoelektrostacija” TEC-2 produced 0.79 Mt CO₂. The minimum volume in the Cambrian aquifer at the Dobele structure is evaluated at 56 Mt (value in GeoCapacity database).
Figure 2.2: Dobele structure.

**Blidene and North Blidene structures**

The North Blidene and Blidene structures are situated in western Latvia, up 89 km to the west from the CO\(_2\) source – TEC-2. The top of the reservoir within the N. Blidene structure occurs at the depth 950–1050 m (Figure 2.3). Its total thickness varies from 45 m at the dome of the high to 53 m in the periclinal zone, the effective thickness, from 37 to 41 m. The average open porosity of the sandstone comprises 21%, based on the results of log interpretation; the permeability reaches 370–400 mD. The top reservoir of the Blidene structure occurs at the depth 1050–1150 m. The total thickness is equal to 66 m, the effective thickness 60 m. The average open porosity of the sandstone comprises 20%, based on the results of log interpretation; the permeability reaches 860 mD. The aquifer contains confined groundwater with the salinity 100–114 g/l. The well yield comprises about 100 m\(^3\)/day. The hydrostatic reservoir pressure is 100–115 atmospheres; the reservoir temperature is 18º–20ºС.

The structures N. Blidene and Blidene are considered a single object for the purpose of the establishment of a CO\(_2\) storage. The conservative volume in the Cambrian aquifer at the Blidene object at 132 Mt (N. Blidene – 74 Mt and Blidene – 58 Mt). “Rigas Termoelektrostacija” TEC-2 is connected with the Blidene structures by a trunk gas pipeline. The length of the gas pipeline is 125 km.
Figure 2.3: Blidene and North Blidene structures.
2.3.7  **Country summary**

In Table 2.7 below is given a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions). Only 6 sources of big CO₂ emissions (>100000 t/year) were registered in European Emission Trading Scheme in 2005. The bulk of CO₂ emissions come from the energy sector over 77%, 10% was produced by cement industry and 9% by metalworking industry.

At this moment, 16 local structures are considered as the best prospective objects, which are prospective for the storage of CO₂. The total volume of CO₂ (in 16 traps) could reach 404 Mt (Conservative estimate). Figure 2.7 shows the data for the Latvian Republic included in the GeoCapacity database.

Table 2.7: CO₂ emissions and storage capacity estimates in Latvia.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2005</td>
<td>2</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2005</td>
<td>4</td>
</tr>
<tr>
<td>CO₂ storage capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage capacity in aquifers</td>
<td></td>
<td>Effective</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>404</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Effective</td>
<td>404</td>
<td>404</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>404</td>
<td>404</td>
</tr>
</tbody>
</table>
Figure 2.7: Map of CO₂ emissions, infrastructure and storage capacity in Latvia.
2.4 Lithuania

2.4.1 Maps of regional storage potential

Lithuania is situated in the eastern part of the Baltic sedimentary basin that overlies the western margin of the East European Craton (Figure 2.9 and Figure 2.10). The sedimentary pile contains Vendian and all Phanerozoic systems (Figure 2.11). The thickness of the sedimentary cover is 200 m in southeast Lithuania, increasing to 2300 m in west Lithuania.

A number of aquifer layers are identified in the sedimentary cover of the Baltic sedimentary basin. However, only saline aquifers that are not used for the drinking water supply or agricultural irrigation purposes are considered prospective for the CO₂ storage. Moreover, they should be deep enough (about 800 m depth) for CO₂ to reach the supercritical state. Only two aquifers meet those requirements in Lithuania. The Pärnu-Kemeri aquifer of the Lower–lower Middle Devonian age and the Cambrian aquifer are buried to the depths exceeding 800 m in the central and western parts of the Baltic basin (Figure 2.10). They contain high-saline formation water and are not used for the water supply.

Figure 2.8: Depths of the Baltic sedimentary basin. The lines of geological cross-sections A and B are indicated (see Figure 2.9 and Figure 2.10).
Figure 2.9: Geological cross section A. Major deep saline aquifers are shown in blue.

Figure 2.10: Geological cross-section B.

Figure 2.11: The depths and thickness of Cambrian and Lower Devonian aquifers. Pink line marks the area of the supercritical state of CO₂.
Figure 2.12: An example of application of GIS tools for calculating the theoretical storage capacity of Cambrian reservoir. The thickness (upper left), net-to-gross (upper right), and porosity (lower left) are used to calculate the theoretical capacity of the aquifer.

The Cambrian reservoir matches the P-T conditions in western half of Lithuania, whereas only the westernmost part of Lithuania contains the Lower Devonian aquifer deep enough for CO₂ injection and storage (Figure 2.11).

The regional storage capacity of aquifers was assessed:

\[ M_{\text{CO}_2b} = A \times h \times \text{NG} \times \varphi \times \rho_{\text{CO}_2r} \times S_{\text{eff}} \]

Where

- \( M_{\text{CO}_2b} \): regional “bulk” storage capacity
- \( A \): area of regional aquifer that matches P-T conditions for CO₂ storage (m²)
- \( h \): thickness of regional aquifer; \( \text{NG} \): net to gross ratio of regional aquifer
- \( \varphi \): reservoir porosity of regional aquifer
- \( \rho_{\text{CO}_2r} \): CO₂ density at reservoir conditions
- \( S_{\text{eff}} \): storage efficiency factor (0.35 assumed for both reservoirs).

Due to a number of parameters involved that are varying across the basin, the GIS tools (MapInfo Professional) were applied to calculate the theoretical capacity in Lithuania (Figure 2.12).

The theoretical regional storage capacity of CO₂ for the Cambrian aquifer is as large as 17 Gt, and the Lower Devonian can theoretically store 13.7 Gt (Figure 2.13). These are huge numbers that characterise basically the volumetric of the aquifer, whereas the real aquifer potential depends on the availability of the traps to store CO₂, as shown bellow.
2.4.2 Capacity estimation in aquifers

As indicated above, abundant structural traps are identified in the Cambrian reservoir, whereas structures in the Lower Devonian are seemingly too small. Therefore, only Cambrian structures were assessed for the storage capacity. The inventory of 76 onshore uplifts of the Cambrian reservoir was carried out.

The storage capacity of a structural trap was estimated:

\[ M_{\text{CO}_2} = V \times \phi \times \rho_{\text{CO}_2r} \times S \]

Where

- \( M_{\text{CO}_2} \): storage capacity (kg)
- \( V \): volume of the structure (m\(^3\))
- \( \phi \): porosity (typically from 0.25–0.20 in central Lithuania to 0.06–0.10 in west Lithuania)
- \( \rho_{\text{CO}_2r} \): in situ CO\(_2\) density at reservoir conditions (ranges from 600 kg/m\(^3\) to 750 kg/m\(^3\) )
- \( S \): sweeping efficiency, often also referred to as the storage efficiency (assumed 0.35 for Lithuanian Cambrian).

Figure 2.14: Storage capacity of Cambrian structures of Lithuanian onshore (left) and offshore (right).
The total storage capacity of 76 uplifts is as large as 102 Mt of CO$_2$ and one third of it offshore (Figure 2.15). However, the only uplift onshore (Syderiai) and one uplift offshore (D11) were identified to exceed storage capacity of 10 Mt of CO$_2$.

Onshore structures, capacity of which is in the range of 0.1–0.2 Mt of CO$_2$, compose 13% of assessed uplifts, structures of capacity of:
- 0.2–0.4 Mt compose 14%
- 0.4–0.7 Mt compose 24%
- 0.7–1 Mt compose 13%
- 1–2 Mt compose 20%
- 2–5 Mt compose 12%

These are very small structures and have no potential for storing CO$_2$.

The utilization of the largest Syderiai structure, capacity of which is assessed 21.5 Mt of CO$_2$, is the only option (if any) for storage, while the two other “large” Vaškai and D11 structures have storage capacity of respectively 8.8 and 11.3 Mt of CO$_2$.

2.4.3 Capacity estimation in hydrocarbon fields

Description of assumptions and parameters used for the estimation of storage potential in hydrocarbon fields and table of capacity estimates.

Nineteen oil fields have been discovered so far in Lithuania. Eleven oil fields are under operation, all related to the Middle Cambrian sandstone reservoir. In terms of the P-T conditions they are located in the CO$_2$ supercritical window and therefore can be potentially used for the CO$_2$ storage.
The initial oil in place reserves of the producing fields ranges from 0.36 to 3.11 Mt. All oil fields are discovered onshore, despite extensive exploration efforts offshore.

The storage capacity of the Lithuanian hydrocarbon fields has been estimated using the formula from the GESTCO project (Schuppers et al., 2003) assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO₂:

\[ M_{CO₂} = \rho_{CO₂} \times UR_p \times B \]

Where

- \( M_{CO₂} \): hydrocarbon field storage capacity
- \( \rho_{CO₂} \): CO₂ density at reservoir conditions (best estimate)
- \( UR_p \): proven ultimate recoverable oil or gas
- \( B \): oil formation volume factor.

The CO₂ EOR potential was assessed for each oil field using the rule-of-thumb approach based on historical data (Tzimas et al., 2005). Capacity of sixteen oil fields was assessed using this approach, as shown below in Table 2.8.

Table 2.8: Storage and EOR capacity of Lithuanian hydrocarbon fields.

<table>
<thead>
<tr>
<th>Name</th>
<th>CO₂ storage capacity (Mt)</th>
<th>Incremental EOR oil (Mt)</th>
<th>EOR CO₂ net (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.Siupariai</td>
<td>1.14</td>
<td>0.31</td>
<td>0.78</td>
</tr>
<tr>
<td>Genciai</td>
<td>1.22</td>
<td>0.31</td>
<td>0.77</td>
</tr>
<tr>
<td>Vilkyciai</td>
<td>1.46</td>
<td>0.30</td>
<td>0.74</td>
</tr>
<tr>
<td>Girkaliai</td>
<td>0.29</td>
<td>0.24</td>
<td>0.59</td>
</tr>
<tr>
<td>Vezaiciai</td>
<td>0.55</td>
<td>0.22</td>
<td>0.54</td>
</tr>
<tr>
<td>Siupariai</td>
<td>0.49</td>
<td>0.16</td>
<td>0.41</td>
</tr>
<tr>
<td>Kudirka</td>
<td>0.06</td>
<td>0.15</td>
<td>0.37</td>
</tr>
<tr>
<td>Silale</td>
<td>0.34</td>
<td>0.13</td>
<td>0.31</td>
</tr>
<tr>
<td>Diegliai</td>
<td>0.39</td>
<td>0.11</td>
<td>0.27</td>
</tr>
<tr>
<td>Sakuciai</td>
<td>0.38</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>Kretinga</td>
<td>0.34</td>
<td>0.09</td>
<td>0.23</td>
</tr>
<tr>
<td>Nausodis</td>
<td>0.43</td>
<td>0.09</td>
<td>0.23</td>
</tr>
<tr>
<td>Pociai</td>
<td>0.11</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>Ablinga</td>
<td>0.29</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Plunge</td>
<td>0.04</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Lauksargiai</td>
<td>0.04</td>
<td>0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Figure 2.16: CO₂ storage capacity of oil fields.

The total estimated CO₂ storage capacity for Lithuanian hydrocarbon fields amounts to 7 Mt. The largest three oil fields can accommodate from 1.14 to 1.46 Mt of CO₂, the rest fields are much smaller, the capacity does not exceed 0.5 Mt of CO₂. Therefore the CO₂ storage potential of Lithuanian oil fields is negligible and from practical point of view is considered as a zero.

EOR assessment shows that this option is not an effective solution for reducing GHG emissions in Lithuania. The estimated total EOR net volume of CO₂ is 5.7 Mt. The commercial value of this option is also ubiquitous. The total incremental oil is evaluated 2.3 Mt.

2.4.4 Capacity estimation in coal fields

Only a few m-scale lignite layers are identified in the geological section of SW Lithuania. They are of Lower Jurassic age and occur at 200–300 m depths. Lignite has no commercial value and has no CO₂ storage potential either.

2.4.5 Case studies

The largest structures identified in Lithuania are the Vaškai and Syderiai uplifts in north Lithuania and D11 structure located in the Baltic Sea 5 km from the mainland (Figure 2.17). All structures are related to the Telšiai fault striking west-east across north Lithuania. The major parameters are presented in Table 2.9. The two onshore structures were chosen for the case study, as the offshore activities are strongly opposed by public and government.
Figure 2.17: Location of the largest onshore and offshore structures. The Mazeikiai oil refinery and Akmene cement plant are selected for the case study. The link is adjusted to the existing pipe lines (white lines).

Table 2.9: Main parameters of the Syderiai and Vaškai (onshore) and D11 (offshore) structures.

<table>
<thead>
<tr>
<th>Name</th>
<th>Syderiai</th>
<th>Vaškai</th>
<th>D11</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Coordinates (WGS-84)</td>
<td>22.43</td>
<td>24.25</td>
<td>20.9</td>
</tr>
<tr>
<td>Y Coordinates (WGS-84)</td>
<td>55.92</td>
<td>56.07</td>
<td>56.02</td>
</tr>
<tr>
<td>VOLUME (m3)</td>
<td>100000000</td>
<td>50200000</td>
<td>50200000</td>
</tr>
<tr>
<td>CAPACITY (MtCO₂)</td>
<td>21.5</td>
<td>8.7</td>
<td>11.3</td>
</tr>
<tr>
<td>HEIGHT (m)</td>
<td>57</td>
<td>57</td>
<td>65</td>
</tr>
<tr>
<td>DEPTH (m)</td>
<td>1458</td>
<td>920</td>
<td>1700</td>
</tr>
<tr>
<td>AQUIFER RADIUS (m)</td>
<td>300000</td>
<td>300000</td>
<td>300000</td>
</tr>
<tr>
<td>TRAP RADIUS (m)</td>
<td>5100</td>
<td>3500</td>
<td>5000</td>
</tr>
<tr>
<td>WELL RADIUS (m)</td>
<td>0.073</td>
<td>0.073</td>
<td>0</td>
</tr>
<tr>
<td>PERMEABILITY (mD)</td>
<td>400</td>
<td>800</td>
<td>300</td>
</tr>
<tr>
<td>POROSITY</td>
<td>0.16</td>
<td>0.22</td>
<td>0.1</td>
</tr>
<tr>
<td>DENSITY (kg/m3) CO₂</td>
<td>710</td>
<td>580</td>
<td>750</td>
</tr>
<tr>
<td>SWEEP EFFICIENCY (%)</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>NET2GROSS</td>
<td>0.75</td>
<td>0.5</td>
<td>0.35</td>
</tr>
<tr>
<td>TRANSMISSIVITY (Kh)</td>
<td>0.0004</td>
<td>0.0005</td>
<td>0.0003</td>
</tr>
<tr>
<td>SALINITY (g/l)</td>
<td>122</td>
<td>127</td>
<td>120</td>
</tr>
<tr>
<td>TEMPERATURE (K)</td>
<td>323</td>
<td>306</td>
<td>325</td>
</tr>
<tr>
<td>PRESSURE (MPa)</td>
<td>15.3</td>
<td>9</td>
<td>17.5</td>
</tr>
<tr>
<td>STRATIGRAPHIC UNIT</td>
<td>M.Cambrian</td>
<td>M–L Cambrian</td>
<td>M.Cambrian</td>
</tr>
<tr>
<td>LITHOLOGY</td>
<td>Sandstone</td>
<td>Sandstone</td>
<td>Sandstone</td>
</tr>
</tbody>
</table>

**Vaškai**

The Vaškai uplift is located 10 km from the region centre Pasvalys. 168 km seismic lines were carried out in 1992–1999 and five wells were drilled that was related to the evaluation of the Vaškai structure for UGS. The structure was eventually abandoned due to uncertainty of tightness of the bounding faults, as the Vaškai structure is limited by two faults trending west-east. The length of the structure is 12 km. The Telsiai fault zone is 500 m to 1000 m wide, the
Cambrian reservoir is set off for 250 m. The main aquifer reservoir is presented by the Lower–Middle Cambrian that consists of medium to fine-grained sandstones with shales and siltstones. Porosity of Cambrian sandstones is in the range of 19.5–24.5%, permeability is 90–1628 mD. Net-to-gross is 0.5. The tightness of Ordovician caprock was proved by drill stem test, logs in the wells and threshold pressures measurements on cores. The thickness of the sealing shales of the Ordovician–Silurian age is about 360 m. The area of the Vaškai uplift is 11×3.2 km, it has a pop-up geometry. The closure is 36 m amplitude. It is however not clear if the closure is controlled by faults on the either side of the uplift or the Cambrian layer is flexed at the faults. The storage capacity of the Vaškai structure is assessed 8.7 Mt of CO₂.

The Vaškai structure is in a favourable geographical position. It is located close to the pipeline. The distance from one of the largest sources Akmenes cement plant is about 120 km adjusted to the pipeline network. The plant’s annual production is 0.8 Mt of CO₂.

Figure 2.18:
Depths of top of Cambrian aquifer of Vaškai structure.

Syderiai

Syderiai was defined as a prospective structure for oil in eighties. It is bounded by the Telsiai fault from the south, the amplitude of the fault is a about 200 m. In the east the structure is bordered by smaller scale fault trending NE–SW, the amplitude is 100 m. The structure is of oval shape, the amplitude is of 80 m. The structure is 12 km long and 8 km wide.

The reservoir is comprised by the Middle Cambrian sandstones of 58 m thick, net–to-gross is 0.75, the average porosity is 16%, the permeability is 400 mD. The sandstone package is divided into two parts by several-meters thick shale and seems to have no hydraulic communication. The
reservoir is sealed by 560 m thick Ordovician and Silurian shales. The storage capacity of the Syderiai uplift is assessed 21.5 Mt of CO₂.

The location of the Syderiai structure is most favourable for CO₂ storage. The largest sources (Mazeikiai oil refinery and Akmenė cement plant) are located at a distance of about 55 km. Furthermore both sources and the structure are linked by existing pipelines. The calculated distance adjusted to the pipelines is 100 km. The Akmenė plant and Mazeikiai refinery produce annually respectively 0.8 and 1.9 Mt of CO₂.

Figure 2.20: Depth of top of Middle Cambrian reservoir of Syderiai uplift and Stratigraphy of well Syderiai-1.

### 2.4.6 Country summary

CO₂ emissions in Lithuania are rather low compared to most of other European countries. It is mainly due to employment of the nuclear energy that covers most of country’s needs for electricity. Ten sources emitting more than 0.1 Mt of CO₂ per year are in the database. Those are ammonia plant, two cement plants, oil refinery, the rest are power and heat producers. They produced 5.5 Mt of CO₂. An increase in emissions is forecasted after closing Ignalina NPP in 2010.

Two large deep saline aquifers meet basic requirements for CO₂ storage, i.e. Cambrian and Lower Devonian. The theoretical regional storage capacity of CO₂ of the Cambrian aquifer is as large as 17 Gt, and that of the Lower Devonian is 13.7 Gt. The compilation of the detail structural maps for both formations revealed a number of uplifts (potential traps), the size of which is however far below the required volumes for storage of CO₂, essentially in the Lower Devonian. In Cambrian more than 100 structures were assessed in terms of the storage capacity both offshore and onshore. Only two structures were identified to exceed storage capacity of 10 Mt of CO₂, the largest reaching 21.5 Mt. Those few structures have the total potential of 37.5 Mt.
which covers 7 years of the countries emissions. However, the prospect of application of Lithuanian structures is rather ubiquitous due to rather small size and the practical potential of the country for sequestration of GHG is assessed rather as zero.

Table 2.10: CO₂ emissions and storage capacity estimates in Lithuania.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2005</td>
<td>6</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2005</td>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage in aquifers (bulk volume)</td>
<td>Theoretical</td>
<td>30700</td>
<td>30700</td>
</tr>
<tr>
<td>Storage in aquifers (structure specific)</td>
<td>Effective</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Effective</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td>Effective</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Practical storage capacity</td>
<td>Practical</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2.21: Map of CO₂ emissions >0.1 Mt of CO₂ (rectangles - black are power and district heating sources, pink is the ammonia plant, yellow are cement plants), gas pipelines (line) and oil pipelines (dotted line). Yellow area indicates distribution of the Cambrian reservoir at P-T conditions suitable for CO₂ geological storage. The white polygons indicate Syderiai (Syd) and Vaškai (Vask) structures. Brown polygons are oil fields.
Figure 2.22: Map of CO₂ emissions, infrastructure and storage capacity in Lithuania.
2.5 Poland

2.5.1 Maps of regional storage potential

The best conditions for geological CO2 storage in aquifers occur within significant part of Polish Lowlands (Northern and Central Poland). There occur sedimentary rocks of miscellaneous age (mainly Mesozoic and Cenozoic), geologically well defined. Especially Mesozoic rocks are featured with good reservoir properties and reveal large thickness, extent and porosity, less fractures or fissures. At the top they are sealed with thick impermeable rocks. An analysis of deep aquifers of Polish Lowlands needed data on occurrence of thick reservoir rocks, separated from potable water aquifers, placed deep enough (below 1000 m), well recognized geologically. Existence of the overburden seal allowed indicating 3 regional aquifers (Lower Triassic, Lower Jurassic and Lower Cretaceous) as the most adequate sites to quest for reservoirs suitable for geological carbon dioxide storage.

Potential of CO2 storage in regional aquifers was estimated. Following data were used to calculate CO2 storage capacity: average porosity, average contribution of permeable layers, average density of CO2 in reservoir conditions, structural and thickness maps of relevant horizons. Transformation of digital models into maps together with application of constant parameters revealed capacity values of the aquifers. It was assumed that the storage will be run in an area where the aquifer occurs at a depth interval of ~1000–3000 m. Rocks’ volume values of individual aquifers resulted from superposition of structural and thickness maps. Pore volumes of rocks were calculated from average porosity and net gross ratio. Average porosity and proportion of permeable layers were adjusted basing on data from Mesozoic aquifer boreholes recognition. For Lower Cretaceous deposits there were analyzed data from 90 boreholes, in which relevant rock porosity balanced from 10% to 34%, average one reached 20.5%. For Lower Jurassic deposits there were analyzed data from 140 boreholes, porosity values varied from 10% to 46%, average one reached 17.3%. For Lower Triassic deposits there were analyzed data from 140 boreholes, porosity values balanced from 5% to 25%, and the average porosity amounted to 9.7%.

Pore volume is largest for the Lower Jurassic formation 3,130.4 km³, less for the Lower Triassic 2,207.8 km³ and the least for the Lower Cretaceous 477.9 km³. A constant density of CO2 in reservoir conditions was presumed for individual aquifers at 800 kg/m³ for the Lower Cretaceous, 700 kg/m³ for the Lower Jurassic and 600 kg/m³ for the Lower Triassic. Assumed storage efficiency is 2%.

![Maps of regional storage potential](image)

Figure 2.23: Extent and CO2 storage capacity of Lower Cretaceous (a), Lower Jurassic (b) and Lower Triassic (c) aquifers in the Polish Lowlands.
The largest CO₂ storage capacity occurs in Lower Jurassic formations 43,825.7 Mt, less in Lower Triassic formations 26,494.1 Mt, the least in Lower Cretaceous formations 7,646.9 Mt.

The estimations of storage capacities for hydrocarbon and coal fields presented in D10 are preliminary and approximate, but calculated with the use of the same methodologies applied already for EU 15 countries in FP5 project GESTCO several years ago and recently for the most of European states within the frames of EU GeoCapacity project.

In D10 main areas where suitable hydrocarbon fields occur, which differ in geology and production history are characterised. Storage capacity estimations for these individual fields refer generally to effective capacities, making in total not so impressive figure of 764.3 Mt. Storage capacities in coal fields were assessed for Polish Silesian Coal Basin only, rejecting other two basins as unsuitable and/or insufficiently explored. The approach based on the assessment of Producible Gas in Place was used and both theoretical and (a very preliminary) effective storage capacities were calculated (the latest make in total 414.6 Mt).

2.5.2 Capacity estimation in aquifers

Numerous tectonic structures (anticlinal structures and grabens) were defined within the Mesozoic aquifers (K₁, J₁, T₁) of the Polish Lowlands. They are manifestations of salt tectonism. Some of them, having been minutely examined, can prove to be adequate geological structures suitable for carbon dioxide underground storage (Tarkowski & Uliasz-Misiak, 2005, 2006).

Within this structures there were chosen and minutely characterized 18 anticline structures. As potential CO₂ sinks there were defined 7 structures in Lower Cretaceous formations, 7 ones in Lower Jurassic and 5 ones in Triassic formations as well. Geological data on structures presented in the Aquifer Injection Point database were obtained from documentation of deep wells (localization, depth of reservoir bottom and top, thickness, net gross ratio). Reservoir parameters (porosity and permeability) were collected from documentation of deep wells and publications.

Storage volume of the defined 18 tectonic structures was calculated as product of the structure area, effective thickness, porosity, CO₂ density in deposit conditions and sweep efficiency 20%. Total storage capacity within the defined tectonic structures amounts to 3,522.2 Mt of carbon dioxide. It allows storing Poland's 11 year emission (referring to emission level in 2004).

2.5.3 Capacity estimation in hydrocarbon fields

Possibilities of CO₂ storage within depleted/depleting hydrocarbon fields in Poland were analysed from the viewpoint of three criteria; proven Ultimate Reserves (UR), depth range and production history. Storage capacity figures were calculated using approach of FP5 GESTCO project (Schuppers et al., 2003) based on assumption of 1:1 volumetric replacement of extracted hydrocarbons with supercritical CO₂ within reservoirs, which refers generally to effective capacity, though a very preliminary one. For the studies on CO₂ storage capacity in hydrocarbon fields 31 structures were selected in EU GeoCapacity.

UR means the sum of production till now and of remaining exploitable resources (using standard production technology). The threshold of 1 Bcm was selected for gas fields and 1 Mt for oil fields (slightly lower than in GESTCO (Christensen & Holloway, 2003), because of small size of fields in Poland) for the start but because of shortage of oil fields of assumed size and some other reasons, two smaller fields were added. UR and expansion factors (because UR refers to
volumes of hydrocarbons in conditions on earth's surface, not within the reservoir) together with CO₂ density estimations within the reservoir make it possible to calculate storage capacities of the sinks under the above mentioned assumptions.

The upper depth range defines the threshold below which carbon dioxide appears in supercritical form. Though it depends on pressure and temperature, average depth was assumed, after GESTCO studies, of 800 metres. The lower depth range was assumed usually as of 2500 metres (where reservoir properties become poor), in case of good reservoir properties even slightly deeper (up to 2700 metres in Rotliegend sandstones of relative good porosity and permeability). Production history refers to status of particular hydrocarbon field; whether it has been developed recently, or exploited for a longer time, about to be depleted, or already depleted (and used for other purposes or not). Fields developed recently and/or for which production reached already does not make a substantial part of UR yet were ruled out, because hydrocarbon production using standard technology will likely last in these cases for a quite long time (at least for a dozen of years). For one oil field (BMB - developed quite recently and oil production reached only 20% of UR) an exception was made, because this is the biggest oil field in the country, and of likely large EOR potential. One depleted oil field Kamien Pomorski was selected for a case study.

Storage potential of bigger gas fields (and to lesser extent, some oil field) is enough to store emissions of some medium size industrial point sources, like smaller power and CHP plants, smaller refineries and manufacturing industries.

2.5.4 Capacity estimation in coal fields

Of three hard coal basins known in Poland suitable conditions for CO₂-ECBMR exist likely only in the (Upper) Silesian Coal Basin (SCB – southern Poland). Two remaining coal basins (Walbrzych area of Lower Silesia, or SW Poland, and Lublin area in eastern part of the country) have likely either unsuitable geological conditions or are not sufficiently explored.

Standard approach used in FP5 GESTCO project on calculating PGIP (producible gas in place = methane reserves in case of ECBM) and storage capacities was applied (Bergen & Wildenborg, 2002; Wójcicki et al., 2007), same as used in GESTCO project for coal basins and fields of the Netherlands, Belgium and Germany. It consists in estimation of pure coal volume and mass within the coal beds in question and collecting data on methane content within pure coal substance (after laboratory analyses) and assuming CH₄ – CO₂ replacement ratio and CO₂ density. Generally deep (of depth range 1–2 km, as suggest RECOPOL experiences) coal/CBM fields under good seal were considered, what is necessary in such area where mining activities have been carried out for a very long time.

Theoretical storage capacity of un-mined, methane bearing coal seams within the part of SCB in question, based on basin wide estimations of Producible Gas in Place (methane reserves for ECBM), was calculated as 1254 Mt.

Similar, though more site specific approach was used for selected 27 coal fields located mostly in southern half of the basin (depth range of 1–2 km as for the basin, good seal in overburden), thus referring rather to effective capacity. For these fields total storage capacity is 414.6 Mt and storage capacities calculated for these fields vary from 0.4 to 46.1 Mt (Zory-Suszec). These (effective, though rather preliminary) storage capacity estimations are included in the table.
In theory, the storage potential of coal beds in Silesian Coal Basin is quite significant in comparison to industrial emissions on this area, but the question when a mature CO$_2$-ECBMR technology could be used there is open.

2.5.5 Case studies

Case study 1 - Case study Dzierzanowo storage in aquifer in Poland

A case study of CO$_2$ storage in aquifer in Poland was made for Dzierzanowo anticline. The Dzierzanowa anticline occurs in the Warsaw Trough (Plonsk unit), formed on a SW flank of the Eastern European platform; 60–70 km North-West from Warsaw.

Geostructural development of the Dzierzanowo anticline is closely linked with a system of faults deeply rooted in the sub-Zechstein basement. The faults developed as a result of vertical movements of the basement, especially intense during the Late Triassic. They were also periodically manifested as synsedimentary faults in the Early and Middle Jurassic and in the Early Cretaceous. The synsedimentation semi-graben formed during that time was then transformed, together with a clearly visible anticline in the deeper sections of the complex, during regional inversion into flat overlying anticline. During that time, salt masses could have cut through Lower Buntsandstein formations.

The Dzierzanowo anticline was penetrated by a seismic survey and 5 boreholes: The structure’s peak is defined by the contour line of the Upper Cretaceous (Upper Albian–Cenomanian) base, reaching a depth of ÷850 m (Dzierzanowo 1 well, 814 m). Assuming conventionally that the anticline outline is defined by the contour line of the Upper Albian base down to a depth of 1000 m, the anticline length is about 15 km and its width is 5 km. Considering the Cretaceous structural surfaces, the anticline shows a clear symmetry. Their W and E wings dip at the angle of 2–3%. Deeper structural surfaces reveal their asymmetry: the NE wing dips relatively gently, whereas the SW wing is steeper.

The optimal reservoir horizon to store CO$_2$ is formed by Barremian–Middle Albian age sandstones (Mogilno formation), composed mainly of sandstones (85%), second-rate (15%) claystones and mudstones. The Bottom of the Barremian–Middle Albian deposits lies on depth from 939.0 m (Dzierzanowo 1 well) to 1082.5 m (Dzierzanowo 3 well). Thickness of the deposits varies from 135.0 m (Dzierzanowo 3 well) do 147.5 m (Kobylniki 1 well).

Porosity of the Mogilno formation sandstones amounts to from 15% to 30%. Permeability values range around several hundred mD and may sometimes reach 3500 mD. The Mogilno formation sandstones are situated within a zone of intense exchange of hydrocarbonate-sodic waters of the maximum mineralization of approximately 10 g/dcm$^3$. Reservoir is sealed by Upper Cretaceous formations (Upper Albian–Cenomanian to Mastrichtian) 700 m thick, characterised with low permeability. Seal is composed prevailing from limestones, marls, gaizes, second-rate sandy. Mogilno formation and their seal don’t tectonised. Faults there are in deeper parts of Permian – Mesozoic complex (Zechstein–lowest Lower Cretaceous). Within the Dzierzanowo, faults disappear in Cretaceous formations and are not carried to the storage formation, which is important in the perspective of carbon dioxide storage safety.

To estimate storage capacity of CO$_2$ in Dzierzanowo structure there were used following data: area of structure: 75 km$^2$, thickness of reservoir: 122 m, porosity 20% and storage efficiency 20%. Estimated CO$_2$ storage capacity is 260 Mt.
Figure 2.24: Structural map of the Dzierżanowo anticline according to the base of the Upper Albian–Cenomanian, referred to the sea level.

Figure 2.25: Cross-section through the reservoir horizon in Dzierżanowo Anticline.
Case study 2 – Depleted hydrocarbon field Kamień Pomorski and chemical combine Police

The chemical combine Police produces fertilizers (NPK fertilizers, NP fertilizers,) and titanium dioxide. It includes ammonia production of about 200 kt a year and an equivalent production of about 100 kt of pure CO₂. The combine includes also two CHP plants, the total CO₂ emission of the combine is 629 kt per year. In 2007 (after the company report) it produced 136.3 kt of chemicals (50% of NPK fertilizers, 28% NP fertilizers and 22% of urea) and 37.6 kt of titanium dioxide. The owner is Zaklady Chemiczne (Chemical Works) “Police” SA. Other (less favourable) options include 2 CHP and on steel plant in Szczecin, then farther big power plants Dolna Odra and Lubmin (in Germany) and Schwedt chemical combine in Germany (not considered later).

It is a good choice for source to sink scenario for a not a very big, but depleted oil field Kamien Pomorski, which production started after 1972 and now is about to an end (production of 40% of original oil in place, or 1.9 Mt). In 1976 flooding was applied in order to enhance oil recovery till 1982 and since 1994 another measure, sour gas (produced in place) reinjection. Despite the presence of sour gas within the reservoir it seems CO₂ injection might be the only solution to enhance oil recovery from this mature field. The operator of the oil field is Polish Oil and Gas Company who got a production permit from (Polish) Ministry of Environment till year 2018.

The way of transporting could be either ship transport (storage tanks) or a new pipeline utilizing transport corridors of gas pipelines of Polish Oil and Gas Company present there. The distance from source(s) to sink is 45 km in a straight line.

2.5.6 Country summary

The best conditions for geological CO₂ storage in aquifers occur within significant part of Polish Lowlands (Northern and Central Poland). Regional Mesozoic aquifers (Lower Triassic, Lower Jurassic and Lower Cretaceous) are the most adequate sites to quest for reservoirs suitable for geological carbon dioxide storage. Mesozoic aquifers make the most of country storage capacity.

The largest CO₂ storage capacity occurs in Lower Jurassic formations 43,825.7 Mt, less in Lower Triassic formations 26,494.1 Mt, the least in Lower Cretaceous formations 7,646.9 Mt. Numerous tectonic structures (anticlinal structures and grabens) were defined within the Mesozoic aquifers of the Polish Lowlands. As potential CO₂ sinks there were defined 7 structures (Bodzanow, Dzierzanowo, Sierpc, Turek, Trzesniew, Tuszyn, Zyrów) in Lower Cretaceous formations, 7 ones (Aleksandrow Lodzki, Chabowo-J, Choszczno, Marianowo, Nowa Wies Wielkie, Suliszewo, Trzebiez) in Lower Jurassic and 4 ones (Chabowo-T, Kliczkow, Kobylnica, Szubin) in Triassic formations as well. Total storage capacity within the defined tectonic structures amounts to 3,522.2 Mt of carbon dioxide. It allows storing Poland's 11 year emission (referring to emission level in 2004).

Hydrocarbon fields in Poland are generally located in two areas, which differ in geology and production history, in south-eastern and western part of the country. In SE part (Carpathians/Carpathian foredeep) twelve depleted/depleting gas have been considered, most of them not very big, and two small oil fields. In western part of the country thirteen gas fields mostly of Rotliegend or Zechstein reservoirs have been assessed together with two oil fields, one depleted and one developed recently but relatively big (BMB). One (not so big) depleting offshore oil field (B3 – Polish economic zone of Baltic sea) is out of this picture because the reservoir is of Cambrian age. The total storage capacity in hydrocarbon fields is 765.3 Mt (assuming 1:1 volumetric ratio-hydrocarbons replaced with CO₂ within the reservoir) and it
refers mostly to gas fields of small and medium size, four of them exceed 50 Mt (Przemysl in SE and Zuchlow, Zalecze-Wiewierz and Bogdaj-Uciechow in western part of the country).

Regarding storage in coal fields the only coal basin considered is Silesian Coal Basin of Carboniferous age. Storage capacities are based on estimations of PGIP calculated for the considered depth range for 27 individual fields (located mostly in southern half of the basin) and for the whole range of coal basin. Storage capacities of these fields reach in total 414.6 Mt. Estimated storage capacities of particular fields vary from 0.3 Mt (Moszczenica) to 46.1 Mt (Zory-Suszec). A regional storage capacity, at depth range 1–2 km, for the range of coal basin where methane content is known at the depth in question is 1254 Mt.

Table 2.11: CO₂ emissions and storage capacity estimates in Poland.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2004</td>
<td>188</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2004</td>
<td>325</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>effective</td>
<td>1761</td>
<td>3522</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>effective</td>
<td>764</td>
<td>764</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>effective</td>
<td>415</td>
<td>415</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>2940</td>
<td>4701</td>
</tr>
</tbody>
</table>

The storage capacities described above and summarized in Table 2.11 represent the content of the GeoCapacity database for Poland. In the paper “CO₂ storage capacity of geological structures located within Polish Lowlands' Mesozoic formations; Gospodarka Surowcami Mineralnymi", 24/1, p.101–111 (2008)” R. Tarkowski has recently presented new data on CO₂ storage underground structures. This paper (December 2008) presents results on recognition of geological structures for CO₂ storage within Mesozoic brine aquifers (Lower Cretaceous, Lower Jurassic, Lower and Upper Triassic) of Polish Lowlands. 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. Total capacity of these structures comes to 22342 Mt (that is: volumetric 17490 Mt, dissolution based 4852 Mt), considering capacity volume from several dozen up to over 2 000 Mt of carbon dioxide.
Figure 2.26: Map of CO₂ emissions, infrastructure and storage capacity in Poland.
2.6 Czech Republic

2.6.1 Maps of regional storage potential

The territory of the Czech Republic belongs to the Bohemian Massif (western part) and the Carpathians (eastern part). A significant part of the country area is formed of crystalline rocks. Nevertheless, several major sedimentary formations, representing potentially suitable CO$_2$ storage areas, can be found. The assessment of the sedimentary basins 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 in the Czech territory.

Regarding aquifers, the attention was aimed at vertically closed structures with suitable depth, 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.

From more than 40 hydrocarbon fields registered in Czechia, only the 6 biggest were selected for further evaluation of their CO$_2$ storage potential. The other ones are too small and their storage capacity is negligible.

Among the Czech coal-bearing sedimentary basins, 4 areas were selected as potentially suitable for CO$_2$ storage. Only unmined coal seams were taken into account. For this reason, the largest coal basin, the Upper Silesian Basin, was divided into exploration/production blocks, and only the 3 most promising blocks were selected for the GIS & database, while the other three smaller basins were evaluated at basin scale.

The results of the storage potential mapping of the Czech Republic are shown in Figure 2.27.

2.6.2 Geological description, aquifers

As mentioned above, 22 deep saline aquifer structures were identified as potentially suitable for geological storage of CO$_2$. 17 of them are situated in the Carpathians (eastern part of the country) and 5 in sedimentary basins of the Bohemian Massif (western part). 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 Figure 2.27.

The Carpathian aquifers are situated in the Carpathian Foredeep (Vlkos-Lobodice, Musov, Drnholec, Ivan, Vlasatice) and in the Flysch Zone (Korycany, Osvetimany-Stupava, Zdounky, Barice, Rusava, Kozlovice-Lhotka, Frydlant nad Ostravicí, Výšní Lhoty-Morávka, Mikulov, Nosislav-Nikolecice, Kloberice, Kobylí). Promising structures were selected with help of a former study aimed at identification of aquifers suitable for underground natural gas storage sites.

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, Frydlant 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 (Zatec, Roudnice, Mnichovo Hradiste, Nova 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 arkoses 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 as 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. The aquifers of the Central Bohemian basins were subject of a separate case study (see 2.6.6).

2.6.3 Capacity estimation in aquifers

The assessment of CO$_2$ storage capacity in deep saline aquifers in the Czech Republic is based on evaluation of 17 individual structural traps and 5 regional aquifers. The capacity estimates in the GeoCapacity database for all 22 structures have been calculated according to the methodology described for deep saline aquifers in GeoCapacity deliverable D24 “Storage capacity standards”, using the formula (simplified after Bachu et al., 2007):

$$M_{CO_2t} = A \times h \times NG \times \phi \times \rho_{CO_2r} \times S_{eff}$$

where:

- $M_{CO_2t}$: “trap” storage capacity
- $A$: area of aquifer in trap
- $h$: average height of aquifer in trap
- $NG$: average net to gross ratio of aquifer in trap (best estimate)
- $\phi$: average reservoir porosity of aquifer in trap (best estimate)
- $\rho_{CO_2r}$: CO$_2$ density at reservoir conditions (best estimate)
- $S_{eff}$: storage efficiency factor (for trap volume)

The area of the structures has been determined based on contour maps of stratigraphic horizons near or at the top of the reservoir formation. Thickness and porosity have been evaluated using data from exploration wells drilled on the structure or extrapolating information from wells on nearby structures.

The CO$_2$ density varies with depth as a function of pressure and temperature and has been estimated using the p-T diagram for CO$_2$ density (Tarkowski et al., 2005).

The aquifer systems surrounding and connected to the reservoir formations in the individual traps (Carpathian area) have been assumed to be open (unconfined) aquifers. Based on the “rule-of-thumb approach” described for open and semi-closed aquifers in the GeoCapacity deliverable D24 “Storage capacity standards”, a storage efficiency factor of 40% has been assumed corresponding to open high quality reservoirs. For the aquifers from the area of the Bohemian Massif, the value of 6% has been used for the storage efficiency factor. This approach results in a total effective storage capacity of 2,863 Mt CO$_2$ for the 22 selected structures. This value corresponds to the data in the project GIS database.
Stratigraphic unit, formation and lithology of reservoir and seal formations as well as top depth and permeability of the reservoirs have been evaluated using data from exploration wells drilled on the structures or extrapolating information from wells at nearby structures.

The aquifers are considered to react as open reservoirs, i.e. the reservoir pressure is assumed to be equal to hydrostatic pressure; the gradient has been calculated at 10 MPa/km. The reservoir temperature is estimated from regional geothermal gradient, i.e. 30ºC/1000 m. Based on these assumptions, p-T conditions for supercritical stage of CO2 can be expected at depths below 800 m.

In addition to the calculations described above, a more conservative estimate has been calculated for comparison. The conservative estimates have been calculated for the Carpathian aquifers, assuming that the aquifer systems surrounding and connected to the reservoir formations in the trap structures are closed (confined) aquifers. The storage efficiency factor has been determined using the “table approach” described for closed aquifers in GeoCapacity deliverable D24 “Storage capacity standards”, assuming a total compressibility (c_pore+c_fluid) of 10^{-4} bar^{-1}, hydrostatic pressure, an allowable average pressure increase of 10 % and total aquifer volume 100 times the trap aquifer volume. For the 17 structural traps in the Carpathians, the calculated conservative storage efficiency factor of 10 % was used, resulting in a total effective storage capacity of 295 Mt CO2.

In the case study focused on the Upper Palaeozoic (Permian–Carboniferous) Central Bohemian basins (see 2.6.6.), the volumes of aquifers were calculated using 3D volumetric geological models, and three different values of the storage efficiency factor S_{eff} were used for storage capacity estimations, based on the US-DOE methodology (US DOE, 2007) and the “table approach” described for closed aquifers in GeoCapacity deliverable D24 “Storage capacity standards”. Due to their late completion, these new results could not be included in the project GIS and database. The average value of the efficiency factor of 2.4% (US DOE, Monte Carlo simulation for 50% confidence) was used for the “conservative estimate” of storage capacities in the Bohemian Massif aquifers; the result of this estimate is a storage capacity of 471 Mt CO2. Hence, the total conservative estimate for Czech aquifers is 766 Mt CO2.

2.6.4 Capacity estimation in hydrocarbon fields

At present, there are more than 40 oil and gas 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 Palaeozoic sediments as well. In some cases, hydrocarbon reservoirs are situated in weathered crystalline complexes.

Some of the reservoirs are practically depleted, especially the shallow structures in the Vienna Basin. Deeper structures in the Vienna Basin are still producing, as e.g. the reservoirs Hrusky (oil and gas), Tyneč (oil), Lanzhot (oil), Poddvorov (oil and gas), Vraco (oil), Luzice (oil), Postorná (oil) and Prusanky (oil and gas). Most of the structures in the Vienna Basin represent tectonic traps in the Neogene filling.

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. Dolni 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 Damborice-Uhrice and Zarosice fields (tectonic traps in combination with elevation). Production layers are sediments building the basement of Flysch nappes, i.e. Jurassic and Carboniferous. There are also some gas fields in Miocene sediments (Zdanice area) and small oil reservoirs in the crystalline basement (Zdanice, Lubna-Kostelany) there.

Many of the partly depleted oil fields in the Vienna Basin and the Carpathian Flysch Zone are suitable for CO₂-driven Enhanced Oil Recovery (EOR). Their operator shows interest in using this technology in future but, until now, no suitable source of CO₂ has been available.

For the calculations of the CO₂ storage capacity of oil and gas reservoirs, 6 major hydrocarbon fields were considered. 4 of them are situated in the Carpathian Flysch Zone (Lubna –Kostelany, Zdanice, Damborice-Uhrice, Zarosice) while the 2 remaining belong to the Vienna Basin (Hrusky and Poddvorov). The size of other reservoirs is too small and their storage capacity can be regarded as negligible.

The capacity estimates in the GeoCapacity database for the 6 selected fields have been calculated according to the methodology described for hydrocarbon fields in the GeoCapacity deliverable D24 “Storage capacity standards”, using the formula:

\[
M_{CO_2} = \rho_{CO_2r} \times UR_p \times B
\]

where:

- \(M_{CO_2}\): hydrocarbon field storage capacity
- \(\rho_{CO_2r}\): CO₂ density at reservoir conditions (best estimate)
- \(UR_p\): proven ultimate recoverable oil or gas
- \(B\): oil or gas formation volume factor

The CO₂ density varies with depth as a function of pressure and temperature and has been estimated using a p-T diagram (Tarkowski et al., 2005)

\(UR_p\) is the sum of the cumulative production and proven reserves. The cumulative production (production history) was taken from archive final reports stored in the CGS archive (the last report concerning cumulative production refers to 2000). The yearly production of oil and gas as well as the proven reserves for each HC field were used (as published by the Ministry of Environment and CGS-Geofond) for the \(UR_p\) calculations for the years after 2000. The cumulative data of \(UR_p\) used for calculations of the CO₂ storage capacities in hydrocarbon fields refers to 2004.

CO₂ replacement of oil and gas, respectively, has been calculated separately. The formation volume factor for oil varies regionally depending on the oil type and a fixed formation volume factor of 1.0 has been used for the oil replacement (no more exact values were available). The formation volume factor used for gas varies with depth as a function of pressure and temperature. Relevant information was kindly provided by local operators of gas fields and underground gas storages.
To convert the calculated pore volume into CO₂ storage capacity, the average CO₂ density value of 630 kg/m³ (corresponding to the typical pressure and temperature conditions of the reservoirs) was used for all structures.

In the case study focused on the Hrusky field (see 2.6.6), where water-flooding was applied, the influence of injected water has been added in the calculations (Bachu et al., 2007):

\[ M_{CO2} = \rho_{CO2} \times ((URp \times B) – Vi + Vp) \]

where Vi and Vp are volumes of injected and produced water.

The total storage capacity of the 6 major fields has been assessed at 32.6 Mt CO₂. This means that hydrocarbon structures do not play a significant role as potential CO₂ storage sites, but, on the other hand, they represent an interesting potential from the EOR point of view.

### 2.6.5 Capacity estimation in coal fields

History of coal mining in the Czech Republic is very rich but the majority of Czech coal mines have been closed. At present, active black coal mines are located in the Upper Silesian Basin only. For the purposes of CO₂ storage, 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 Coal Basin and in the Permian–Carboniferous Central Bohemian basins.

The Upper Silesian Basin (USB) represents the most promising area for potential geological storage of CO₂ in coal and/or CO₂-ECBMR in the Czech Republic and was subject of a separate case study (see 2.6.6). The estimation of CBM (coal-bed methane) reserves for the whole area of the Czech part of the USB is at minimum 100 billion cubic meters (Bcm), while the proven reserves (conventional) in all development licences awarded for CBM have been calculated at about 25 Bcm.

The Central Bohemian fields (Slany, Peruc, Melnik-Benatky) 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. However, the plans to open new coal mines in these areas have not become reality.

CO₂ storage capacity in coal seams denotes the quantity of CO₂ that could replace CBM. For this purpose, the CBM is defined as producible gas in place accessible for CO₂-ECBMR (PGIP\textsubscript{CO2}), which differs from conventional PGIP. The storage capacity is a function of PGIP\textsubscript{CO2}, CO₂ density at standard condition and exchange ratio of CO₂ to methane (see deliverables D18, D24):

\[ C_{CO2} = PGIP_{CO2} \times \rho_{CO2} \times ER \]

where \( C_{CO2} \) is the CO₂ storage capacity, \( \rho_{CO2} \) is the CO₂ density at standard conditions (1.89 kg/m³) and ER is the CO₂ to methane exchange ratio. The exchange ratio of about 2 is typical for hard coal as suggested e.g. by van Bergen (2002). The storage capacity calculated from producible gas in place represents the effective storage capacity (Bachu et al., 2007).
For CO2-ECBMR use, the producible gas in place can be estimated (according to van Bergen et al., 2001) by:

\[ \text{PGIP}_{\text{CO2}} = \text{IGIP} \times \text{Rf} \times \text{Cf} \]

where PGIP_{CO2} is PGIP for CO2-ECBMR use, Rf is recovery factor, Cf is completion factor and IGIP is initial gas in place. The completion factor Cf represents an estimate of that part of the net cumulative coal thickness within the drilled coal zone that will contribute to gas production or storage; it strongly depends on the individual thickness of the separate coal seams and on the distance between them, and is lower for thin coal seams than for thick ones. The recovery factor Rf represents the fraction of gas that can be produced from the coal seams. In accordance with RECOPOL project experience in the Polish part of the USB, we have used the value 0.6 for completion factor Cf and the value 0.7 for recovery factor Rf for PGIP_{CO2} calculations (see deliverables D18, D20).

In case of gas already adsorbed by the coal, like coal-bed methane, IGIP is usually calculated by the relation (e.g. van Bergen et al., 2001):

\[ \text{IGIP} = C_p \times MC, \]

where \( C_p \) is the pure coal mass (in tons) and MC is methane content (refers to pure coal, in m³/ton). Pure coal mass can be calculated as follows:

\[ C_p = C \times (1 - F_a - F_m), \]

where \( C \) is the total coal mass (in tons), \( F_a \) and \( F_m \) are the ash and moisture weight fractions of the coal. Data on coal mass reserves and their parameters (\( F_a, F_m \)) as well as the values of methane content MC were purchased from the database of OKD (domestic coal company operating the mines in the USB). Data for Central Bohemian fields were partly taken from the Czech Mining Authority database and partly estimated on the base of published results of laboratory measurements.

For the purposes of the project GIS and database, the Central Bohemian coal fields (Slany, Peruc, Melnik-Benatky) were handled at basin scale, while the better-known Upper Silesian basin was divided into CBM exploration blocks, of which only the 3 most promising ones were selected. The total CO2 storage (effective) capacity of these 6 units was calculated at 54 Mt.

In case the USB storage capacity was calculated at basin scale, the total figure would be approximately doubled. The ECBMR and CO2 storage potentials of the Upper Silesian Basin were subject of a separate case study (see 2.6.6).

### 2.6.6 Case studies

Three case studies were elaborated representing the three main options of CO2 geological storage in the territory of the Czech Republic. The case studies are focused on the following structures:

- Deep saline aquifers of Central Bohemian Upper Palaeozoic (Permian–Carboniferous) basins;
- Hrusky hydrocarbon field;
- Unmined coal seams of the Upper Silesian Basin.
Deep saline aquifers of Central Bohemian Upper Palaeozoic basins

Deep saline aquifers of the Central Bohemian Upper Palaeozoic basins represent the largest potential for geological storage of CO₂ in the Czech Republic. The basins occupy an area of more than 5,000 km² in Central and Western Bohemia. Upper Carboniferous to Lower Permian continental clastic series fills a large intramontane basin. The thickness of the Upper Palaeozoic continental sequence varies mostly between 800–1200 m, but it can reach more than 1500 m in main depocentres. The Upper Palaeozoic sediments are partly covered by a tens of meters to 500 m thick sequence of marine sandstones to marls of Upper Cretaceous age. The westernmost area is also covered by Cenozoic continental clastics and volcanites. The main saline aquifers consist of arkosic sandstones and conglomerates mostly of braided fluvial origin located at the base or at the lower parts of the continental sequence.

The aquifers offer a relatively interesting potential for CO₂ storage. There are 3 potentially suitable areas for carbon dioxide storage in the western (Zatec Basin), central (Central Bohemian/Roudnice/ Basin) and north-eastern (Mnichovo Hradiste Basin) parts of the basin area. 3D volumetric geological models were constructed for all the 3 basins using the ArcGIS software. These models were utilised for calculations of aquifer volumes that were used for enhanced estimations of storage capacities. The cumulative theoretical storage capacity of the 3 basins was estimated at 18 Gt of CO₂. The effective capacity estimations, however, range only between 18 and 726 Mt, depending on the storage efficiency factor (S_{eff}, see 2.6.3). Due to the fact that the case study was finalised at late stage of the project, these new results could not be included in the project GIS and database.

The capacity calculations, as well as the geological modelling itself, are based on the available fragmentary dataset, which represents the most limiting factor, not allowing any more precise determination of the S_{eff} values. The current knowledge is limited to several tens of structural boreholes, tens of old seismic cross-sections and geological maps. The level of exploration differs for each potential site; the most under-explored areas are the Zatec and Mnichovo Hradiste Basins, while the exploration level of the Central Bohemian Basin is higher, especially thanks to the presence of coal seams.

Another uncertainty linked with potential CO₂ storage seems to be the tectonic fault deformation of the basin fill and the faults at the basin margins. Localised tectonic dislocations affect aquifer and sealing connectivity ensuring ideal reservoir conditions. Additionally, all potential reservoirs are bounded by faults that act usually as impermeable barriers; some of the faults, however, could potentially serve as migration pathways.

Future studies and geological/geophysical exploration seem to be necessary in order to make a final decision on the suitability of these structures for permanent geological storage of CO₂. The work should focus on improving the knowledge of the basin structure, including tectonic framework and dislocations, on evaluation of sealing and/or leaking character of tectonic faults, on aquifer and sealing connectivity and on determination of petrophysical properties of both aquifer and sealing rocks. Re-processing and re-interpretation of existing seismic cross-sections and experimental testing of flow properties on rock samples would be of high importance. This also implies more accurate storage capacity calculations that are now burden with extensive uncertainty connected with the limited amount of geological and petrophysical data. To be able to obtain more reliable results, additional data is necessary. Without new data allowing at least preliminary reservoir modelling, no more precise CO₂ storage capacities can be calculated.
Hrusky hydrocarbon field
The Hrusky field is located in the south-eastern part of the Czech Republic, only 5 km from Czech-Slovakian and 10 km from Czech-Austrian borders. The area of the field is approximately 25 sq km; it is about 11 km long and on average 2 km wide. The field is the biggest hydrocarbon field on the territory of the Czech Republic. Nowadays, its oil and gas production is very low (2.4 Kt of oil and 6.2 millions of cubic meters of gas in 2007). From the primary production point of view, the field is practically depleted. The water-flood enhanced oil recovery was applied in three selected reservoirs with partial success in the 1970s. The operator of the Hrusky field has been the domestic oil company Moravske naftove doly (MND).

The Hrusky oil and gas field is, like the majority of the HC fields in the Vienna Basin, tectonically induced. The Steinberg fault, one of the main faults in the Vienna Basin, forms a very deep structure in the Czech (Moravian) part of the Vienna Basin, called the Central Moravian Depression. The south-eastern limitation of this structure is formed by the Lanzhot-Hrusky fault. The Hrusky field has originated close to this fault which functions as the sealing element.

The field consists of many hydrodynamically isolated reservoirs in Karpatian, Badenian and Sarmatian (Miocene) formations of the Vienna Basin Neogene sedimentary fill. Only gas is accumulated in Sarmatian sediments, especially in the so-called 7th–14th Sarmatian horizons. The Karpatian and Badenian horizons contain oil and gas (mainly dissolved). From the oil production point of view, the main horizons are the so-called 6th and 7th Badenian horizons.

Carbon dioxide driven enhanced oil recovery was modelled by IFP for 6 selected oil reservoirs in the 6th and 7th Badenian horizons of the field (see project deliverable D19). The modelling results show that the amount of additional oil that might be produced is about 300 Kt. This amount is economically significant, since it is approximately equal to the average annual oil production of the Czech Republic.

The modelled potential CO2 permanent storage capacity in the oil reservoirs amounts to 1.4 Mt. This value is consistent with the volumetric calculation based on oil production and proven reserves. The storage capacity is fully suitable for a pilot CCS project. A potential CO2 source might be the near lignite-fired power plant in Hodonín.

Unmined coal seams of the Upper Silesian Basin
The Upper Silesian Basin (USB) represents the most suitable area for CO2 storage in coal seams in the area of the Czech Republic. It is a large and complex paralic–limnic sedimentary structure, located mostly in Poland; only a small part (20 % of the whole area) extends into the territory of the Czech Republic. In the northern part of the Czech area, extensive coal mining activity has been carried out while the southern and south-eastern parts (deeper and partly covered by Carpathian Flysch nappes) remained unmined.

Pit coal occurs here within Westphalian and Namurian formations of Upper Carboniferous and has been exploited since the 18th century. At present, the coal is mined in 5 collieries, which produce about 10 Mt of pit coal per year. The coal-bed methane is exploited together with coal as a secondary resource, for safety reasons, in producing collieries (“degasification”). The majority of CBM is, however, produced from unmineable seams or from abandoned mines. The production of CBM from the Czech part of the USB reaches 40 million cubic meters per year, which represents about 30 % of the whole production of natural gas (methane) in the Czech Republic.
The CBM reserves (initial gas in place) of the Czech part of the USB are estimated at 100 milliard m³/Bcm. Using this estimation, the theoretical CO₂ storage capacity of the Czech part of the USB might be up to 380 Mt.

During the national “CBM Programme” (1993–2000), seventeen blocks for CBM exploration were awarded in unmined areas of the Czech part of the USB. Coal reserves, methane content and conventional producible gas in place were calculated in the frame of this programme. In the case study, the producible gas in place for CO₂-Enhanced Coal Bed Methane Recovery (CO₂–ECBMR) has been re-calculated for each exploration block and effective CO₂ storage capacity in coal seams of these blocks has been estimated.

Using the methodology described in 2.6.5, the total effective storage capacity of the selected 17 blocks has been estimated at 110 Mt CO₂. (Due to the fact that the case study was finalised at late stage of the project, these new results could not be included in the project GIS and database.) This amount represents an important portion of the total effective CO₂ storage capacity of the whole Czech Republic. The calculated reserves of about 29 Bcm of CBM that might be obtained by application of the CO₂–ECBMR technology are also important; they might significantly support the present domestic CBM production, which currently represents about 30% of the total national production of natural gas (methane).

2.6.7 Country summary

Table 2.12 below shows a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions) and of storage capacities in aquifers, hydrocarbon fields and coal seams. Figure 2.27 shows the data for the Czech Republic included in the GeoCapacity database.

Table 2.12: CO₂ emissions and storage capacity estimates in the Czech Republic.
Figure 2.27: Map of CO₂ emissions, infrastructure and storage capacity in the Czech Republic.
3 WP 2.2 CENTRAL EAST GROUP

3.1 Hungary

Hungary is situated in the central part of the Pannonian Basin, a marginal basin of the Alps with thin lithosphere, which was formed at late stages of the Alpine orogeny, during the convergence of the Adriatic and European plates (Juhász, 1998). The major driving forces of basin formation are believed to be continuous subduction on the northern and eastern interfaces of the forming basin and synchronous extrusion of the basin units from the Alpine compressional belt.

The area of Hungary is mainly flat-lying and most of its area are plains with thick sedimentary cover from a few hundred meters up to more than 6000 m of sedimentary sequence. Several formations within this sedimentary sequence are thick sandstones, which are frequently interlayered with clay. In some cases the thick sandstone beds are regionally covered by thick impermeable layers. Hence, Hungary has a relatively high potential for storing carbon dioxide.

3.1.1 Maps of regional storage potential

Detailed mapping, using the publicly available data, was carried out, in order to estimate size and location of potential storage sites in Hungary. All onshore options (i.e., deep saline aquifers, depleted hydrocarbon fields, unmineable coal seams) were studied.

In case of aquifers geological maps, borehole geological and geophysical data were used to select the so-called “base conglomerates” that were deposited in the Middle Miocene to Miocene and represent a high porosity (10%), high permeability (several 100 mD) strata according to borehole geophysical data and hydrocarbon exploitation experience. Seven potential deep saline aquifer storage sites were indicated with a cumulative area of 8170 km². These represent sediment-covered basement highs in Hungary, which are known as the best occurrences for the “base conglomerates”. In these areas, the thickness of base conglomerates can reach 50 m or even higher values. However, 50 m was used as average thickness in the estimations.

Hydrocarbon fields are far better known and were studied in more detail in Hungary thanks to the century-long exploration history of Hungarian hydrocarbon resources. The data shown on the map are hydrocarbon mining areas from the database of the Hungarian Mining and Geological Bureau and do not represent the exact locations of the reservoirs. However, the indicated areas contain the actual reservoirs. In case of the hydrocarbon fields, no publicly available database exists that contains necessary data for all hydrocarbon fields. There is only a database for the largest fields available and this was used to estimate the storage potential in depleted fields in Hungary.

In case of the coal fields the knowledge level of the different occurrences was variable. The Mecsek-area in the southern portion of the country with hard coal layers is well known and well explored. Contrarily the occurrence of lignite, formed in the Pliocene is far less known, excluding the outcropping areas, because the lack of studies in this field. Outside its outcropping area, lignites were only identified in full core borings and accidentally, during oil exploration. Therefore, the lignite occurrences shown on the D10 maps are approximations. In case of the Mecsek-area coals, the reserves were given by the Hungarian Geological Survey, 2007, whereas for the sub bituminous coals (lignites) the reserves were calculated from approximate distribution and thickness of the formation.
3.1.2 Capacity estimation in aquifers

Deep aquifers are amongst the potentially suitable candidates for geological storage of captured CO₂. In Hungary there are no major locations for deepwater utilization, though the thin crust results in an extremely high temperature in shallower depth as well. The average heat flow is 100 mW/m², which is greater than the average on the continent. The thermal gradient is 46–56 °C/km.

Seven large areas, outlining major basement maximums and with proven presence (borehole geological and geophysical data) of thick (~50 m) conglomerate layers were outlined. A depth range from 2000 to 1000 meters were selected, assuming that these units for each individual area are hydrodynamically connected. These aquifers are regional ones. At the moment there is no publicly available database that could be used to define closed structures within the aquifers. Nevertheless, oil exploration and hydrocarbon exploitation experience in these formations demonstrated that the “base conglomerates” are regionally sealed.

Volumes were calculated using the outlined areas and multiplied by the average conglomerate thickness (50 m). Porosities were taken from publicly available databases. Temperature and pressure values were assumed based on average depth (1500 m) and temperature conditions for the aquifers.

In order to estimate the storage capacity of the selected aquifers 2 different methods were used. The method recommended by the CSLF (for more details see GeoCapacity Deliverable D24) using storage efficiency factors 1 to 4% and the “TNO method” where overpressure and closed structure-regional aquifer volume ratios (to include compressibility of the fluid-filled porous system) are taken into account.

Following the “CSLF” method the cumulative storage capacity in the selected aquifers varies between 140–561 Mt CO₂ (with storage efficiency factor 1 and 4 %, respectively), with values somewhat above 14 Mt for the smallest occurrence and above 290 Mt for the largest area (taking 4% storage efficiency factor into consideration). Using the “TNO-method” which seems to be much more conservative than the one recommended by the CSLF the estimated storage capacity is an order of magnitude lower (with efficiency factor of 0.3%, an average depth of 1500 m and the allowable overpressure at 20%). The cumulative storage potential of the selected formations is 42 Mt CO₂. The low cumulative storage capacity is due to the relatively small bulk volume of the regional aquifers and the extremely low compressibility of the fluid filled porous medium (in the order of 10⁻⁵/bar).

3.1.3 Capacity estimation in hydrocarbon fields

The publicly available data for CO₂ storage estimation are partly coming from the Mining and Geological Bureau of Hungary (Mining Bureau of Hungary, 2005). Almost all the potential oil and gas fields in Hungary belong to MOL Rt. More detailed data were only available for the fields used for case studies. There are data about all the locations of the mining areas, but only for the 10 largest oil and 10 largest gas fields ultimate recovery data are given. We had to match the individual mining areas and the available field names (one field has more mining area). The ultimate recovery data for a given field is divided in between the appropriate mining areas. It means that the resulting UR data are not true for a particular mining area, but true for the given field only. Only depth and temperature values were available, hence the CO₂ storage capacity estimation is based purely on the ultimate recovery values and a very conservative estimate of...
oil or gas replacement by CO₂. We have used a formation volume factor for gas and oil (Bgi and Boi) of 0.004 and 1.2, respectively and a CO₂ density of 0.5 t/m³.

The total UR figure of the Hungarian natural gas fields (10 largest) is 168000 Mm³.

Using the formula \( M_{\text{CO₂}} = \text{UR} \times B_{\text{gi}} \times \rho_{\text{CO₂}} \)

the storage capacity was estimated to be 336 Mt. In case of the oil fields the total UR figure is 88 Mm³ (using a very conservative oil density of 1 t/m³). Replacing Bgi, with Boi gives an estimated capacity for CO₂ storage of 53 Mt. Thus, the total sum for the approximated CO₂ storage capacity in the 10 largest Hungarian oil and gas fields is 389 Mt. This can be compared to the annual production of 23 Mt CO₂ by the major point sources in Hungary.

3.1.4 Capacity estimation in coal fields

The estimation of storage capacity in coal fields involved detailed study of 3 major coal fields in Hungary: the Mecsek Coal Formation, MCF, Bukkalja Lignite Formation, BLF and Torony Lignite Formation, TLF were calculated to the interval between 1000–2000 m. The parameters used for estimating the storage capacity are found in Table 3.1 and Table 3.2 below, whereas the method used for estimation is described in D18, D20 and D24.

Table 3.1: Summary of information on individual coal fields/basins in Hungary.

<table>
<thead>
<tr>
<th>Field name</th>
<th>Stratigraphic unit</th>
<th>Formation</th>
<th>Top depth (m)</th>
<th>Coal type</th>
<th>Coal rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mecsek</td>
<td>Jurassic</td>
<td>J1 – Mecsek coal</td>
<td>1150</td>
<td>volatile bituminous</td>
<td>medium</td>
</tr>
<tr>
<td>Toronyi</td>
<td>Miocene</td>
<td>M3 – Toronyi lignite</td>
<td>1000</td>
<td>lignite</td>
<td>low</td>
</tr>
<tr>
<td>Bukkalja</td>
<td>Miocene</td>
<td>M3 – Bukkalja lignite</td>
<td>1100</td>
<td>lignite</td>
<td>low</td>
</tr>
</tbody>
</table>

Table 3.2: Storage capacity estimation for coal fields/basins in Hungary.

<table>
<thead>
<tr>
<th>Field name</th>
<th>PGIP (10⁶ m³)</th>
<th>CO₂ density (t/ m³)</th>
<th>Exchange ratio</th>
<th>Total estimated CO₂ storage capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mecsek</td>
<td>3725</td>
<td>0.002</td>
<td>2.0</td>
<td>14.9</td>
</tr>
<tr>
<td>Toronyi</td>
<td>2189</td>
<td>0.002</td>
<td>9.0</td>
<td>39.4</td>
</tr>
<tr>
<td>Bukkalja</td>
<td>1833</td>
<td>0.002</td>
<td>9.0</td>
<td>33.0</td>
</tr>
<tr>
<td>Total estimated CO₂ storage capacity in coal fields (Mt)</td>
<td>87.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.1.5 Case study 1 - depleted hydrocarbon field, Szeghalom

Introduction

Szeghalom area, a large depleted oil and gas field in the eastern part of Hungary has been selected as one of the case study locations in Hungary. The area is one of the typical hydrocarbon occurrences in Hungary with considerable amount of oil and gas trapped in the basement high that is covered by thick low permeability siliciclastic sediments.

The depleted hydrocarbon field is surrounded by several medium size emission sources, namely power plants. Two plants are modern ones with NGCC technology; one is a gas-fired older power plant and one burns coal and biomass. The four plants produce annually 1.5 Mt CO₂. The
high pressure gas pipeline infrastructure is available in the area and provides a good connection from the power plants to the depleted field.

**Geological background**
In the eastern portion of Hungary, north of the Békés depression several highs, generally composed of metamorphic rocks are present. These highs emerge above the basin centres with 2000–3000 meters. Their formation is related to Miocene extension and core complex formation. The top-most zone of these blocks is always heavily fissured. Above the fissured blocks weathered brecciated material of the blocks can be found, which is covered by several tens of meters of breccia, conglomerate and coarse grained sandstone that was formed from the block-building rocks during Miocene transgression. The coarse grain siliciclastic sediments are always covered by biogene Lithothamnium limestone that has high porosity. Finally the whole sequence is covered by thick clay.

**General description of the Szeghalom field**
Szeghalom hydrocarbon filed is found on one of the blocks northwest of the Békés depression. The studied reservoir is a productive oil reservoir with large gas cap with an extent of 33 km². The storage formation is Miocene sand, conglomerate, breccia and the fissured top-most zone of the metamorphic block. The reservoir is built up of two major structures that are in direct hydrodynamic contact.

The reservoir is situated in the fissured metamorphic block and the coarse grain siliciclastic covering strata. The reservoir rock of the oil is mainly the fissured metamorphic body of the block, with unpleasant reservoir properties. The relatively large amount of oil in the reservoir is poorly accessible, because 1) the oil does not form a coherent body and 2) the fissures are sub-vertical and are well connected to the bottom water, therefore the oil production wells rapidly get wetted by seep-through. Most of the gas is situated in the Miocene strata in more favourable stratigraphic position than the oil. The original gas-oil contact (GOC) was at 1972 m, the original water-oil contact (WOC) at 1995 meters. The porosity is relatively low, around 5%. The OOIP is around 4 Mt, whereas the OGIP around 8000 Mm³.

**Production history of the Szeghalom field**
The reservoir does not behave uniformly, but relatively large pressure differences have evolved between the different parts of the reservoir. Based on the exploitation experience the development of new wells on the reservoir is not possible due to watering. In fact, due to the intensive watering of the reservoir, the production will decay in the near future.

**Emission sources in the 50–100 km vicinity of the depleted HC fields**
There are 6 larger emission sources within the 50–100 km vicinity of the depleted Szeghalom field. Among the 6 emission sources, four are power plants, responsible for the power and heat supply of the area. The two other sources are chemical and glass plants, respectively.

Table 3.3: Large CO₂ point sources near the Szeghalom field.

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Location</th>
<th>X coordinates</th>
<th>Y coordinates</th>
<th>Annual emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) DKCE</td>
<td>Debrecen</td>
<td>47.51866861</td>
<td>21.63044944</td>
<td>0.302379</td>
</tr>
<tr>
<td>2) NYKCE</td>
<td>Nyíregyháza</td>
<td>47.95672806</td>
<td>21.69888167</td>
<td>0.091210</td>
</tr>
<tr>
<td>3) AES Tisza II</td>
<td>Tiszajúváros</td>
<td>47.9168475</td>
<td>21.07592833</td>
<td>0.862381</td>
</tr>
<tr>
<td>4) AES Tiszapalkonya</td>
<td>Tiszapalkonya</td>
<td>47.90586806</td>
<td>21.05853861</td>
<td>0.331095</td>
</tr>
</tbody>
</table>
3.1.6 Case study 2 - depleted hydrocarbon fields, Bajcsa, Barcs and Kiskunhalas

The Pannonpower power plant is a medium-size power plant providing electric and heat power supply for the south-western part of the country, especially the city of Pécs, the fifth largest city of Hungary. The power production was originally based on hard coal, mined in the vicinity of Pécs area, but in the early years of 2000, the plant has made a significant fuel change, switching from coal to biomass and natural gas, dramatically decreasing its annual emissions.

In this case study we have selected 4 depleting oil fields which are believed to be capable of storing the emissions of the power plant for somewhat more than 25 years.

General geology of the Bajcsa field
Natural gas reservoirs occur in Lower Pannonian stratigraphic traps of the Szolnok Formation, a deep water turbidite of the Pannonian sedimentary cycle. The sandstone layers form 7 reservoirs, of which 5 contain natural gas.

The basement is strongly metamorphosed andesite and more mafic vulcanites also occur. Their age is Palaeozoic or Triassic. The basement is discordantly covered by Middle Miocene strata, which has a thickness of 5–290 m with pelitic and coarse grain sandstone and also conglomerates. The Tortonian sediments are 10–100 m thick. They are sandy at the bottom of the sequence, whereas at higher levels volcanic layers frequently occur. These rocks are covered with Sarmatian marl with about 18 to 150 m thickness. Lithologically they are dominated by marls, calcareous marls, rarely with thin sandstones. The Miocene sediments are covered by thick Pannonian sedimentary sequence. Sandstone, sandy clay and claymarl are the dominant rock types. The source rocks are Miocene and Lower Pannonian marls rich in organic matter.

General geology of the Barcs field
The whole reservoir behaves as a single hydrodynamic unit. It occurs on the eastern flank of the Dráva Basin. The deeper part of the reservoir consists of medium grade metamorphic rocks. It is largely composed of the Permian Volcanic Complex and Triassic quartzite, dolomite and dolomite breccia. The Triassic rocks are directly covered by Miocene sandstones and conglomerates. There is continuous sedimentation in the area from the Badenian to the Late Pliocene, except for the Sarmatian. The Lower Pannonian consists of alternating claymarls and sandstones with thickness around 15–40 m. The cumulative thickness of this sequence can reach 1000 m. The reservoir itself is a cracked horst and is strongly heterogeneous in terms of reservoir parameters.

General geology of the Kiskunhalas field
The field is an oil reservoir with large gas cap. It consists of fractured metamorphic rocks and carbonates with karstic alteration. The metamorphic rocks are strongly tectonized, mylonitized and brecciated on the top of the occurrence. The carbonates are limestones and dolomites of Lower Cretaceous age. These rocks are covered by Miocene conglomerates and Lithothamnium limestones. Followed by Pliocene sediments, dominantly marls. The whole reservoir is very heterogeneous.

The emission source
The largest, and practically only large point source in the SW-Hungary region is the Pannonpower power plant. The power plant produces energy (electric and heat) for the region, especially for the city of Pécs, which is the 4th largest city in Hungary with almost 160 000 inhabitants. The power plant is a combined heat and power generating plant. Its energy
production was based on coal until 2004, mined in the nearby open pit and deep mines. Since 2004 the fuel has been replaced by natural gas and biomass (mainly woodchips). With this fuel switch, the emissions have undergone drastic changes, from 1604 kt in 2003 to 255 kt in 2005. Most important capacity data are summarized in Table 3.4 below:

- Energy production 250 MWe
- Heat production : 225 MWth
- Steam production: 25 MWth

Table 3.4: Large CO₂ point source near the fields.

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Location</th>
<th>X coordinates</th>
<th>Y coordinates</th>
<th>Annual emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pannonpower Rt.-Hőerőmű</td>
<td>Pécs</td>
<td>46.064125</td>
<td>18.26304389</td>
<td>0.2558</td>
</tr>
</tbody>
</table>

3.1.7 Country summary

In 2006, total emissions of greenhouse gases in Hungary, were 78.6 Mt carbon dioxide equivalents. With less than 8 t, the Hungarian per capita emissions are below the European average. By ratifying the Kyoto Protocol, Hungary committed to reducing its GHG emissions by 6%. Now, our emissions are 32% lower than in the base year (average of 1985–87). However, this significant reduction is a consequence of radical decline in the output of the national economy, the production decreased in almost every economic sector including also GHG relevant energy, industry and agriculture.

Emissions decreased by 2% (−1.6 Mt) between 2005 and 2006. However, there is no significant trend in the emissions of the last 10 years, they fluctuate around 79 Mt.

Point source emissions in 2005 added up to somewhat above 28.5 Mt, out of which about 23 Mt comes from large point sources with emissions above 0.1 Mt. Almost 75% of the large point source emissions come from power industry (electricity and/or heat generation).

In Hungary, which is dominantly covered by sedimentary basins there are several available geological storage options (i.e., saline aquifers, depleted hydrocarbon fields, coal seams) to store the emissions of large point sources. However, due to restricted access to data concerning some important information is missing from the capacity estimation of the potential storage sites. The largest possible storage could have been attributed for the deep saline aquifers, but only a very basic, speculative estimation is presented in this report.

Using the ultimate recovery method for hydrocarbon reservoirs a storage capacity of 408 Mt was estimated. In case of saline aquifers both the “TNO” method and the one recommended by CSLF were used to estimate the storage capacity. The former method gives a relatively low value of 40 Mt for the 8000 km² and 50 m average thickness of aquifers. Whereas the CSLF method gives values in the range of 140–560 Mt depending on the magnitude of efficiency factor used. Storage capacity of unmineable coal seams was estimated using the method recommended by the CSLF. Storage capacity estimates applied in the selected fields (1 Jurassic, 2 Pliocene fields) give storage potential around 87 Mt.
Table 3.5: CO₂ emissions and storage capacity estimates in Hungary.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2005</td>
<td>23</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2006</td>
<td>79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>theoretical</td>
<td>140</td>
<td>561</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>effective</td>
<td>389</td>
<td>389</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>effective</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td>effective</td>
<td>616</td>
<td>1037</td>
</tr>
</tbody>
</table>
Figure 3.1: Map of CO₂ emissions, infrastructure and storage capacity in Hungary.
3.2 Romania

Romania is situated in the south-eastern part of Central Europe. It has an area of 238,390 km², of which 62 percent is under agriculture, 27 percent is forest (all managed), and 4 percent is water. Due to its geographical position and relief, the country has a temperate continental climate. Of the total population, which amounted to 22.731 million in 1994, around 55 percent inhabit urban areas. Between 1989, the country’s base year, and 1994 the population decreased by around half a million inhabitants, and projections indicate a continuation of this trend.

![Simplified Geological Map of Romania](image)

Figure 3.2: Simplified Geological Map of Romania.

The Romanian territory is included in the general geological ensemble of Central and South-East Europe as a part of the Alpidic pericratonic belt of Carpathians–Balkans + Rhodopes–Pontides, of the intracratonic belt North Dobroudja–South Crimea–Great Caucasus as well as of their foreland represented by the East European Platform, the Central European Platform (Scythian Platform) and the Moesian Platform. The Alpidic system, represented in the Western Europe by a single belt, continues to the East in two branches: the Dinaric Alps with a Southeast direction and the Carpathians and Balkans, developed to the North and East with a specific sigmoidal pattern up to the Black Sea basin. Between the two mentioned branches, a large, sunk intracarpathic region is developed, represented by the Pannonian, Vienna, Western Danube, Transylvania and Maramures molassic depressions. Inside the intracarpathic region some mountain ranges are present, the main being Apuseni Mountains (in Romania) and Bukk, Bakony, Mecsek and Villany (in Hungary). The orogenic belt of Carpathians was built during the closure of the Tethys ocean, the most important geological events occurring in Cretaceous and Miocene. Its main tectonic units were formed by the deformation of the Tethys ocean domain and its continental margins, complicated by rifts and marginal basins. As a result of the
various stages of compression, the former ocean was transformed to the present belt, showing, in its central part, some remnants of basaltic crust of the major Tethysian suture. The three platforms and the intracratic belt of the Northern Dobroudja have their extensions in the continental shelf of the Black Sea. The Carpathian belt may be divided into three longitudinal segments: the Western Carpathians (in Czechoslovakia and Poland), Eastern Carpathians (in the Ukraine and Romania) and Southern Carpathians (in Romania and Serbia). Each segment can be further divided into three major tectonic elements: the Inner Carpathians, the Outer Carpathians and the Carpathian Foredeep. The Carpathian foreland includes platforms of different ages. The oldest one is the East European platform, having a Precadomian basement, covered by Riphean–Neogene sediments. This platform is bordered to the south and west by the Central European (Scythian) Platform of Hercinian age, covered by Upper Palaeozoic–Neogene sediments. To the south-west of the Alpine Intracratonic Belt of Northern Dobroudja and Southern Crimea, as well as to the south-west of the Scythian Platform, the Moesian Platform develops, with Cadomian basement covered by Middle Cambrian–Neogene sediments.

3.2.1 Maps of regional storage potential

It is now almost unanimously accepted in the international scientific community that the Earth’s climate changes have anthropogenic causes, first of them being the greenhouse gas (GHG) emissions among which the carbon dioxide occupies the main place. It is emitted in the atmosphere mainly from industrial installations and vehicles with engines with internal combustion engines. They reach 30.000 Mt every year, while the concentration of carbon dioxide in the atmosphere is now at 380 ppm and growing at a rate of over 2 ppm per year.

Worldwide efforts are made to reduce such emissions.

If for the transport vehicles the solutions lie in more efficient engines, hybrid propulsion or even hydrogen combustion, for fixed industrial installations the efforts are toward improving the installations efficiency as well as capture of CO₂ emitted.

One, probably the only feasible solution of disposing of the captured CO₂ is its safe storage for long periods of time if not forever, the best being the geological storage (Bennaceur et al., 2004). After all, the fossil fuels used today (coal, oil, gas) that produces the unwanted gas are extracted from the earth, it is only logical that the carbon left after the humans have taken and used the energy to be returned back in the earth (Schiermier, 2006).

Romania is a European country with a long and documented history of hydrocarbon production and an earlier leader in application of geophysical methods for exploration and field development. The first oil production of the world has been officially recorded in Romania, in 1857, at a rate of 275 t/year (1719 bbl). This is one year ahead of William’s well at Oil Springs in Ontario and two years before Drake’s discovery well in Pennsylvania. However, foreign travellers since the first half of the 16th century have mentioned the extraction of crude in the Romanian provinces of Moldavia and Wallachia. In 1900, Romania was the third largest oil producer of the world with a production of 0.3 Mt/year (1.855×10⁶ bbl). During 1953–1955 the oil output of Romania was around 9 to 10 Mt/year (60.291×10⁶ bbl), and in 1976 a maximum of oil output of 14.6 Mt (91.219×10⁶ bbl), was achieved (See Figure 3.3 below).

After the Second World War the oil production of Romania have drastically diminished to 3.8 Mt (23.9×10⁶ bbl), and some of the production went to pay for war reparations. Over 23,300
wells have been drilled in Romania, discovering 19.2 Billion barrels of oil-in-place and 23.7 Tcf gas-in-place, located in 473 oil and 201 gas reservoirs. Some of the fields were earlier classified as giants, but their production has substantially declined since (e.g. Moreni, Baicoi, Boldesti). 40% of the Romanian oil production is obtained by secondary technologies as water, air, CO₂ injection, underground combustion and others.

Figure 3.3: Romanian oil production.

New producing areas were discovered in the Moesian Platform, Getic Depression, Pannonian Depression, Moldavian Platform, North-Dobrogean Promontory and Black Sea shelf. In the same time new oil and gas fields were discovered in the older producing areas of East Carpathians, the Miocene–Pliocene zone and the Transylvanian Depression. The peak of hydrocarbon production was reached in 1976 with 14.6 Mt (91.219×10⁶ bbl), and 34 billion cubic meters of gas. After 1976, crude production in Romania first decreased gradually and then more rapidly during the eighties, reaching 6.8 Mt (42.778×10⁶ bbl), in 1990.

Detailed mapping, using the publicly available data, was carried out, in order to estimate size and location of potential storage sites in Romania. All onshore options (i.e., deep saline aquifers, depleted hydrocarbon fields) where studied.

3.2.2 Capacity estimation in aquifers

As far as the authors are aware, until now there are no generally accepted standards and methodologies to calculate and even estimate the CO₂ storage capacity of a formation, structure, basin, area, country and even at worldwide level. That explains in part the wide variety of published results on estimates made by various authors based on various data and various computing procedures (Bradshaw et al., 2006). However, a worldwide capacity estimate accepted by IEA - GHG in 2004 is of 400–10,000 Gt in deep saline aquifers, 980 Gt in depleted oil and gas reservoirs and 30 Gt in unmineable coal seams (CO₂ NET, 2006).

When calculating capacity, several types of estimates can and often are made, depending on the nature and purpose of the assessment and they all lie across different regions of the resource pyramid (Bradshaw et al., 2006). This pyramid considers three technical and economic categories named Theoretical, Realistic and Viable Capacity.
It is evident that our estimations falls at the base of the pyramid being the first of this sort ever carried out in Romania.

For the capacity calculations in saline formations we have used a volumetric equation recommended by many authors (RCSP, 2006, Bachu, 2007, etc):

\[ G_{CO2} = A \times h \times \phi \times \rho \times E \]

Where

- \( G_{CO2} \) (Mt): Storage capacity
- \( A \) (Sq. km): Area that defines the region being assessed
- \( h \) (km): Gross thickness of the saline formation(s)
- \( \phi \) (%): Average porosity of entire saline formation(s) over thickness \( h \)
- \( \rho \) (Mt/Sq.km): Density of \( CO_2 \) evaluated at reservoir pressure and temperature
- \( E \) (%): \( CO_2 \) Storage Efficiency Factor

As almost everywhere in the world the saline aquifers are poorly known. So in calculating their storage capacity we had to introduce several estimations (especially on reservoir thickness and porosity). The Romanian sedimentary basins potentially containing saline formations have been combined in 4 big zones (Moesian platform and S. Carpathians foredeep, Moldavian platform and E. Carpathians foredeep, Transylvanian basin and Pannonian basin). Out of their total surface areas, the surface with sedimentary cover thinner than 800 m have been eliminated from calculations as such areas are not suitable for \( CO_2 \) storage. The efficiency factor considered is only 2% as was recommended by \( CO_2 \) GeoCapacity studies. The results are presented synthetically in Table 3.6.

Table 3.6: Estimated \( CO_2 \) storage capacity in deep saline aquifers in Romania.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Surface area (km²)</th>
<th>Reservoir geological formations</th>
<th>Estimated reservoir Thickness (m)</th>
<th>Estimated porosity</th>
<th>( CO_2 ) storage capacity (Gt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moesian Platform and South Carpathians Foredeep</td>
<td>38.000</td>
<td>Pontian Meotian Sarmatian Cretaceous Triassic</td>
<td>70</td>
<td>0.20</td>
<td>5.2</td>
</tr>
<tr>
<td>Moldavian Platform and East Carpathians Foredeep</td>
<td>24.000</td>
<td>Sarmatian Tortonian</td>
<td>50</td>
<td>0.20</td>
<td>2.5</td>
</tr>
<tr>
<td>Transylvanian Depression</td>
<td>22.000</td>
<td>Buglovian Sarmatian Tortonian</td>
<td>200</td>
<td>0.20</td>
<td>8.8</td>
</tr>
<tr>
<td>Pannonian Depression</td>
<td>15.000</td>
<td>Pannonian Tortonian Cretaceous</td>
<td>70</td>
<td>0.20</td>
<td>2.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.6</td>
</tr>
</tbody>
</table>

Efficiency factor = 2%
3.2.3 Capacity estimation in hydrocarbon fields

The CO₂ storage capacity in depleted or declining hydrocarbon (oil and gas) fields can be calculated either by a similar volumetric equation or by a production-based equation if acceptable records of volume of hydrocarbons produced are available. It is only necessary to apply an appropriate formation volume factor (B) to convert hydrocarbon volumes reported as production to subsurface volumes. The equation is of the form:

\[ G_{CO2} = URP \times B \times \rho \]

where \( URP \) is the Ultimate Recoverable Oil (or Gas) based on sum of produced volumes and expected reserves.

Romania has a history of 150 years of oil industry. It is estimated that during such a long period of time, some 720 Mt of oil and 1122 Gm³ have been extracted from its underground (Gilbert, 2007). Today it may be considered a “mature” oil and gas province with 70–80 percent of its resources already exploited. However, the percentage of hydrocarbons produced varies in various geological units (see Table 3.7).

Our calculations were based on total oil and gas reserves in each region. It was assumed that in 20–30 years the majority of remaining hydrocarbons will be exploited and more fields will become depleted and hence available for CO₂ storage. On the other hand, the same time span of 20–30 years will probably be the period until the CO₂ storage will become a mature technology for disposing of the unwanted gas and such a technology will be employed on a large scale. Also the possibility of using EOR and EGR should be taken into consideration.

Table 3.7: Estimated CO₂ storage capacity in oil and gas deposits in Romania.

<table>
<thead>
<tr>
<th>Geological Units</th>
<th>Produced Mt oil</th>
<th>Gm³ gas</th>
<th>Produced estimated % oil</th>
<th>% gas</th>
<th>Total Mt oil</th>
<th>Gm³ gas</th>
<th>Gt CO₂ capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Oil d.</td>
</tr>
<tr>
<td>Pannonian depr.</td>
<td>47</td>
<td>25</td>
<td>80</td>
<td>85</td>
<td>57</td>
<td>29</td>
<td>0,03</td>
</tr>
<tr>
<td>Transylvanian depr.</td>
<td>-</td>
<td>772</td>
<td>-</td>
<td>85</td>
<td>-</td>
<td>908</td>
<td>-</td>
</tr>
<tr>
<td>Barlad Depression</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N. Dobrogean Pro.</td>
<td>6</td>
<td>13</td>
<td>6</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>East. Carpathians</td>
<td>377</td>
<td>90</td>
<td>85</td>
<td>90</td>
<td>560</td>
<td>100</td>
<td>0,34</td>
</tr>
<tr>
<td>Getic Depression</td>
<td>120</td>
<td>125</td>
<td>70</td>
<td>65</td>
<td>156</td>
<td>192</td>
<td>0,09</td>
</tr>
<tr>
<td>Moesian Platform</td>
<td>169</td>
<td>95</td>
<td>75</td>
<td>70</td>
<td>211</td>
<td>136</td>
<td>0,13</td>
</tr>
<tr>
<td>Total</td>
<td>720</td>
<td>1122</td>
<td></td>
<td></td>
<td>981</td>
<td>1384</td>
<td>0,59</td>
</tr>
</tbody>
</table>

Formation volume factor : Total \( 4,00 \)
Oil \( 1,5 \)
Gas \( 0,005 \)
CO₂ density \( 0,5 \)

3.2.4 Capacity estimation in coal fields

The Romanian coal fields do not offer appropriate conditions for CO₂ storage.

3.2.5 Case study Ghercesti – Malu Mare

Geological background
The Ghercesti-Carcerea-Malu Mare structure is located in the north and the east part from the city of Craiova, in the south-eastern portion of Romania. This structure is situated in the western
sector of Moesian Platform and is constituted by anticlines oriented N-S and W-E. The structure contains oil and associated gases in the Dogger level and free gases in the Dogger and Pontian levels. The wells drilled on this structure revealed three sedimentation cycles: Late Permian–Triassic, Dogger–Cretaceous, Badenian–Pleistocene. The oil is contained in Middle Jurassic (Dogger) deposits. There are two complexes: Dogger I and Dogger II. The Dogger I complexes consists of sands, limy sandstones, siliceous sandstones, limestones, dolomites, marls, shales and siderites. The complex has a width of 130 m at Simnic and 40–90 m at Malu Mare. Dogger II has a mixed character. It consists of breccias, micro conglomerates, siliceous sandstones, marls, limy sandstones. The Pontian level is disposed continuously over Meotian deposits. This level is formed of marly deposits of 150–200 meters thickness, 30–50 meters of marly sands and 20–30 meters of gray-yellowish marls.

Description of the selected reservoir
The Ghercesti-Carcea-Malu Mare structure is located in the western part of the Moesian Platform and corresponds to an uplift. From a structural point of view, there are three culminations along the Ghercesti-Carcea-Malu Mare uplift as well as numerous tectonic accidents. The studied structure is compartmentalized in several blocks by longitudinal and transversal faults. The hydrocarbons are located in the Dogger complexes I and II. Dogger I has a narrow oil band situated around the big gas cap throughout the three structures. The same situation is encountered in the Dogger II. Free gas deposits are known in both complexes. The water-oil contact corresponds to the isobath of 1584–1592 and the gas-oil limit to the isobath of 1575–1578. The Ghercesti structure has four gas cap oil deposits and an oil deposit in Dogger I. The Carcea structure has five gas cap oil deposits in Dogger I. The Malu Mare structure has three free gas deposits and a cap gas deposit in Dogger I and six free gas deposits in Dogger II. At the Pontian level there are five faults: Ghercesti, Carcea, Malu Mare and Urechesti. The Pontian is marked in this zone by the existence of a sand bed. The effective thickness of this sand bed varies between 2 and 30 m. The Pontian sands contain free gas, especially at Ghercesti.

Production history
The first drilled wells lead to the discovery of the Pontian free gas reservoir. Later exploration investigations made in Mesozoic structures revealed Dogger hydrocarbon reservoirs. The exploitation on the Ghercesti structure started in 1959 with 25 t/day and ended with 0.5 t/day in 1978. Up to 1975 452 kt oil was produced. In the period 1976–1986 were extracted 4.57 kt oil. The production in the Carcea structure started in 1961 with 50 t/day and decreased in eight years to 2 t/day, ending in 1984 with 0.5 t/day. Up to 1978 90 % of oil was extracted (716 kt). The remaining 10 % were extracted in the period 1979–1989. The exploitation on the Dogger I level from Malu Mare structure started in 1966 with 4 t/day. Up to 1978 99 % of oil was extracted. The remaining 1 % was extracted in the period 1979–1989.
Figure 3.4: Location of Romanian Case studies.

Table 3.8: Reservoir geological parameters.

<table>
<thead>
<tr>
<th>Field</th>
<th>Ghercesti, Dg I</th>
<th>Caracea, Dg I</th>
<th>Malu Mare, Dg I</th>
<th>Malu Mare, Dg II</th>
</tr>
</thead>
<tbody>
<tr>
<td>X coordinates</td>
<td>298104.84</td>
<td>298586.10</td>
<td>298706.40</td>
<td>-</td>
</tr>
<tr>
<td>Z coordinates</td>
<td>5256299.27</td>
<td>5248587.40</td>
<td>5246659.42</td>
<td>-</td>
</tr>
<tr>
<td>WOC [m]</td>
<td>1584</td>
<td>1592</td>
<td>1587</td>
<td>-</td>
</tr>
<tr>
<td>GWC [m]</td>
<td>-</td>
<td>-</td>
<td>1573</td>
<td>1575</td>
</tr>
<tr>
<td>GOC [m]</td>
<td>1575</td>
<td>1575</td>
<td>1578</td>
<td>-</td>
</tr>
<tr>
<td>Etage [m]</td>
<td>190</td>
<td>180</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>22</td>
<td>16</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Initial pressure [atm]</td>
<td>158</td>
<td>158</td>
<td>158</td>
<td>158</td>
</tr>
<tr>
<td>Initial temperature [ºC]</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Boi [m3/m3]</td>
<td>1.32</td>
<td>1.32</td>
<td>1.32</td>
<td>-</td>
</tr>
<tr>
<td>Bgi [m3/m3]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0062</td>
</tr>
<tr>
<td>O.O.I.P [kt]</td>
<td>2235</td>
<td>2569</td>
<td>225</td>
<td>-</td>
</tr>
<tr>
<td>O.G.I.P (cap) [Mm3]</td>
<td>1089</td>
<td>948</td>
<td>32</td>
<td>629</td>
</tr>
<tr>
<td>O.G.I.P (solved) [Mm3]</td>
<td>408</td>
<td>435</td>
<td>35</td>
<td>931</td>
</tr>
<tr>
<td>Producible oil [kt]</td>
<td>457</td>
<td>716</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>Producible cap gas [Mm3]</td>
<td>-</td>
<td>-</td>
<td>79</td>
<td>232</td>
</tr>
<tr>
<td>Producible solved gases [Mm3]</td>
<td>495</td>
<td>683</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>CO₂ storage capacity [Mt]</td>
<td>9.59</td>
<td>8.75</td>
<td>2.44</td>
<td>3.56</td>
</tr>
</tbody>
</table>
Table 3.9: Emission sources in the 50–100 km vicinity of the HC fields.

<table>
<thead>
<tr>
<th>No.</th>
<th>Powerplant</th>
<th>Location</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Annual emission (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S.C. Energy Complex Rovinari S.A.</td>
<td>Rovinari</td>
<td>23°09'05.55&quot;</td>
<td>44°55'47.53&quot;</td>
<td>6.103822</td>
</tr>
<tr>
<td>2</td>
<td>S.C Govora Power Plant SA</td>
<td>Ramnicu Valcea</td>
<td>24°17'12.25&quot;</td>
<td>45°03'05.72&quot;</td>
<td>1.585185</td>
</tr>
<tr>
<td>3</td>
<td>S.C. Energy Complex Turceni S.A.</td>
<td>Filiasi</td>
<td>23°24'30.93&quot;</td>
<td>44°40'32.60&quot;</td>
<td>6.837217</td>
</tr>
<tr>
<td>5</td>
<td>S.C. Energy Complex Craiova S.A. - SE Craiova II</td>
<td>Craiova</td>
<td>23°48'44.79&quot;</td>
<td>44°20'54.34&quot;</td>
<td>2.022746</td>
</tr>
</tbody>
</table>

3.2.6 Case study Tataru

Geological background

Tataru field is located in the Miocene–Pliocene subzone in Muntenia. This region is characterized diapir origin of most of the structures which are disposed along at least five main alignments, parallel, in general, to the Carpathian chain. The Miocene–Pliocene subzone constitutes one of the most prolific zones of accumulation in Romania in which numerous hydrocarbon deposits, located in Oligocene, Burdigalian–Helvetian, Sarmatian, Meotian, Pontian, Dacian and Levantine have been discovered. Tataru structure is situated 40 km NE from Ploiesti and is disposed between the structural alignments Boldesti and Ceptura-Ur-latı -Malu Rosu. The drillings carried in this area revealed geological formations from Miocene and Pliocene. Hydrocarbon accumulations (petroleum) were highlighted in Meotian. The petroleum is loaded in the Meotian sands, protected by the Pontian marls. The trap is of structural type.

Description of the selected reservoir

Tataru hydrocarbon field is found in the Miocene–Pliocene subzone in Muntenia, on the internal flank of the Carpathian Foredeep. The studied reservoir is a productive oil reservoir. The storage formation is Miocene sands protected by the Pontian marls. The structure has the form of a faulted anticline oriented W–E, affected by a system of longitudinal and transversal faults. This system of faults divides the structure in several tectonic blocks, from which only one quarters hydrocarbon accumulations. Tataru reservoir is loaded in the western, more sunk pericline in whose axis outcrops the Meotian. The formations intercepted by the wells are Sarmatian, Meotian and Pontian. The Sarmatian deposits were intercepted by 13 wells. The inferior level is 800 m thick and is represented by marls. The superior level has a maximum thickness of 200 m and presents a succession of marls, sands and limestones. All the production probes effectuated on Sarmatian deposits infirmed the presence of hydrocarbons. The Moetian was intercepted by all the wells in this area and has a maximum thickness of 600 m. The Moetian was divided in three sandy complexes: Me II (140–150 m thick), Me int (25–30 m thick) and Me I (140–150 m thick). Till present only Me II is known to carry hydrocarbons. The Pontian is the last stratigraphical formation intercepted by most of the wells and has a maximum thickness of 500 m. Pontian is represented by marls and constitutes the protective rock of the Moetian oil reservoir. The reservoir is situated in the Meotian sands protected by the Pontian marls. Tataru structure is an oil and dissociated gases reservoir loaded in a structural trap. The reservoir has no primary gas cap. The reservoir rock is marly sand, thin and poor consolidated. The average
porosity is 20%. The current reservoir pressure is 11 atm. The medium depth of the reservoir is 750 m.

Production history
The first wells, drilled in the period 1925–1935, had initial output of 15–16 t/day. In the period 1935–1950 the reservoir has not been exploited. In 1950 was drilled here a well with an eruptive start of 18 t/day. It produced till 1952 862 t of oil and 21000 Stm3 associated gases. The exploitation was stopped again in the period 1953–1964. In 1964–1965 were drilled three wells with the initial production of 2–4 t/day. Two of them were abandoned in 1981. Their final production was 0.2–0.5 t/day. In 1984–1985 were drilled other three wells, with an initial output of 1–4.5 t/day. The exploitation developed uninterrupted till 1997, when was stopped the final well with a final production of 0.5 t/day. In 2000 were restored two wells with an initial production of 0.2 t/day, 1 t/day respectively. The exploitation of the field was stopped in 2006. Till 2007, 41000 t of oil has been extracted (10 % of initial oil resources) and 1.5 millions Stm3 associated gases (10.7 % of initial gas resources).

Table 3.10: Reservoir geological parameters.

<table>
<thead>
<tr>
<th>Field</th>
<th>Tataru</th>
</tr>
</thead>
<tbody>
<tr>
<td>X coordinates</td>
<td>480047.6639</td>
</tr>
<tr>
<td>Z coordinates</td>
<td>5348964.1206</td>
</tr>
<tr>
<td>WOC [mbsl]</td>
<td>711</td>
</tr>
<tr>
<td>Etage [m]</td>
<td>456</td>
</tr>
<tr>
<td>Porosity [%]</td>
<td>18–26</td>
</tr>
<tr>
<td>Avg water saturation [%]</td>
<td>40</td>
</tr>
<tr>
<td>Initial pressure [atm]</td>
<td>40</td>
</tr>
<tr>
<td>Initial temperature [°C]</td>
<td>31</td>
</tr>
<tr>
<td>Boi [m3/m3]</td>
<td>1.05</td>
</tr>
<tr>
<td>Bgi [m3/m3]</td>
<td>0.0242</td>
</tr>
<tr>
<td>O.O.I.P [kt]</td>
<td>409</td>
</tr>
<tr>
<td>O.G.i.P (solved) [Mm3]</td>
<td>13</td>
</tr>
<tr>
<td>Producible oil [kt]</td>
<td>41</td>
</tr>
<tr>
<td>Producible solved gases [Mm3]</td>
<td>2</td>
</tr>
<tr>
<td>CO₂ storage capacity [Mt]</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 3.11: Emission sources in the 50–100 km vicinity of the HC fields.

<table>
<thead>
<tr>
<th>No.</th>
<th>Powerplant</th>
<th>Location</th>
<th>Longitudes</th>
<th>Latitudes</th>
<th>Annual emission (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S.C. Termoelectrica S.A. - SE Doiçeşti</td>
<td>SE Doiçeşti</td>
<td>25°23'36&quot;.13</td>
<td>44°59'48&quot;.31</td>
<td>0.192023</td>
</tr>
<tr>
<td>2</td>
<td>S.C. Petrotel - Lukoil S.A.</td>
<td>Teleajen</td>
<td>26°03'30&quot;.48</td>
<td>44°57'10&quot;.07</td>
<td>0.850224</td>
</tr>
<tr>
<td>3</td>
<td>S.C. Dalkia Thermo River SRL - Point of Brazi</td>
<td>Brazi</td>
<td>25°59'16&quot;.48</td>
<td>44°53'14&quot;.85</td>
<td>0.340204</td>
</tr>
<tr>
<td>4</td>
<td>S.C. Electrocentrale Bucharest SA - SE Bucharest - Bucharest West PP</td>
<td>Bucharest</td>
<td>28°58'56&quot;.43</td>
<td>44°25'40&quot;.45</td>
<td>0.645957</td>
</tr>
<tr>
<td>5</td>
<td>S.C. Electrocentrale Bucharest SA - SE Bucharest - Grozăveşti PP</td>
<td>Bucharest</td>
<td>26°03'49&quot;.48</td>
<td>44°26'43&quot;.47</td>
<td>0.304473</td>
</tr>
<tr>
<td>6</td>
<td>S.C. Electrocentrale Bucharest SA - SE Bucharest - Bucharest South PP</td>
<td>Bucharest</td>
<td>26°09'16&quot;.54</td>
<td>44°24'35&quot;.45</td>
<td>1.489860</td>
</tr>
<tr>
<td>7</td>
<td>S.C. Electrocentrale Bucharest SA - SE Bucharest - Progresu PP</td>
<td>Bucharest</td>
<td>25°53'16&quot;.48</td>
<td>44°53'14&quot;.85</td>
<td>0.678890</td>
</tr>
</tbody>
</table>

3.2.7 Country summary

With regard to domestic primary energy production, in 1998, natural gas had the highest share (39%), followed by crude oil (21%), lignite and hard coal (18%), hydroelectricity and nuclear power (11%), and wood and other fuels (11%). Since 1989 the production of natural gas has fallen due to resource depletion, while coal output has been affected by low productivity and high production costs. Imports of crude oil, oil products, natural gas, coal, coke and electricity has also dropped by half between 1989 and 1994. In 1994, imported energy constituted around 26 per cent of primary energy consumption. Uranium reserves are expected to last another 20 years or so, based on current consumption trends and crude oil reserves another 20 to 30 years.

The CO₂ emissions from large stationary point sources included in the GeoCapacity database are presented below as well as the storage capacity in aquifers and in hydrocarbon fields are presented in Table 3.6 and Table 3.7 (see section 3.2.2 and 3.2.3) and a country summary is given in Table 3.12.

74.4 Mt allowances of CO₂ was allocated for the year 2007 to 244 industrial installations of Romania (mentioned with black numbers in Figure 3.5). The method used for allocation is a combination of the historical approach and forecast approach. The base year for CO₂ emissions projections is the year 2003. The historical reference period is 2001–2004. The relevant emissions of an installation are the average emissions of the two years with the highest emissions within the historic reference period. The sectors distinguished are: Energy, Refineries, Production and processing of ferrous metals, Cement, Lime, Glass, Ceramics, Pulp and paper (see Figure 3.5). From 244 industrial installations with CO₂ allowances, only 63 (mentioned with red numbers in Figure 3.5) have significant emissions (>0.1 Mt CO₂).
Figure 3.5: Distribution and number of industries with CO₂ allowances.

Table 3.12: CO₂ emissions and storage capacity estimates in Romania.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2007</td>
<td>67</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2007</td>
<td>74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Theoretical</td>
<td>7500</td>
<td>18600</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Theoretical</td>
<td>1500</td>
<td>4000</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td>theoretical</td>
<td>9000</td>
<td>22600</td>
</tr>
</tbody>
</table>
Figure 3.6: Map of CO₂ emissions, infrastructure and storage capacity in Romania.
3.3 Bulgaria

3.3.1 Capacity estimation in aquifers

The assessment of CO₂ storage capacity in deep saline aquifers in Bulgaria is based on evaluation of 2 individual structures and 6 local zones. The capacity estimates in the GeoCapacity database for all of them have been calculated according to the methodology described for deep saline aquifers in GeoCapacity deliverable D24 Storage capacity standards, using the formula:

\[ M_{CO2t} = A \times h_{ef} \times \phi \times \rho_{CO2r} \times S_{eff} \]

where:

- \( M_{CO2t} \): “trap” storage capacity
- \( A \): area of aquifer in trap
- \( h_{ef} \): average effective thickness of aquifer (best estimate)
- \( \phi \): average reservoir porosity of aquifer (best estimate)
- \( \rho_{CO2r} \): CO₂ density at reservoir conditions (best estimate)
- \( S_{eff} \): storage efficiency factor (for trap volume)

The area of the structures has been determined based on contour maps of stratigraphic horizons near or at the top of the reservoir formation. Thickness, net to gross ratio and porosity have been evaluated using data from exploration wells drilled on the structure.

The CO₂ density varies with depth as a function of pressure and temperature and has been estimated using different diagrams.

The aquifer systems surrounding and connected to the reservoir formations in the selected individual structural traps and zones have been assumed to be open or semi-closed. Based on the approach, described for open and semi-closed aquifers in GeoCapacity deliverable D24 Storage capacity standards, a storage efficiency factor between 5 % and 10 % for the different aquifers has been assumed. This results in a total effective storage capacity of 2658 Mt CO₂ for all 8 selected aquifer subjects.

This estimate for CO₂ storage capacity in deep saline aquifers in Bulgaria can be characterized as slightly conservative because the used values for some calculative parameters in the used formula are a little bit less than expected. So, in further investigations and qualification of selected aquifer structures and zones there are real opportunities for increasing of aquifers potential.

A more conservative estimate has been calculated in this report for comparison with the estimates in the database. The conservative estimates have been calculated assuming that the aquifer systems surrounding are with more changeable characteristics than was accepted. This more conservative evaluation approach results in a total effective storage capacity of 2100 Mt CO₂.
3.3.2 Capacity estimation in hydrocarbon fields

The assessment of CO\textsubscript{2} storage capacity in Bulgarian hydrocarbon fields is based on evaluation of all discovered 12 economic fields. However most of them are out of right depth interval for effective CO\textsubscript{2} storage, which is 800–2500 m. Only in two gas fields the depth window for the reservoirs is favourable. But one of them was converted into sub-surface gas storage in 1974 and still operating.

So, only one gas field (located offshore) was considered for estimation of CO\textsubscript{2} storage capacity. Nevertheless that the field is small, it suggests good opportunities for CO\textsubscript{2} storage (excellent reservoir parameters and depth). However there is a big interest for conversion of this field after depletion into sub-surface gas storage.

The capacity estimates in the GeoCapacity database have been calculated according to the methodology described for hydrocarbon fields in GeoCapacity deliverable D24 Storage capacity standards, using the formula:

\[
M_{\text{CO}2} = \rho_{\text{CO2r}} \times UR_p \times B
\]

where:

- \(M_{\text{CO2}}\): hydrocarbon field storage capacity
- \(\rho_{\text{CO2r}}\): CO\textsubscript{2} density at reservoir conditions (best estimate)
- \(UR_p\): proven ultimate recoverable oil or gas reserves
- \(B\): oil or gas formation volume factor

The CO\textsubscript{2} density varies with depth as a function of pressure and temperature and has been estimated using diagrams.

\(UR_p\) is given as the sum of produced volumes and the low estimate for residual recoverable reserves.

The formation volume factor for oil varies regionally depending on the oil type and a fixed formation volume factor of 1.2 has been used for the oil replacement. The formation volume factor used for gas varies with depth as a function of pressure and temperature.

The storage capacity of the hydrocarbon fields has been estimated assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO\textsubscript{2}. This results in a total storage capacity of 6.6 Mt CO\textsubscript{2}.

A more conservative estimate has been calculated in this report for comparison with the estimates in the database. The conservative estimates amounts to 3 Mt CO\textsubscript{2}.

3.3.3 Capacity estimation in coal fields

Most of un-mined coal reserves in Bulgaria occur at shallow depth, no favourable for safety injection of CO\textsubscript{2}. Deeper occurrence of coal-bearing formations (>800 m), suitable for CO\textsubscript{2} storage, exists only in two fields.

In CASTOR WP1.2 these two coal fields, possibly perspective for CO\textsubscript{2} storage, were identified. In GeoCapacity was made first evaluation of geological conditions in order to assess CO\textsubscript{2} storage feasibility and capacity in coal seams within the two fields.
The CO₂ storage capacity in coal field (S) is a function of PGIP (producible gas in place), CO₂ (gas) density and CO₂ to CH₄ exchange ratio (ER):

\[ S = \text{PGIP} \times \text{CO₂ density} \times \text{ER} \]

CO₂ storage capacity S denotes quantity of CO₂ which could replace PGIP, to the extent specified by ER (hard coal has usually the ratio of about 2, brown coal and lignite may have higher ratios).

PGIP means coal bed methane reserves for CO₂-ECBMR (Enhanced Coal-Bed Methane Recovery with the use of CO₂ storage). The standard approach on calculating PGIP consists in estimation of volume and mass of (pure) coal within the seam(s), assuming methane content in coal, recovery factor and completion factor (the last one after RECPOL results):

\[ \text{PGIP} = (\text{Pure}^*) \times \text{Coal Volume} \times \text{Coal density} \times \text{CH}_4 \text{ content} \times \text{Completion factor} \times \text{Recovery factor} \]

*excluding ash and moisture, if CH₄ content refers to pure coal samples.

The total estimated CO₂ storage capacity in selected two coal fields in Bulgaria is 27.4 Mt.

3.3.4 Country summary

In Table 3.1 below is given a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions) and storage capacity in aquifers, hydrocarbon and coal fields. Figure 5.6 show the data for Bulgaria included in the GeoCapacity database.

Table 3.1: CO₂ emissions and storage capacity estimates in Bulgaria.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2006</td>
<td>42</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2006</td>
<td>52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td></td>
<td>2100</td>
<td>2658</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td></td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td></td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>2120</td>
<td>2692</td>
</tr>
</tbody>
</table>
Figure 3.7: Map of CO$_2$ emissions, infrastructure and storage capacity in Bulgaria.
3.4 Albania

3.4.1 Maps of regional storage potential

In Albania has not been carried out any estimation of regional storage potential. Only local estimations for the storage capacity in oil and gas fields and in a big salt dome.

3.4.2 Dumrea salt dome

In Albania there were not available data for the aquifers in order to carry out estimations for CO\textsubscript{2} storage capacity. There are data for a salt dome of large size and the capacity estimation was done for this option. The evaporite formations in Albania occur in some regions such as Dumre, Xare, Delvine etc. The biggest outcrop of such depositions is found in Dumre region, which represents a diapir of considerable extension with dimensions of 18 x 12 km, see Figure 3.8.

The geological-geophysical data acquired up to now support the idea that after having burst out from the depth through the fault plane in the westward side of Kuçova-Maraku limestone structures, the evaporite depositions have flowed west ward and south westward covering the in-depth structures of Dumrea region.

Figure 3.8: Location of Dumrea diapir.
Concerning the relationship of diapir with the structures and depositions around we could say that they are in general classified. In the north, these depositions are in contact with the flysch depositions of Oligocene; in the east, they are covered by limestone and flysch and limestone depositions; in the south, they are in contact with flysch and limestone depositions (Kuçova anticline); in the west, Dumrea diapir contact the Oligocene and Lower Miocene depositions. In the upper part, the evaporite depositions are covered by the cap rock of a thickness of 0–300 m, while the maximum depth of the salt floor is expected to be 6000 m (according to data of well Dumre-7).

Concerning the mineral composition, the evaporate depositions are represented by gypsum, anhydrites, halite’s, knitted by dolomites and erogenous material. A considerable heterogeneity of evaporate depositions is seen from the diagram of drilled wells. This is also seen within a section of individual wells. According to log diagrams and cores from the wells drilled in this region, dolomite and terrigenous material intercalated with gypsum anhydrite and halite predominate in the evaporate diaper up to a depth of 1400–1500 m. Further down, there predominate the halites, anhydrites and gypsum rarely intercalated with dolomites and terrigenous material.

The halites are of crystal appearance, white to gray as well as of melted glass appearance in dark gray. There are often dolomites encountered in the halite mass 0.5–6 cm big, rarely 20 cm. The anhydrites are of halite and dolomite type, of average to big grains with massive texture, of gray to dark gray. The gypsum is of small to big grains, re-crystallized, dark gray, non-uniform. Often, it contains clay material. The terrigenous material is represented by clay, aleurolites and sands of small to average grains, of gray colour. The limestone material is represented by dolomite of gray to black colour, in the form of breccias.

In Dumrea region, 6 exploration wells have been drilled to explore for oil-bearing formations on the sides and under evaporate depositions.

### 3.4.3 Capacity estimation for Dumre salt dome

*The data for the case study come from the Albanian Geological Survey which has the rights for them.*

The case study for Albania refers to CO₂ storage in a big salt dome in Dumre area in south central part of the country. The CO₂ source, a power plant emitting 180000 t/year, is located close to Fier city which is found about 50 km SW of Dumre dome.

The salt dome is of Triassic (Carnian) age and has been emplaced in limestones of Ionian zone. The dimensions of the dome on the surface exposure are 12 by 18 km and the vertical thickness exceeds 6 km (Figure 3.9 and Figure 3.10).

The CO₂ storage can be carried out after the creation of caverns. The caverns are to be made by solution of salt formations as is shown in Figure 3.11.
Figure 3.9: Regional map of Dumrea diapir.

Figure 3.10: Longitudinal geological profile 18/87+89 (II-II) in the region of Dumrea.
A single cavern created this way with dimensions $R=40$ m and $H=300$ m has a storage capacity of about 1 Mt of CO$_2$ in supercritical state. The calculation is based on the formula:

$$M_{CO_2} = \pi \times R^2 \times H \times \rho_{co2}$$

where,

- $R$: radius of cavern
- $H$: vertical height of cavern
- $\rho_{co2}$: density of CO$_2$ at the depth of 2000 m
- $\pi$: 3.14

Therefore in the area of the dome (12 by 18 km) more than 50 caverns could be created and the storage capacity potential exceeds decades of millions of CO$_2$. Compared to the current annual emissions from the Fier source (181 kt/year), it is possible to store its emissions for many decades of operation.
Table 3.13: Summary of information on the Dumre salt dome.

<table>
<thead>
<tr>
<th>Structure/Zone</th>
<th>Stratigraphic unit</th>
<th>Formation</th>
<th>Lithology</th>
<th>Top depth (m)</th>
<th>Permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dumrea dome</td>
<td>Carnian</td>
<td>Diapiric Salt</td>
<td>Salt</td>
<td>2000</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.14: Storage capacity estimation for the Dumre salt dome.

<table>
<thead>
<tr>
<th>Structure/Zone</th>
<th>Area (m²)</th>
<th>Effective thickness (m)</th>
<th>CO₂ density (t/ m³)</th>
<th>Storage efficiency factor</th>
<th>Total estimated CO₂ storage capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dumrea dome</td>
<td>5000 x 10 = 50000</td>
<td>300</td>
<td>0.700</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Total estimated CO₂ storage capacity (Mt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

3.4.4 Capacity estimation in hydrocarbon fields

The main oil and gas fields of Albania occur in reservoirs in sandstones and limestones and are shown in the Table 3.15 and in Figure 3.12.

The reserves of oil

According to the official data of 01-01-2006, the oil and gas reserves are shown in Table 3.16. Almost half of increase of reserves, in the main productive parts of oil, has resulted from their re-evaluation, taking into consideration the progress of technology of growth and finding of reserves and the prices of market.

Globally the quantity of oil that has been accumulated initially in the underground reservoirs of known fields of Albania was 437,024,179 t oil. According to the nature of oil reservoirs it is evident that in the sandstone Fields they have been stored 77.75% of total of geological reserves OOIP (338,696,109 t), while in the carbonate reservoirs (limestones) have been stored little more than 22%.

Up to 31-12-2005, 50,594,760.15 t of oil has been produced and the remaining geological reserves amount to 386,371,989 t.

The reserves of gas

The reserves of gas discovered and developed up to now in Albania belong to the fields that have been categorized as:

1. Fields of natural gas or dry gas with content more than 90% of methane in gas (Divjaka, Ballaj, Frakuella, Povelca, and Panaja).
2. Fields of condensed gas (Delvina, and initially Cakrani, sequence Bubullima).
3. Fields of accompanying gas that are found dissolved in oil or in the gas cap in the Fields of oil (Kucova, Patos, Marinez, Visoke, Ballsh-Hekal, Cakran-Mollaj, Gorisht-Kocul, Ammonice, Finiq-Krane).
Figure 3.12: Hydrocarbon wells and injection points in Albania.

Below are presented in form of tables the quantities of gas in the Fields of oil and condensed gas as in the Fields of natural gas.

Based on the following tables for the existing Fields of oil and natural gas we conclude that:

- In the known Fields of oil and natural gas in Albania on 1/1/2005, there exist 3.630 billion Nm$^3$ recoverable reserves of gas. From them roughly 22 millions of N m$^3$ occur in the Fields of natural gas while 3.610 billions of Nm$^3$ of gas occur in the Fields of oil and condensed gas and in the form of dissolved gas in oil or condensed and free gas in the gas caps of certain Fields.

_The potential for storage of CO$_2$ in Albanian hydrocarbon fields_

The storage capacity of the Albanian hydrocarbon fields has been estimated using the formula from the GESTCO project (Schuppers et al., 2003) assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO$_2$: 
\[ \text{Mco}_2 = \rho_{\text{co}_2r} \times \text{UR}_p \times \text{B} \]

where:
- \( \text{Mco}_2 \): hydrocarbon field storage capacity
- \( \rho_{\text{co}_2r} \): CO\(_2\) density at reservoir conditions (best estimate)
- \( \text{UR}_p \): proven ultimate recoverable oil or gas
- \( \text{B} \): oil or gas formation volume factor

In Table 3.15 below is given a summary of information on the individual fields and in Table 3.16 is given the basis for the capacity calculation and the estimated CO\(_2\) storage capacity for each field. The total estimated CO\(_2\) storage capacity for the Albanian hydrocarbon fields amounts to 111 Mt.

### Table 3.15: Summary of information on individual hydrocarbon fields.

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Stratigraphic unit</th>
<th>Lithology</th>
<th>Depth (m)</th>
<th>Content</th>
<th>Start of prod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cakran - Mollaj</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td>3000</td>
<td>Oil and Gas</td>
<td>1978</td>
</tr>
<tr>
<td>Ballsh - Hekal</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td>1000</td>
<td>Oil and Gas</td>
<td>1967</td>
</tr>
<tr>
<td>Gorisht - Kocul</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td>800</td>
<td>Oil and Gas</td>
<td>1966</td>
</tr>
<tr>
<td>Karbunare</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td>1650</td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>Amonice</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td>2240</td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>Visoke - Kolonj</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td>1090</td>
<td>Oil and Gas</td>
<td>1963</td>
</tr>
<tr>
<td>Delvine</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td>3580</td>
<td>Oil and Gas</td>
<td>1987</td>
</tr>
<tr>
<td>Finiq - Krane</td>
<td>U. Cret. / Eocene</td>
<td>Limestone</td>
<td></td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>Drashovica</td>
<td>Oligocene</td>
<td>Flysch</td>
<td>200</td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>S. Bubullima</td>
<td>Tertiary</td>
<td>Sandstone</td>
<td></td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>S. Marinza</td>
<td>Tertiary</td>
<td>Sandstone</td>
<td>1500</td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>S. Driza</td>
<td>Tertiary</td>
<td>Sandstone</td>
<td></td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>S. Gorani</td>
<td>Tertiary</td>
<td>Sandstone</td>
<td></td>
<td>Oil and Gas</td>
<td></td>
</tr>
<tr>
<td>Kucove</td>
<td>Tertiary</td>
<td>Sandstone</td>
<td>1100</td>
<td>Oil and Gas</td>
<td>1935</td>
</tr>
<tr>
<td>Rase - Pekisht</td>
<td>Tertiary</td>
<td>Sandstone</td>
<td></td>
<td>Oil and Gas</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.16: Storage capacity estimation for Albanian hydrocarbon fields.

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Proven ultimate recoverable gas (10(^6) m(^3))</th>
<th>Proven ultimate recoverable oil (10(^6) m(^3))</th>
<th>Bgas</th>
<th>Boil</th>
<th>CO(_2) density (t/m(^3))</th>
<th>Total estimated storage capacity (Mt)</th>
<th>CO(_2) storage capacity for all Albania hydrocarbon fields (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cakran - Mollaj</td>
<td>8000</td>
<td>9.05</td>
<td>0.0043</td>
<td>1.2</td>
<td>0.7</td>
<td>31.68</td>
<td></td>
</tr>
<tr>
<td>Ballsh - Hekal</td>
<td>545.3</td>
<td>6.49</td>
<td>0.0065</td>
<td>1.2</td>
<td>0.7</td>
<td>7.93</td>
<td></td>
</tr>
<tr>
<td>Gorisht - Kocul</td>
<td>594.3</td>
<td>15.45</td>
<td>0.0065</td>
<td>1.2</td>
<td>0.7</td>
<td>15.68</td>
<td></td>
</tr>
<tr>
<td>Karbunare</td>
<td>8.1</td>
<td>0.15</td>
<td>0.0055</td>
<td>1.2</td>
<td>0.7</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Amonice</td>
<td>69.1</td>
<td>1.65</td>
<td>0.0050</td>
<td>1.2</td>
<td>0.7</td>
<td>1.63</td>
<td></td>
</tr>
<tr>
<td>Visoke - Kolonj</td>
<td>239.4</td>
<td>7.82</td>
<td>0.0065</td>
<td>1.2</td>
<td>0.7</td>
<td>7.66</td>
<td></td>
</tr>
<tr>
<td>Delvine</td>
<td>1170</td>
<td>0.18</td>
<td>0.0038</td>
<td>1.2</td>
<td>0.7</td>
<td>3.26</td>
<td></td>
</tr>
<tr>
<td>Finiq - Krane</td>
<td>878</td>
<td>0.18</td>
<td>0.0050</td>
<td>1.2</td>
<td>0.7</td>
<td>3.23</td>
<td></td>
</tr>
<tr>
<td>Drashovica</td>
<td>0.26</td>
<td>0.03</td>
<td>0.0065</td>
<td>1.2</td>
<td>0.7</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>S. Bubullima</td>
<td>200.9</td>
<td>0.51</td>
<td>0.0050</td>
<td>1.2</td>
<td>0.7</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>S. Marinza</td>
<td>926.5</td>
<td>9.32</td>
<td>0.0057</td>
<td>1.2</td>
<td>0.7</td>
<td>11.53</td>
<td></td>
</tr>
<tr>
<td>S. Driza</td>
<td>501.5</td>
<td>22.29</td>
<td>0.0057</td>
<td>1.2</td>
<td>0.7</td>
<td>20.72</td>
<td></td>
</tr>
<tr>
<td>S. Gorani</td>
<td>74.6</td>
<td>2.27</td>
<td>0.0060</td>
<td>1.2</td>
<td>0.7</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>Kucove</td>
<td>912.2</td>
<td>13.08</td>
<td>0.0065</td>
<td>1.2</td>
<td>0.7</td>
<td>15.14</td>
<td></td>
</tr>
<tr>
<td>Rase - Pekisht</td>
<td>1.8</td>
<td>0.22</td>
<td>0.0050</td>
<td>1.2</td>
<td>0.7</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>

Total estimated CO\(_2\) storage capacity for all Albania hydrocarbon fields (Mt) 122
3.4.5 Capacity estimation in coal fields

Coal occurs in Albania under the form of lignite. Hard coal does not exist. Albanian lignites are connected with the last phases of the Alpine orogenic cycle. There is a migration of the peat formation from the internal to the external zones, forming sedimentary basins of various age and features.

Therefore three main classes of lignite bearing basins can be classified (Figure 3.13):
The lignite basins of Oligocene to lower Miocene were developed in the Albanian-Thessalian basin (in fact the Mesohellenic basin extending from central Greece to Albania) and filled with molasse formations. In these formations three lignite seams, of peat bog type, develop following the direction of marine transgression from SE to NW (e.g. in the areas of Drenova, Gora and Mokra).

The lignite bearing basins of Tortonian (U. Miocene) have a wider development in the Ionian zone, in the Mesohellenic basin and in the Adriatic foredeep. The lignite was formed in lagoon conditions and it is located in the basins of Tirana’s, Erzeni, Memaliaj, etc...

The Pliocene lignite bearing basins are of continental origin and have a narrow development. They are located in the areas of Korce-Devoll, Pogradec, Kolonje, Xare, etc. The lignite is of lacustrine origin.

The total known reserves of lignite in Albania amount up to decades million tons with a mean net calorific value of ~3200 Kcal/kg. There are some peat deposits too, mainly in the area of Maliq-Korce, with reserves of 150 Mt.

The lignite seams contain many lignite layers ranging in thickness between 0.4 to 2.5 m. the main producing deposit was that of Mamaliaj area. Mining was carried out by underground operation and some 15 Mt were produced up to 2003 when mining stopped due to economic reasons. The remaining reserves amount up to 30 Mt with deep development.

For the purpose of CO₂ storage (ECBM) the lignite seams of Albania are not suitable due to small reserves and future use for power generation.
3.4.6 Case studies

The data for the case study come from the Albanian Geological Survey which has the rights for them.

The case study for Albania refers to CO2 storage in a big salt dome in Dumre area in south central part of the country. The CO2 source, a power plant emitting 180000 t/year, is located close to Fier city which is found about 50 km SW of Dumre dome. The salt dome is of Triassic (Carnian) age and has been emplaced in limestones of Ionian zone. The dimensions of the dome on the surface exposure are 12 by 18 km and the vertical thickness exceeds 6 km (Figure 3.14).
The CO₂ storage can be done after the creation of some caverns by water injection. A single cavern created this way with dimensions R=40 m and H=300 m can accept about 1 Mt of CO₂ in supercritical phase. Therefore the big area of the dome can accommodate a big number of caverns and the storage capacity potential exceeds decades of millions of CO₂. Compared to the current annual emissions from the Fier source, it is possible to store its emissions for many decades of operation.

3.4.7 Country summary

In Table 3.17 a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database and storage capacity in aquifers, hydrocarbon and coal fields are given.

Table 3.17: CO₂ emissions and storage capacity estimates in Albania.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>CO₂ storage capacity</td>
<td>Pyramid class</td>
<td>Conservative estimate (Mt)</td>
</tr>
<tr>
<td>Storage capacity in aquifers</td>
<td>effective</td>
<td>20</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>effective</td>
<td>111</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>NA</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>131</td>
</tr>
</tbody>
</table>
Figure 3.15: Map of CO$_2$ emissions, infrastructure and storage capacity in Albania.
3.5 FYROM

3.5.1 Maps of regional storage potential
In FYROM the estimation of regional storage potential has not been carried out, only some local estimation.

3.5.2 Capacity estimation in aquifers
The data for the saline aquifers of FYROM come from MAGNA which holds the rights for the data.

The data from small scale oil exploration have been very useful for the estimation of the CO₂ storage capacity in aquifers. As it was mentioned earlier, only two important Tertiary basins exist in the country.

The first one in the west (Prilep-Bitola basin) is the north extension of the big long graben that starts from the Greek city of Kozani and through Ptolemais and Florina ends close to Prilep in FYROM (Figure 3.16). This graben host, in a few sedimentary basins, the main Greek and Macedonian lignite deposits which are exploited intensively since 1950’s and provide most of the electricity of both countries. The main feature of this graben is the small total thickness of the sediments filling as they do not exceed 1000 m in thickness and they host the most important lignite sources of both countries. Therefore any thought for CO₂ storage in these basins is not realistic at the present and the near future time.

![Figure 3.16: Kozani-Ptolemais-Florina-Bitola-Prilep graben.](image-url)
The second sedimentary basin of FYROM (Vardar basin) lies in the east side of the country starting near the Greek border and through a NNW direction it approaches the north border (Figure 3.17). The basin was explored in the 1970’s for hydrocarbons. Four deep boreholes were drilled up to 3000 m deep.

Drilling provided a lot of information on the stratigraphy of the basin. It is filled with thick sedimentary rocks ranging in age from Paleocene up to Neogene, exceeding in thickness 4000 m. In the base of the sedimentary rocks there are thick (many hundred meters) beds of clastic sediments (conglomerates, sandstones with some clay intercalations) with good porosity (=>15%), salt content 100000 ppm, probably of Paleocene–Eocene age. They are overlain by thick argillites (~ 170 m thick) which form a good cap rock seal. On top of the argillites there is a thick alternating sequence of younger sandstones, conglomerates and clays, probably of Miocene age. All the above lithological units have a regional development in the whole Vardar basin although their thickness varies locally.

![Figure 3.17: Location of the Vadar basin and deep oil boreholes (inside the red polygon).](image)

For capacity estimations in aquifers the formula recommended in the standards set by the GeoCapacity project (deliverable D24) has been used (common for both regional and trap aquifers):

\[ M_{CO2} = V \times NG \times \phi \times \rho_{CO2} \times S_{eff} \]

Where:
M\text{CO}_2: \text{storage capacity in regional or trap aquifer}
V: \text{volume of regional or trap aquifer}
NG: \text{net to gross ratio of regional or trap aquifer}
\varphi: \text{porosity of regional or trap aquifer}
\rho_{\text{CO}_2}: \text{CO}_2 \text{ density at reservoir conditions}
Seff: \text{storage efficiency factor for regional or trap aquifer}

For the storage capacity in the Vadar basin two calculations have been carried out. The first one refers to the whole basin assuming a conservative mean thickness of the clean sandstone and the whole surface area of the basin. The second one is more local in the polygon area enclosing the exploration boreholes KR-1, OP-1, TV-1, SN-1 and was based on the results of the drilling and the correlation between the holes (Figure 3.17).

The storage capacity for the whole basin is 1050 Mt CO\textsubscript{2} using a storage efficiency factor of 4 % and for the polygon area the storage capacity is 630 Mt CO\textsubscript{2} (also using 4 %).

A more conservative storage capacity of the basin was calculated for an interval of 1800–2500 m filled with sandstones and conglomerates. The salinity of the water in this interval is 10000 ppm. The storage capacity amounts to 390 Mt (storage efficiency factor 1.5 %) and it can accommodate the emissions from the nearby power station of Negotino (540 kt/year) for many years. It can also become a central sink site for the whole emissions of the country given the small distances of CO\textsubscript{2} sources.

### 3.5.3 Capacity estimation in hydrocarbon fields

From the geological information received with terrain explorations and results from the deep drilling, resulted the information that the possible reservoirs contain rocks mostly very cemented in the detrital and terrigenous deposits. Having the general concept for the deposition of these sedimentary rocks which has created helped by depositing, compression cementing of minerals and rock pieces, in the most including material from organic origin.

Analyzing the study in global, from geological and geophysical information, can be completed the following conclusions:

- Oil or hydrocarbon perspectives on the territory of the R. FYROM, can be considered that only Vardar zone as geotectonic unit, can be included in for exploration for exploring eventual deposits of hydrocarbon. For confirmation of this thesis included are explorations performed in Greece, where Vardar zone continues to south and explored deposits of oil and gas in similar tectonic conditions, as in Panonski basin in Serbija, Hungary and Romania, in Neogene strata, as the strata in FYROM.

- From the exploration drillings performed in Ovcepole’s, Veles’s, and Tikves’s basin with depth from 800m till 2703m, and performed geophysical explorations: electrical well logging, induction logging, micro logging and acoustic(sonic) logging, it was detected a horizon full of water enriched with salt water which points out saltines of oiled water enriched with NaCl and registered appearance of gases. With the former degree of exploration, there are no detected appearance of oil and gas for exploitation.
3.5.4 Case studies

The case study includes the local sink of the polygon area in Figure 3.17 and matching with the power plant of Negotino-Kavadarci using lignite as a fuel. The estimated storage capacity exceeds 630 Mt of CO₂. The gas pipeline system of the country is well developed and passes close to the main CO₂ emitters and the sink. The source of Negotino emits about 550 kt of CO₂ per year and therefore the sink can accommodate these emissions for hundreds of operational years. Furthermore this sink can accommodate the whole emissions of FYROM from static large point sources (3.9 Mt of CO₂ per year) for many years of operation.

3.5.5 Country summary

In Table 3.18 a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database and storage capacity in aquifers, hydrocarbon and coal fields are given.

Table 3.18: CO₂ emissions and storage capacity estimates in FYROM.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td></td>
<td>2006</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td></td>
<td>2006</td>
</tr>
<tr>
<td>CO₂ storage capacity</td>
<td>Year(s)</td>
<td>Average CO₂ emissions (Mt)</td>
</tr>
<tr>
<td>Storage capacity in aquifers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Effective</td>
<td>390</td>
<td>1050</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td>Effective</td>
<td>390</td>
<td>1050</td>
</tr>
</tbody>
</table>
Figure 3.18: Map of CO$_2$ emissions, infrastructure and storage capacity in FYROM.
4 WP 2.3 SOUTH GROUP

4.1 Croatia

4.1.1 Maps of regional storage potential

Croatian territory is usually subdivided into three large units, each with distinctive characteristics of the subsurface geological setting, Pannonian basin, Dinarides and Adriatic offshore. Only the first and the third unit can offer locations with favourable conditions for geological storage of carbon dioxide, the Dinarides can largely be ruled out due to several reasons. Firstly, this mountain region is in Croatia mostly composed of Mesozoic carbonates that are karstified to depths exceeding 1000 m. Karst hydrogeological system and its groundwater resources effectively prevent any type of geological storage in that region. The other reason is the high neotectonic (and seismic) activity which would put both the surface installations and subsurface storage objects at risk. This means that looking for the favourable natural conditions should be directed both to the south-western part of the Pannonian basin and to the Adriatic offshore.

In the Pannonian basin, the Upper Miocene sandstone-marl sequence is seen as the most prospective formation to define the regional aquifers. It contains multiple sandstone layers with intergranular porosity and there are large regions covered with more than 1000 m thick younger sediments. Notably, the four aquifers delineated on the map of regional storage potential (Figure 4.1) are not structurally defined, these are only “aquifer formations” and their large storage capacity is theoretical. The same is with the Adriatic off-shore which has another drawback. Only the northern part might prove to be economically viable, due to the distance from the major point sources. One aquifer is singled out on the map, and it is assessed based on very scarce data. This is the Miocene clastic formation in the Dugi otok depression, but deeper storage formations might also be found.

Out of more than 60 HC accumulations discovered in Croatia, several oil and gas fields were singled out and detailed capacity estimates were performed rendering significant effective storage capacity. Realistically, this largely depends on their current depletion level and distance from the sources.

Only one coal basin (Istrian or the Raša basin) was depicted on a map, due to its size and regional importance (Figure 4.1). It is not in production and data for the unmined parts are not available so the capacity remained without estimation.

4.1.2 Geological description, aquifers

Due to the complex geological history of the SW part of Panonian basin, the structure of the basement is complex. Elongated basement highs and narrow depressions developed during the Mid-Miocene rifting were refigured by several phases of basin inversion. Most of the sedimentary succession accumulated in these depressions which are separated by uplifted and partially eroded tectonic units. The mentioned structural depressions, the most northern Mura depression, Drava depression, Sava depression and Slavonija-Srijem depression are filled with the Neogene sedimentary and igneous rocks.

Basin fill contains some volcaniclastics but is mostly composed of sediments reaching maximal thickness of e.g. 5000 m in Sava depression or over 6000 m in Drava depression. This large sequence of lacustrine-marine-lacustrine-fluvialite environments contains major unconformities,
the Base Neogene, the Base Pannonian and the Base Pliocene unconformities, which usually separate the onlapping deposits from uplifted, tilted and eroded older rocks. Even a fifth, Quaternary unconformity exists, as the reflection of the youngest uplift in the marginal part of depressions. The oldest Neogene sediments are of Early to Middle Miocene age and comprise syn-rift and early post-rift sediments. Terrestrial sandstones, subordinate coal seams, sedimentary bodies of talus breccia (mainly Lower Miocene), reefs (mainly Badenian), coastal and shallow marine sandstones (Karpatian, Badenian) are interlayered with volcanics/volcanoclastics, marls and clayey limestones. The end of Middle Miocene is characterised mostly by fine-grained deposition in the starving brackish-water basin. Late Miocene is characterised by the post-rift thermal subsidence of the Pannonian basin and deposits that were formed in brackish (Pannonian) to freshwater environment (Pontian). Apart from local variations due to pre-Pannonian topography, the sedimentary succession begins with littoral limestones and nearshore transgressive lag overlain by hemipelagic calcareous and clayey marls basin-wide. The deepest depressions were filled by lacustrine turbidite lobes and channel fills of considerable thickness, thus initial basin floor topography gradually became levelled. Turbiditic successions are overlain by shale-prone delta slope and sandy delta front to coastal plain sediments. Deltaic sand bodies or turbiditic sand lobes of this unit are interlayered with silty marls and also make the majority of HC pools discovered in the area. These “regional reservoirs” and also regional cap rocks are here considered to be the most promising units for definition of the deep saline aquifers as a large extensive “aquifer formations”.

Pliocene and Quaternary rocks are sediments which were deposited in the remnants of Lake Pannon and in the subsequent fluvial systems. These are mostly sands and sandy gravels with some clay and silt that have the largest thickness of 1000–1500 m in areas of continuous subsidence.

The oldest formations reached by wells in the Adriatic offshore in Croatia, are of Permian age. They are of heterogeneous lithologic composition, clastic sediments were deposited, mainly sandstone and shale, but carbonate formations are also present, and particularly evaporites. Early Triassic was characterised by intensive tectonic movements and volcanism followed by clastic sedimentation. Middle Triassic unit was affected by the beginning of the Alpine orogenesis and both the shallow water and deep water carbonates are found, frequently with andesite and pyroclastics. In the basal part of the Upper Triassic (Karnian) evaporites can be found but their occasionally diapiric bodies are much more frequent in the Central and Southern Adriatic, while the dolomites prevail in the Northern Adriatic. Generally, shallow water carbonate sedimentation (mainly dolomites) in platform conditions began in Late Triassic and continued in more-less similar platform conditions throughout Early and Middle Jurassic (mainly dolomites), Late Jurassic and Cretaceous (limestones), till the Palaeogene or occasionally Middle Eocene. Towards the end of Cretaceous the platform gradually disintegrated. The thickness of carbonate deposits amounts to 5000 m at most. During the Middle Eocene, Late Eocene and Lower Oligocene, intensive tectonic movements caused opening of the future Adriatic basin. Tectonic movements were accompanied by sedimentation of marl, sandstone and subordinated limestone. Miocene was characterised by hemipelagic marl in the central parts of deep basins and turbidites close to their margins; marl, calcareous and marly siltites interbedded with sandy limestones and sandstones. This unit is considered to have both the reservoir and sealing capabilities needed for a regional deep aquifer. Pliocene sediments resulting from the subsequent transgression include clays, marls and sands. There is a lithologic continuity with Quaternary deposits composed of sands, silts and clays with lignite interbeds. Pliocene–Quaternary deposits can reach the thickness of 2000 m in places and the thickness of Neogene deposits together with Quaternary
deposits can amount up to 4000 m in the deepest subbasins. Thickness of this sequence in the Northern Adriatic reaches 1000 m.

4.1.3 Capacity estimation in aquifers

Trying to estimate the storage capacity in deep saline aquifers, disclosed major problem in the fact that the available data are not detailed enough. Even in the mature petroleum provinces deep aquifers were simply not drilled through in many places and there are just a few analyses of their reservoir properties. That is why even in the cases where the geometry of the reservoir rock formations can be delineated based on the regional subsurface data, other parameters, effective thickness, porosity and temperature have to be extrapolated from the existing hydrocarbon fields in the region. This inevitably burdens the storage capacity estimates with a lot of uncertainties. Even more so knowing that adequate trapping conditions in parts of these regional aquifers will only later be confirmed by targeted surveys. That is why these storage estimates are regarded as theoretical capacity only (bottom of the pyramid). Information of the defined large “aquifer formations” is given in Table 4.1 and their locations in Figure 4.1.

Storage capacities are mostly on-shore, within the sediments of the Pannonian basin. With more than 700 exploration wells in this area, regional subsurface maps allow the generalised geometry of deep Miocene aquifers to be delineated and porosity was taken from the average data acquired in the oil and gas fields of a specific area. Margins of these aquifers were defined based on the two criteria, extension of the Upper Miocene sandstones (from the regional subsurface maps) and thickness of the overlying Pliocene and Quaternary sediments of over 1000m. Top of the aquifer is the top of the Upper Miocene sandstone-marl sequence, while the base of the aquifer is the contact with underlying older Miocene sediments. Net-to-Gross ratio was averaged from the regional exploration wells.

Table 4.1: Storage capacity estimation for aquifers in Croatia.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Area (m²)</th>
<th>Thickness (m)</th>
<th>Net/gross ratio</th>
<th>Porosity (%)</th>
<th>CO₂ density (t/m³)</th>
<th>Storage efficiency factor (%)</th>
<th>Total estimated CO₂ storage Capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drava</td>
<td>1353234016</td>
<td>1000</td>
<td>0.60</td>
<td>25</td>
<td>0.373</td>
<td>3</td>
<td>2271.038</td>
</tr>
<tr>
<td>Osijek</td>
<td>41085959</td>
<td>2500</td>
<td>0.70</td>
<td>20</td>
<td>0.418</td>
<td>3</td>
<td>180.460</td>
</tr>
<tr>
<td>Sava Central</td>
<td>517134191</td>
<td>1700</td>
<td>0.32</td>
<td>18</td>
<td>0.450</td>
<td>3</td>
<td>691.780</td>
</tr>
<tr>
<td>Sava West</td>
<td>314735506</td>
<td>1500</td>
<td>0.33</td>
<td>17</td>
<td>0.401</td>
<td>3</td>
<td>321.745</td>
</tr>
<tr>
<td>Dugi Otok</td>
<td>1135546278</td>
<td>1170</td>
<td>0.20</td>
<td>10</td>
<td>0.755</td>
<td>3</td>
<td>601.652</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>4066.675</strong></td>
</tr>
</tbody>
</table>

Capacity declared for the Dugi Otok aquifer in the Adriatic off-shore is really a preliminary and rough estimate because its reservoir rock properties are based only on the data from 3 wells, and its outline follows the contours of the entire sub-sea Dugi Otok basin for which more detailed subsurface maps were not obtainable.

It also has to be noted that the storage efficiency factor is taken to be 3%, meaning that only such a small proportion of the estimated available pore volume might probably once be filled with carbon dioxide (at several locations that are still to be found). This capacity might be prepared for use only after the deliberated exploration of these objects not only to fully investigate their reservoir properties, but also to confirm the integrity of their cap rocks. Differently to some of the other countries in the project, no structurally defined aquifers are given here.
4.1.4 Capacity estimation in hydrocarbon fields

Current EOR pilot studies in the Pannonian part of Croatia rendered favourable results, indicating that the significant proportion of injected CO₂ will remain in the reservoir permanently. These operations are seen as the source of practical knowledge to start preparing feasibility studies for CO₂ storage in depleted HC fields of the southern Pannonian basin.

Altogether more than 60 uneconomic HC accumulations were discovered here in the last 60 years. Depending on the depth of the main reservoir, reliable cap rocks and relatively tectonically undisturbed structure 15 fields have been selected as potential storage sites in this region. They are all small to medium-sized with a potential storage capacity in the 7 oil fields that sums up to 39 Mt, while the capacity in the 8 gas fields is much larger about 118.5 Mt. There is an important practical difference between the two numbers, because oil fields are much more depleted and might be converted to carbon storages in the near future while this is not so with the gas fields.

Explaining geology of these reservoirs, Upper Miocene sandstones are the most frequent type of reservoir rocks that might be used because they are numerous, reliably correlated and usually in the convenient depth range (1000–2500 m). At some locations, large capacity is estimated in the Base Neogene breccia-conglomerate bodies, and particularly where those reservoirs are hydraulically connected with the underlying Mesozoic or Palaeozoic basement rocks. To construct underground carbon storages in these reservoirs might be complicated due their large depths (and consequently high pressure and temperature), and the extensively developed fracture porosity, but significantly higher injection rates might prove to be obtainable.

As for the off-shore possibilities, only the Northern and Central Adriatic are geographically/economically reachable and three types of reservoirs are worth investigating; Pliocene/Quaternary sands/sandstones that are documented to be gas-tight but these gas pools are either too shallow or at the marginal depth (750–850 m). The other two options are the Upper Cretaceous limestones with secondary porosity covered with impermeable Miocene or Pliocene sediments and Miocene formation that is locally developed between the first two, especially in the deep depressions like the Dugi Otok basin. The three assessed gas fields are all in the Northern Adriatic and their reservoirs are Pliocene–Quaternary sands/sandstones plus one reservoir in Upper Cretaceous limestones. They are not nearly depleted yet and their potential storage capacity is 32.2 Mt.

Storage capacity was estimated assuming that the amount of CO₂ that can be put underground into depleted oil or gas field is equal to total oil or gas produced. Summary of the historic data from the fields in production was made available the Croatian national oil company (INA Industrija nafte d.d.).

\[ m_{CO_2} = UR \times \rho_{CO_2} \times B \text{ where:} \]

\[ B = \frac{V_{reservoir \ conditions}}{V_{standard \ conditions}} \]

- \( m_{CO_2} \): mass (kg) of CO₂ that can be stored
- \( \rho_{CO_2} \): CO₂ density at reservoir conditions
- \( UR \): total volume of oil or gas produced i.e. proven ultimate recoverable oil or gas
For calculation of CO₂ density the Span & Wagner real gas equation of state was used (Span & Wagner, 1996). Formation volume factor for oil is very accurate because it was measured in laboratory. For the gas fields, assuming that the real gas volume correction, i.e. the compressibility factor \( Z \) of the gas at the surface is 1, volume factor \( B_g \) can be expressed as:

\[
B_g = \frac{T_R}{P_R} \cdot \frac{T_R}{Z} \text{ where:}
\]

- \( T_R \): reservoir temperature (K)
- \( P_R \): reservoir pressure (bar).

The CO₂ storage capacity in Croatian oil and gas fields was firstly assessed as part of the CASTOR project (WP 2.1). This assessment has now been updated/revised and three new fields from the Adriatic off-shore were added (Table 4.2). The methodology was the same but new calculations were done using more accurate data and with adequate redefinition of the storage objects with respect to the storage safety. Locations of the hydrocarbon fields included in the GeoCapacity database are given in Figure 4.1. The exact outline of hydrocarbon reservoirs has been slightly modified due to confidentiality of such data.

### Table 4.2: Storage capacity estimation for hydrocarbon fields in Croatia

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Proven ultimate recoverable gas (10⁶ m³)</th>
<th>Proven ultimate recoverable oil (10⁶ m³)</th>
<th>( B_g )</th>
<th>( B_{oil} )</th>
<th>CO₂ density (t/ m³)</th>
<th>Total estimated CO₂ storage capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beničanci</td>
<td>0.000</td>
<td>17.852</td>
<td>1.33</td>
<td>0.3711</td>
<td>0.3711</td>
<td>8.800</td>
</tr>
<tr>
<td>Bokšić</td>
<td>4.876</td>
<td>0.000</td>
<td>0.0071</td>
<td>0.3919</td>
<td>0.3919</td>
<td>13.649</td>
</tr>
<tr>
<td>Gola Duboka</td>
<td>2.412</td>
<td>0.000</td>
<td>0.0039</td>
<td>0.6113</td>
<td>0.6113</td>
<td>5.808</td>
</tr>
<tr>
<td>Ida</td>
<td>2.407</td>
<td>0.000</td>
<td>0.0051</td>
<td>0.3812</td>
<td>0.3812</td>
<td>10.502</td>
</tr>
<tr>
<td>Ika</td>
<td>2.520</td>
<td>0.000</td>
<td>0.0045</td>
<td>0.5977</td>
<td>0.5977</td>
<td>11.903</td>
</tr>
<tr>
<td>Ivanić</td>
<td>0.000</td>
<td>9.471</td>
<td>1.31</td>
<td>0.4438</td>
<td>0.4438</td>
<td>5.496</td>
</tr>
<tr>
<td>Kalinovac</td>
<td>13.648</td>
<td>0.000</td>
<td>0.0039</td>
<td>0.6012</td>
<td>0.6012</td>
<td>31.641</td>
</tr>
<tr>
<td>Kloštar</td>
<td>0.000</td>
<td>7.523</td>
<td>1.26</td>
<td>0.2888</td>
<td>0.2888</td>
<td>2.741</td>
</tr>
<tr>
<td>Legrad</td>
<td>1.539</td>
<td>0.000</td>
<td>0.0071</td>
<td>0.3751</td>
<td>0.3751</td>
<td>4.089</td>
</tr>
<tr>
<td>Lipovljani</td>
<td>0.000</td>
<td>5.359</td>
<td>1.30</td>
<td>0.4588</td>
<td>0.4588</td>
<td>3.205</td>
</tr>
<tr>
<td>Marica</td>
<td>1.816</td>
<td>0.000</td>
<td>0.0038</td>
<td>0.5396</td>
<td>0.5396</td>
<td>9.707</td>
</tr>
<tr>
<td>Molve</td>
<td>30.992</td>
<td>0.000</td>
<td>0.0025</td>
<td>0.3032</td>
<td>0.3032</td>
<td>42.805</td>
</tr>
<tr>
<td>Okoli</td>
<td>4.443</td>
<td>0.000</td>
<td>0.0042</td>
<td>0.3058</td>
<td>0.3058</td>
<td>7.280</td>
</tr>
<tr>
<td>Šandrovac</td>
<td>0.000</td>
<td>8.802</td>
<td>1.20</td>
<td>0.3305</td>
<td>0.3305</td>
<td>1.719</td>
</tr>
<tr>
<td>Stari Gradac</td>
<td>1.254</td>
<td>0.000</td>
<td>0.0039</td>
<td>0.5936</td>
<td>0.5936</td>
<td>2.907</td>
</tr>
<tr>
<td>Stružec</td>
<td>0.000</td>
<td>20.723</td>
<td>1.24</td>
<td>0.1206</td>
<td>0.1206</td>
<td>3.501</td>
</tr>
<tr>
<td>Žutica</td>
<td>3.581</td>
<td>0.000</td>
<td>0.0057</td>
<td>0.4996</td>
<td>0.4996</td>
<td>10.139</td>
</tr>
<tr>
<td>Žutica</td>
<td>0.000</td>
<td>18.200</td>
<td>1.44</td>
<td>0.4938</td>
<td>0.4938</td>
<td>12.937</td>
</tr>
</tbody>
</table>

The total estimated CO₂ storage capacity for all Croatian hydrocarbon fields (Mt) **188.83**

The total potential storage capacity in the chosen 18 Croatian HC fields is 189 Mt (Table 4.2). This is more than significant in comparison with the annual emission from the point sources which is 5–6 Mt for the entire country. Apart from the marked differences in availability for storage due to different levels of depletion, there is a marked difference in size of these reservoirs which might limit their use for the large sources like power plants but they still might serve as storage sites for the medium-sized industrial sources. Notably, the type of porosity and of the mineral composition of the reservoir rock and seal are also different and these factors greatly affect the realistic storage potential at each of the locations.
4.1.5 Capacity estimation in coal fields

There is a history of coal production both in the Pannonian part of Croatia and in the Dinarides but all mines were closed in the 1960–1990 period. There are no systematic data available to try to estimate the storage capacity in the still unmined sections of the coal basins, but the coal seams in the Pannonian basin are generally not very deep, while the ones in the Dinarides were subjected to extensive tectonics and are therefore highly fractured.

Only the largest coal basin was included in the database and that is the Rasa basin in Istria that actually extends to the NW in Slovenia. Because of no data for its unmined parts no attempt has been made to estimate the storage potential.

4.1.6 Case studies

Case study 1 – Ivanić oil field

In late 1970s and early 1980s, majority of Croatian oil fields were comprehensively evaluated as potential candidates for application of various EOR technologies and Ivanić oil field was identified as a good target for application of CO2 injection. This spurred an extensive laboratory research program with the aim of quantifying the thermodynamical interaction between CO2 and Ivanić reservoir oil and verifying the ability of CO2 to mobilise the capillary trapped oil from the pore space of actual reservoir rock samples. Both lab data and engineering analyses showed that the most efficient way of displacing oil from Ivanić reservoirs is water-alternating-gas (WAG) injection, water being a mobility control agent for the more mobile CO2, preventing it’s too early breakthrough into producing wells.

3D seismic survey was done in 1998, and the acquired seismic data were processed in house. Analysis of seismic attributes provided the additional information about thickness variation of the sedimentary body, quality of reservoir properties and reservoir discontinuities. Correlation between porosity and permeability was established on the basis of extensive laboratory measurements of reservoir core samples, 3869 porosity, 1744 horizontal permeability and 1537 vertical permeability measurements obtained from 28 wells distributed throughout the field area. A correlation was established between log-derived porosity and laboratory measurement data. The log porosity data were then corrected to match the lab data and used for porosity (and correlated permeability) distribution throughout the reservoir volume.

Numerical simulation model was built by upscaling the geological model on the basis of porosity, and curvilinear gridding around major fault lines. Simulation model was then initialized on the basis of the available well log data and laboratory measurements of reservoir rock and fluid properties. Statistically averaged capillary pressure lab data were used as a starting point in saturation distribution, and were then fine-tuned to achieve a match to the saturations derived from well logs. Pilot injection was done in 2003–2005 including 1 injector, 2 production wells and 2 observation wells. Based on this experience a high resolution model of a reservoir section was built for history matching of the CO2 pilot, with production volumes, reservoir/well pressure and CO2 breakthrough time being matched. History matching resulted in a revised gas relative permeability curve which allows significantly faster flow of CO2 through the reservoir than was anticipated in earlier studies. These data were then used in a pattern model of all reservoirs to be CO2–flooded during the full field EOR project.

The gas treatment plant in Molve was chosen as the CO2 source. This plant daily releases into atmosphere around 2000 t of CO2 stripped from natural gas produced from Molve, Kalinovac, Stari Gradac and Gola gas/condensate fields in northern Croatia. Economical analyses of the
Ivanić EOR project showed that a significant part of future operating costs of the project will be incurred by the electricity needed to compress the CO₂ from atmospheric pressure, at which it is released from the Molve plant, up to 35 bar, at which it will be transported from Molve to Ivanić. On the positive side, significant cost reduction for the project will be achieved by avoiding pipeline building costs by utilising an already existing pipeline (earlier used for gas condensate) between Molve and Ivanić for transport of compressed CO₂ over the distance of 88 km. According to the current EOR project schedule, full field CO₂ injection at Ivanić oil field is expected to start in 2009. Facilities at Ivanić field will include membrane separators for stripping CO₂ from the produced gas, but the stripped CO₂ will not be reinjected as it would require doubling of compressor facilities (at Molve and at Ivanić) without an effect to the overall CO₂ emission: the equivalent of reinjected volume at Ivanić would have to be released at Molve.

Over the 25 years foreseen for the project, it is predicted that total of $1.03 \times 10^9$ Sm³ (standard cubic metres) of CO₂ will be injected into Ivanić reservoirs, and $0.29 \times 10^9$ Sm³ of CO₂ will be produced with oil and gas and released into atmosphere. The net sequestration effect of the project is therefore expected to be $0.74 \times 10^9$ Sm³ (1.45 Mt) of CO₂. All the above-mentioned prediction scenarios were simulated with a single target of optimising the incremental oil recovery of Ivanić field. Some additional simulation work, based on the full field model, was performed aside from the main project workflow in order to estimate the possibility of maximising the CO₂ sequestration effects. Simulation results have showed that by increasing the CO₂ injection volumes, reducing water injection and shutting in producing wells with increased CO₂ production rates it is possible to more than double the total volumes of injected CO₂ and significantly improve retention of CO₂ underground, however, with considerable loss of incremental oil production. It remains to be economically evaluated whether loss of oil could be balanced by reduction of CO₂ emission costs during the EOR project life. Also, further work has to be done in order to simulate the possibility of continuing CO₂ injection after the end of oil production until the field is repressured from reservoir pressure of ca. 140 bar (which is predicted at the end of the EOR project) up to the initial reservoir pressure of 183 bar.

**Case study 2 – Beničanci oil field**

Beničanci oil field, situated in the eastern part of Croatia, has original oil in place (OOIP) of $39.8 \times 10^6$ Sm³ and it is one of the largest oil fields in Croatia. The field was discovered in 1969 and production started in 1972. Due to unexpectedly rapid pressure decline water injection started in 1975. Since 1980’s there is a constant oil production decline and an increase in water cut. The field consists of a single massive carbonate reservoir with 266 m of structural closure, in an elongated anticline intersected by sixteen faults. Four structural peaks can be observed along the anticline, separated by faults and structural saddles. Dominant lithology of a reservoir is a Badenian dolomite and limestone breccia, characterised by low primary and secondary porosity and high permeability. Among the breccia bodies there are irregular inserts of variably thick marls. The Beničanci reservoir has significant vertical and lateral variations in lithology and petrophysical parameters but the average parameters are: porosity 8%, permeability 200 mD, initial pressure 191.1 bar, reservoir temperature 123 °C, oil gravity 30 °API and saturation pressure 147.1 bar.

Geological model was constructed on the basis of 3D seismic interpretation and the available well data. Various input data were used (drilling data, core analyses, well logs, production data and well test results), and the outcome of the interpretation were the three structural horizons, top and bottom of breccias and top of Neogene basement, together with and sixteen fault surfaces. New well log analyses were performed using raw data from 44 wells equally
distributed through the field. Petrophysical parameter analysis was performed on porosity, water saturation and shale volume from well logs and core measurements.

The main obstacle in creating a reliable spatial distribution of petrophysical properties in the geological model is a very low number of core samples from the oil producing parts of the reservoir. Core analyses were performed on samples from 10 wells, but 46% of lab data come from cores taken in a single well located at the NW edge of the field where breccia is interchanged with carbonates, which is quite unrepresentative given the size and complexity of the reservoir. Well log porosity was distributed in geological model and subsequently shifted according to its correlation with porosity measured on cores. Values of porosity in the model are in the range from 3.0 to 12.6%. Permeability from cores was correlated to porosity and distributed in the model. Horizontal permeability is in the range between 0.46 and 729 mD. Horizontal permeability was used for evaluation of effective reservoir volume-model cells with permeability less than 1 mD were considered impermeable. Using the obtained porosity to permeability correlation, cut off on porosity of 3% was used. Initial water saturation was distributed using a correlation between well log porosity and water saturation. \( S_w \) is in the range 15–66.5% within the oil saturated zone. The reservoir has a unique water–oil contact at the absolute (subsea) depth of \( ÷1955 \) m.

Both oil and associated gas in Beničanci field have high CO\(_2\) concentration of 20.7% and 44.1%, respectively. Minimum miscibility pressure between reservoir oil and CO\(_2\) is estimated at more than 380 bar, significantly higher than the initial reservoir pressure; any CO\(_2\) injection process is therefore expected to be immiscible. Original hydrocarbons in place (OHIP) were estimated on the basis of the geological model populated with properties as mentioned previously. According to the model, original oil in place is \( 39.9\times10^6 \) Sm\(^3\), and original associated gas in place is \( 3.14\times10^9 \) Sm\(^3\). According to these volumes and the production history, current oil recovery is around 44.9%. To gain an insight into reservoir behaviour, a detailed analysis of pressure and production history was performed using a material balance simulator. Analysis indicates that there are several energy drives contributing to production: aquifer influx, rock and fluid compressibility but the pressure support through water injection is by far the biggest energy contributor. Results of this analysis, as well as seismic and geological data, indicate a large aquifer present beneath the oil reservoir.

The most feasible EOR option seems to be CO\(_2\) injection from the formation top and the downward displacement of the residual oil to the original oil-water contact. The nature of top-to-bottom oil displacement doesn't allow for water-alternating gas (WAG) injection scheme and a considerable volume of CO\(_2\) would have to be available for filling up the pore space of Beničanci structure. CO\(_2\) injection effect on oil recovery as well as the CO\(_2\) storage capacity was estimated by using the MBAL material balance simulator. Two development scenarios were compared: a baseline one with continuing the existing operations, and the second with CO\(_2\) injection and re-injection of produced water. As reservoir pressure is still above the oil saturation pressure (bubble pressure) and there is no secondary gas cap in the reservoir, the main simulation constraint was maximum reservoir pressure which was set at the initial reservoir pressure of 191.1 bar. Simulated scenarios also included reinjection of produced water into the reservoir. Material balance results indicate that the ultimate cumulative CO\(_2\) injection volume is \( 2.25\times10^9 \) Sm\(^3\) (4.4 Mt). Initial injection rate of \( 1\times10^6 \) Sm\(^3\)/day (1956 t/day) is attainable for the first two and a half years, when it starts to decline due to maximum allowable pressure. Gas cap is not formed instantaneously, only after a year of injection.
Compared to the scenario without CO₂ injection, the ultimate oil recovery would be increased by 2.7%. Analytical material balance simulation assumed gas injection into the top of the reservoir. Sweep efficiency was not taken into account, and a volume of injected CO₂ backproduced with oil and gas was not calculated, a more detailed numerical simulation is needed for that.

There are no large point sources of CO₂ in the immediate surroundings of the Beničanci field. Three sources are located within the 50 km radius: two thermal electric power plants in Osijek with total CO₂ emission of 214 kt/year (approx. 300×10³ Sm³/day), and a cement factory in Našice with currently undisclosed CO₂ emission. Taking into account the CO₂ injectivity and storage potential obtained by reservoir engineering analyses, the Beničanci field could rather easily store more than 20 years of the current emission of the two thermal plants in Osijek.

4.1.7 Country summary

In Table 4.3 is given a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions for country) and storage capacity in aquifers and hydrocarbon fields. The database estimate for aquifers is calculated using a storage efficiency factor of 3 % and the conservative estimate using a storage efficiency factor of 2 %.

It can be concluded that there are favourable conditions for geological storage of CO₂ in Croatia both in the southern part of the Pannonian basin and Adriatic offshore. Capacity declared for hydrocarbon fields is better defined than estimates for aquifer formations which still need detailed exploration in order to define the structures for storage.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2003</td>
<td>23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Theoretical</td>
<td>2710</td>
<td>4067</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Effective</td>
<td>189</td>
<td>189</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>N/A</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td>Theoretical</td>
<td>2899</td>
<td>4256</td>
</tr>
</tbody>
</table>
Figure 4.1: Map of CO₂ emissions, infrastructure and storage capacity in Croatia.
4.2 Spain

4.2.1 Maps of regional storage potential

As it was pointed out in Deliverable 10 “Maps of regional storage capacities”, Spain has some large areas where a potential for geological storage exists. The extent of these formations at a basin scale is known because of oil exploration that was carried out between 1960 and 1990, and this information permits a certain capacity of determination of the values of some physical parameters. Therefore, some regions were pre-selected as those with higher potentials for geological storage, comprising Cenozoic basins and also some Alpine mountain ranges.

A first capacity estimation was developed taking in account only geometry and the average value of porosity, using a storage efficiency factor of 6% in order to establish a first number that could serve as a guide in the near future. This number, with no higher scientific value than what it is specified above, came out to be 43 Gt of CO₂. The Western part of the Iberian Peninsula was discarded because of the dominant presence of igneous and metamorphic materials that do not meet the requirements to be considered as potential storages.

In the end, these maps have been used as a first step to determine where to follow up with further investigation and where to apply the project methodology to obtain more accurate capacity estimations.

4.2.2 Capacity estimation in aquifers

Regional aquifers capacities were estimated using a 2 % storage efficiency, as indicated in Deliverable 24 of the Project. For all calculations the thickness used corresponds to what is considered to be the net thickness and therefore Net/Gross ratio is neglected. For specific traps, a storage efficiency factor of 40 % has been used according to D24. As only very little information exist on fault systems (or other geological features reducing the connectivity to the surrounding aquifer systems) it was decided to calculate an optimistic estimate until further information is obtained.

4.2.3 Capacity estimation in hydrocarbon fields

Only one on-shore oil field is known in Spain and it is a very little one. Its storage capacity (0.5 Mt) has been supplied from the oil company and other parameters are not too very well known. Other off-shore hydrocarbon fields are still in use and companies have not supplied data from them, except for the case of Casablanca, which was studied by Repsol YPF within the Castor Project. All available data is provided in Deliverable 17.

4.2.4 Capacity estimation in coal fields

In this case, formulae described in Deliverable 24 for effective capacity have been used to estimate storage capacity through the utilization of CoalSeq simulator. Anyway, PGIP has to be calculated more accurately, because values assigned to Gas Content are many times based in just one or two data.

A field campaign is proposed for further work, and Spanish collieries have been contacted in order to develop more detailed studies.
4.2.5  Case studies
Two case studies have been described in GeoCapacity, both of them in saline aquifers. First case is Almazán, in the East of the Duero River and second case is Tielmes structure in the Madrid-Tajo Basin.

Almazán case study
The Almazán basin forms the easternmost part of the Duero River basin, located mostly in the province of Soria and to a lesser extent, in the province of Zaragoza, (in the communities of Castile and Leon, and Aragon), see Figure 4.1. It covers an area of 4,150 Km².

It is an intra-mountainous basin of tectonic origin, located between the Aragonese and Castilian sections of the Iberian mountain range. The Almazan basin is a synclinal sedimentary basin with a general orientation of WNW–ESE that originated in a compressional regime and was refilled with Palaeogene and Neogene materials, subdivided into nine tecto-sedimentary units (Rey, 2003; Maestro González. 2004).

Figure 4.1: Map of the location of the area to be studied.

The structural characteristics are defined by anticlinal and synclinal alignments with principles similar to those of the Cameros mountain range which it borders to the North. Its Southern border is defined by a thrust fault with N vergence that places the Cretaceous materials of the transition area of the Central System and the Castilian Branch of the Iberian Mountain Range, in contact with the Cainozoic sediments that fill the Almazan basin (Rey, 2003). The basin of the Duero River forms the western border, by a threshold characterised by the decrease in thickness of tertiary sediments.

In identifying and selecting formations, areas and structures of the Almazan basin that are favourable for the geological storage of CO₂, we have applied exclusively geological criteria, thus allowing the definition of a monocline geometry that progressively ascends towards the S
as it is limited by the thrust fault with N vergence, on the edge of which the El Gredal-1 borehole is located (Figure 4.2). The monoclinal is limited to the N, in its deepest part, by a new thrust with N vergence that originates an important structural jump as regards the axis of the depocentre of the Cenozoic basin. There are two sets of storage-seal areas close to the aforementioned thrust that are potentially favourable for the geological storage of CO₂:

- The Buntsandstein formation and its Muschelkalk–Keuper seal.
- The Utrillas facies, a siliciclastic formation of the Lower Cretaceous whose seal is the clayey intercalated levels and the loamy series of the Cenomanian base.

Maximum storage capacity in this area has been calculated to 825 Mt of CO₂.

Figure 4.2: Geological and situation map of the area of study.

**Tielmes case study**

The Tielmes structure was selected, because of its big size and short distance to Madrid industries. The case study was evaluated and two formations were selected:

- Utrillas Sandstone (Cretaceous)
- Buntsandstein Formation (Triassic)

These formations are present in this double domed structure, but a precise description of the process of capacity estimation is not given here.
Tielmes structure, located 50 km to the SE of Madrid. The objective is constituted by the Buntsandstein reservoir with Röt formation seal and Keuper facies. The structural catch is an anticlinal and one could also mention a stratigraphic catch because it is delimited on the west by the Triassic erosion limit.

Tielmes-Aranjuez Structure, very flat anticlinal structure that extends from to the vicinity of the Sierra de Altomira. We consider the reservoir here to be the Utrillas facies of the Early Cretaceous and the carbonates of the Late Cretaceous and the evaporitic formation of the Late Cretaceous. This structure almost completely overlaps that of the Tielmes. The area this structure occupies has the largest extension of all those studied in the Tajo basin.

Figure 4.3: Map of isobaths from the Cretaceous limit and summary of results of analysis of the structure.
4.2.6 Country summary

Summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions for country) and storage capacity in aquifers, hydrocarbon and coal fields are given in Table 4.4.

Table 4.4: CO₂ emissions and storage capacity estimates in Spain

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2006</td>
<td>158</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2006</td>
<td>423</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Effective</td>
<td>14000</td>
<td>23439</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Effective</td>
<td>34</td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>Effective</td>
<td>145</td>
<td>193</td>
</tr>
<tr>
<td><strong>Total storage capacity estimate</strong></td>
<td></td>
<td><strong>14179</strong></td>
<td><strong>23632</strong></td>
</tr>
</tbody>
</table>
Figure 4.4: Map of CO₂ emissions, infrastructure and storage capacity in Spain.
4.3 Italy

4.3.1 Capacity estimation in aquifers

The data we have analyzed consist of boreholes and multichannel seismic data that have been acquired since 1957 by several oil companies for hydrocarbon exploration in the Italian subsoil. These data were made available by the Ministry of the Economic Development in the framework of the project “Visibility of Petroleum Exploration Data in Italy (VI.D.E.P.I).”

The major aquifers lie within the so called “Adriatic-Apulian foredeep” and the “Appenninic foreland”, which represent the Italian major sedimentary basins.

The evaluation of the storage potential in deep saline aquifers has been made using the calculation formula for regional estimates based on bulk volume of the aquifers proposed by Vangkilde-Pedersen et al., 2008 in the framework of the EU GeoCapacity project within “D24-Storage capacity standards”:

\[
M_{CO_2e} = A \times h \times \phi \times \rho_{CO_2r} \times S_{eff}
\]

where:

- \( M_{CO_2e} \): effective storage capacity (t)
- \( A \): area covered by regional aquifer (m\(^2\))
- \( h \): average height of aquifer \times average net to gross ratio (m)
- \( \phi \): average reservoir porosity (%)
- \( \rho_{CO_2r} \): density of carbon dioxide at reservoir conditions
- \( S_{eff} \): storage efficiency factor

The area covered by the regional aquifer has been evaluated through the correlation between the borehole information and the available seismic lines.

The average height of aquifer \times average net to gross ratio (m), which represents the so called “effective thickness”, has been calculated, for every available borehole, considering the sum of the thicknesses of each coarse-grained (i.e. sands, gravels, sandstones, conglomerates) layer in the suitable formation.

The porosity of the potential reservoirs was estimated from the P-waves velocity measurements taken from sonic logs.

Carbon dioxide density at the reservoir depth has been calculated by using a specific software performed in OGS which gives density values every 10 m down from the surface, assuming a temperature and pressure at surface of 15°C and 1 atm, respectively, and a geothermal gradient of 25°C/km.

The \( S_{eff} \) reflects a fraction of the total pore volume that is filled by \( CO_2 \) and ranges between 1 and 4% (U.S. Department of Energy, Regional Carbon Sequestration Partnership, 2008). Because some questions as permeability or trap structures are still to be answered, we have used a storage efficiency factor of 2%, as also suggested in the framework of the EU GeoCapacity project for bulk volumes of regional aquifers (see “D24-Storage capacity evaluation”). It gives a total
effective storage capacity for the Italian deep saline aquifers of about 4795 Mt. This evaluation should not be considered as definitive, as it does not include the estimation of a large potential reservoir located in Southern Italy. Due to the fact that most of the data related to this site are confidential, we cannot provide an evaluation of the potential storage capacity of the reservoir.

4.3.2 Capacity estimation in hydrocarbon fields

The hydrocarbon production in Italy is associated with three main tectonic-stratigraphic systems:

1. biogenic gas in the terrigenous Pliocene–Quaternary foredeep wedges
2. thermogenic gas in the trusted terrigenous Tertiary foredeep wedges
3. oil and thermogenic gas in the carbonate Mesozoic substratum (Bertello et al., 2008)

The storage capacity of the Italian hydrocarbon fields has been calculated using the formula from the GESTCO project (Schuppers et al., 2003) assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO2:

\[ M_{\text{CO2}} = \rho_{\text{CO2r}} \times UR_p \times B \]

where:

- \( M_{\text{CO2}} \): hydrocarbon field storage capacity
- \( \rho_{\text{CO2r}} \): CO2 density at reservoir conditions (best estimate)
- \( UR_p \): proven ultimate recoverable oil or gas
- \( B \): oil or gas formation volume factor

The CO2 density has been estimated using the same software performed in OGS, utilized for the estimation of the potential capacity in deep saline aquifers.

\( UR_p \) is the sum of the cumulative production and the proven reserves. An assessment of the potential storage capacity of 14 depleted fields has been provided. They represent a small portion of the entire amount of the Italian hydrocarbon fields, for which the requested information are available. All of them produced gas, and only 2 produced both oil and gas. The sum of the recoverable reserves and the cumulative production from 1987 to 2007 for gas and oil is 853 billions of m³ and 267 Mt, respectively (UNMIG Report, 2007).

The formation volume factor for oil varies regionally and a fixed formation volume factor of 1.2 has been used for the oil replacement. The formation volume factor used for gas varies with depth as a function of pressure and temperature.

Our best estimates of the capacity of the 14 hydrocarbon fields (where information needed for the capacity evaluations are available), which are pretty far from being definitive due to data confidentiality, are the following:

**Gas reservoirs**

Min: 1.6 Gt; Max: 3.2 Gt

**Oil reservoirs**

Min: 210 Mt; Max: 226.5 Mt
4.3.3 Capacity estimation in coal fields

The main coal basin in Italy is the so called “Sulcis Coal Basin”, Eocene in age, located in SW Sardinia. At present it hosts the only Italian coal mine in activity, the Monte Sinni u/g Mine, managed by the Carbosulcis S.p.a.

Preliminary studies on coals extracted from the mine, show promising developments for ECBM technologies in the area. Table 4.5 shows calculations made about CO2 storage capacity and methane production in the deeper parts of the coal basin. These data need to be confirmed by further studies and then they are far from being definitive.

<table>
<thead>
<tr>
<th>Onshore</th>
<th>Offshore</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.687</td>
<td>4.566</td>
<td>11.253</td>
</tr>
<tr>
<td>12.037</td>
<td>8.219</td>
<td>20.256</td>
</tr>
<tr>
<td>42</td>
<td>29</td>
<td>71</td>
</tr>
<tr>
<td>110,1</td>
<td>83,5</td>
<td>193,6</td>
</tr>
</tbody>
</table>

Table 4.5: CO2 storage capacity and ECBM potentialities of the Sulcis Coal Basin

The amount of CO2 that could be stored through ECBM has been calculated through the following formula:

\[ \text{CO}_2 S = \text{PGI}_P \times \rho \times \text{GC} \times \text{ER} \times 10^{-9} \]

where:

- \( GIP \): gas in place (10^6 m^3)
- \( A \): area (km^2)
- \( h \): net thickness (m)
- \( \rho \): coal density (t/m^3)
- \( GC \): gas content (m^3/t)

and:

\[ \text{PG} = \text{GIP} \times C \times R \]

where:

- \( PG \): producible gas (10^6 m^3)
- \( C \): completion factor
- \( R \): recovery factor

In Table 4.6 the values of GIP and GP utilized for the evaluation of the producible gas reserves in the Sulcis area are presented.
Where:

CO₂S: CO₂ that could be stored (Mt)
PGIP: producible gas in place (m³)
ρCO₂: CO₂ density (t/m³)
ER: hard/bituminous coal

Assuming a PGIP of 20250 x 10⁶ m³ and an ER of 2, CO₂S for the Sulcis area is 71 Mt.

Nevertheless, more CO₂ could be stored, through its adsorption by the coal (45m³/t for the Sulcis area), giving a potential, total storage capacity of 265 Mt.

Table 4.6: Detailed information for evaluation of the Sulcis area.

<table>
<thead>
<tr>
<th>Onshore area (km²)</th>
<th>Offshore area (km²)</th>
<th>Coal density (t/m³)</th>
<th>Net thickness (m)</th>
<th>Gas in place (m³/t)</th>
<th>Completion factor onshore</th>
<th>Completion factor offshore</th>
<th>Recovery factor (CBM)</th>
<th>Recovery factor (ECBM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>228.7</td>
<td>173.5</td>
<td>1.55</td>
<td>10.78</td>
<td>13</td>
<td>0.5</td>
<td>0.45</td>
<td>0.5</td>
<td>0.9</td>
</tr>
</tbody>
</table>

4.3.4 Country summary

A summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions for country) and storage capacity in aquifers, hydrocarbon and coal fields is given in Table 4.7.

Table 4.7: CO₂ emissions and storage capacity estimates in Italy

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database (&gt; 1 Mt/year)</td>
<td>2004</td>
<td>140</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2004</td>
<td>212</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Effective</td>
<td>4669 (S_eff : 2%)</td>
<td>9339 (S_eff : 4%)</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>theoretical</td>
<td>1810</td>
<td>3427</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>N/A</td>
<td>71</td>
<td>265</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>6550</td>
<td>13031</td>
</tr>
</tbody>
</table>
Figure 4.5: Map of CO$_2$ emissions, infrastructures, CO$_2$, natural sources and potential sites for CO$_2$ storage in Italy.
4.4 Slovenia

4.4.1 Maps of regional storage potential
Regional storage potential of Slovenia was assessed by applying the following two criteria:
- merging individual potential storage locations with matching geological features located in geographical proximity
- identifying the potential storage locations which spread over a wider area (region) assuming quasi-homogeneous geological features

Based on these such criteria four potential regions have been identified:

- South-West
- North-Central
- Central
- North-East region

The data availability for individual regions differed. The parameters necessary for calculation of storage potential are based on a) actual data, b) extrapolated/interpolated data or c) assumed data. Parameters such as thickness, porosity etc. were treated in ranges. For storage efficiency factor, the “Tallinn approach” was applied. Evaluation per storage was performed in ranges (minimum–maximum expected volume of CO₂ stored). Total storage capacity per region is a summation of sub-total for individual location within one region.

4.4.2 Capacity estimation in aquifers
Publicly available pre-existing data and calculation parameters were used. Where no authenticated sources were available, we have subsequently interpolated / extrapolated / estimated data to the best expert judgment. Parameters such as thickness, porosity etc. were treated in ranges. For storage efficiency factor, the “Tallinn approach” was applied, but additional re-calculations according to the “TNO approach” was also performed, where applicable. We conclude that the results obtained by the two approaches match well in most of the cases. Evaluation of capacities was performed in ranges (minimum–maximum expected volume of CO₂ stored). We consider the calculated storage potentials for aquifers as effective storage capacity or theoretical/effective storage capacity, depending on the level of information available.

4.4.3 Capacity estimation in hydrocarbon fields
Publicly available pre-existing data and calculation parameters were used. Very few authenticated sources were available, so interpolation, extrapolation and estimation of data were necessary. For some calculation parameters data from hydrocarbon fields from Croatia were used. Due to lack of actual data we consider the calculated storage capacities to be of theoretical / effective rank.

4.4.4 Capacity estimation in coal fields
Coal fields in Slovenia (productive and depleted) were carefully studied aiming at investigation of its convenience for CO₂ storage. However, it was established that most of them are not suitable for this purpose, with the exception of coal in the Mura Depression (NE Slovenia). According to existing prospecting studies, thin coal layers here are very likely to be deposited in
specific lithological formation, but information to estimate the storage potential is too scarce at this time. Regarding potentiality, this location would be worth further studying.

4.4.5 Case studies

Two case studies were carried out in Slovenia. The first one applies to a well defined structure Pecarovc-Dankovc in NE Slovenia, and the second one represents a regional aquifer the Mura Depression, which is part of the wider Pannonian Basin. Storage capacities for both were calculated in accordance with the “Tallinn approach”. However, the capacity for Pecarovc-Dankovc structure was calculated again according to “TNO approach” and the two results match within 5%. Publicly available pre-existing data and calculation parameters were used. Where no authenticated sources were available, we have subsequently interpolated / extrapolated / estimated data to the best expert judgment. We consider the calculated storage potential for Pecarovc-Dankovc structure as effective storage capacity, while for the Mura Depression it is only within the rank of theoretical/effective storage capacity.

I would suggest to keep the figure prepared by BGS, since it is conformal with other countries. In Chapter 446, we would probably say something like "The existing pipeline infrastructure is relatively favourable although not explicitly shown on Figure 4.6." or similar.

4.4.6 Country summary

The potential for storing CO₂ underground in Slovenia exists in aquifers as well as in depleted oil/gas fields. The option to store in unmineable coal layers should not be neglected, but further investigations are necessary. The best potential is expected in aquifers. Using ranges of calculation parameters (area, thickness, porosity, storage efficiency factor etc.) we obtained minimum and maximum values: conservative estimate for storage capacity in aquifers is 92 Mt CO₂, while the optimistic values exceed 500 Mt. The existing pipeline infrastructure is relatively favourable although not explicitly shown on Figure 4.6. Taking into account the yearly emission of the biggest emitter in the country (PP Sostanj) which is approximately 4.6 Mt CO₂, and the total country’s emissions in 2005, which were 20Mt, we could assume that a single capture installation would be sufficient to meet Kyoto commitments in Slovenia.

Three major stationary emitters lie in the area or within a perimeter of 100 km from the most promising storage locations. However, no economic factors, potential conflict of space use (here in particular the geothermal resources), public acceptance or safety conditions have been considered in this project.

Table 4.8: CO₂ emissions and storage capacity estimates in Slovenia

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2005</td>
<td>7</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2005</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Effective (Theoretical in some cases)</td>
<td>92</td>
<td>153</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Theoretical / effective</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td>Theoretical / Effective</td>
<td>94</td>
<td>159</td>
</tr>
</tbody>
</table>

Figure 4.6: Map of CO₂ emissions, infrastructure and storage capacity in Slovenia.
4.5 Bosnia-Herzegovina

4.5.1 Maps of regional storage potential

Bosnia and Herzegovina extends over the two geotectonic units: 1) the fold-thrust belt of the Dinarides, and 2) the southern margin of the Pannonian basin system. Dinarides occupy the most of the territory (around 65 %) in southern and central parts, while the rest in the north belongs to the Pannonian basin system (PBS). The fold-thrust belt of the Dinarides in Bosnia and Herzegovina is classically subdivided into the northern (more internal) and the southern (more external) belt, i.e. the Internal and External Dinarides, respectively.

Internal Dinarides comprise several predominantly NW–SE striking tectonic zones and External Dinarides are composed of tectonic units derived from the eastern part of the Adriatic microplate. Both regions were extensively tectonically disturbed in many phases leaving in the end marked NW trend and SW vergence of km-scale compressional structures (folds and thrusts). After the main compressional tectonic phase in the Dinarides during the Middle–Late Eocene/Oligocene, this fold-thrust belt was affected by Neogene transpressional tectonics accommodated by dextral strike-slip faulting. This resulted in formation of numerous generally NW–SE striking intramontane basins of variable size, dispersed throughout the Dinarides. Most of these Neogene fresh-water basins are characterized by similar lacustrine and coal-bearing sedimentary successions. Together with the castic sediments in several smaller depressions along the southern margin of the Pannonian basin system, these are in principle the only formations with intergranular porosity where significant storage capacity might be estimated. In the larger ones have been depicted as the coal basins and the single most important one as a regional aquifer. Their location conveniently coincides with major point sources.

4.5.2 Geological description, aquifers

Out of many small Neogene sedimentary basins in Bosnia and Herzegovina only the Sarajevo-Zenica basin is significantly deeper than 1000 m and thus represents the single favourable location for geological storage of CO₂. The basin extends NW-SE for about 100 km, and is located in the highly industrialised region of central Bosnia. Structurally, the basin is asymmetric synclinorium 10–15 km wide with coal-bearing horizons cropping out along the north-eastern moderately dipping limb. The basin fill succession progrades to the southwest and is divided into three main groups:

1) The Oligocene–Miocene group is 600–800 m thick and starts with conglomerates, sandstones and clays with coal-seams. These are overlain by platy marls and fresh-water limestones, which grade into “variegated series” composed of conglomerates, sandstones, marls and clays.

2) The Lower Miocene group starts ca. 200 m thick succession of alternating marls, clays, sandstones and coal layers, which represents the “main coal suite”. It is overlain by thin bedded siltstones, marls and sandstones approx. 400 m thick that grade into alternating conglomerates, sandstones, marls and limestones, up to 800 m thick.

3) The Upper Miocene group starts with 500 m thick series of marls, clays and conglomerates, sporadically with some coal layers. It is conformably overlain by conglomerates. The Neogene series is disconformably overlain by Pliocene and Quaternary sandstones and clays. The total thickness of Neogene fresh-water sediments of the Sarajevo-Zenica basin is estimated to about 2500–3000 m.
4.5.3 Capacity estimation in aquifers

A single oil exploration well was drilled in the Sarajevo-Zenica basin, allowing an estimation of the reservoir properties and thickness to be made which led to capacity estimation given in Table 4.9. The number should be regarded as only the really approximate one because of several factors, there was no control of the subsurface geometry of a reservoir (only one well and few seismic sections), and effective thickness and porosity were extrapolated as an average in the entire area. With the same storage efficiency factor as taken for Croatia (3%), this resulted in a significant capacity simply because of the size and thickness of the basin. It should be noted that no deep structures were defined (there was simply no data for that) meaning that the given value is still just a theoretical capacity, i.e. it belongs to the “bottom of the pyramid”.

Table 4.9: Storage capacity estimation for aquifers.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Area (m²)</th>
<th>Thickness (m)</th>
<th>Net/gross ratio</th>
<th>Porosity (%)</th>
<th>CO₂ density (t/m³)</th>
<th>Storage efficiency factor (%)</th>
<th>Total estimated CO₂ storage capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarajevo-Zenica</td>
<td>792670321</td>
<td>250</td>
<td>0.40</td>
<td>15</td>
<td>0.830</td>
<td>3</td>
<td>296</td>
</tr>
</tbody>
</table>

Total estimated CO₂ storage capacity in deep saline aquifers (Mt) 296

4.5.4 Capacity estimation in hydrocarbon fields

In spite of the historic findings and minor production that took place in the 1930’s in northern Bosnia, no hydrocarbon fields were put in the database due to lack of reliable data. From what is known, this could not render the significant storage capacity anyway.

4.5.5 Capacity estimation in coal fields

Several coal basins were included in the database (2 in northern Bosnia and 3 in Herzegovina), and their characteristics were described. Based on the data taken from the mined sections, the coal seams are too shallow for CO₂ storage and capacity was not estimated.

4.5.6 Case studies

Only one case study was carried out. This is actually taken from the studies made for the possible construction of the underground gas storage at the location called Tetima in NE Bosnia, at the margin of the Tuzla basin. Construction of UGS in salt deposits was planned and the estimated capacity is limited, surely inadequate for the power plant nearby but might prove to be interesting for a smaller industrial point source.

The vertical thickness of salt exceeds 140m allowing the construction of cylindrical caverns 60m high and 50-60m in diameter. Each cavern could have a volume of up to 230000 m³. The average depth at location is around 700 m, too close to the upper limit of the interesting interval for storing supercritical CO₂, but slightly deeper locations might be found nearby and mechanical properties of both the salt and overlying sediments are investigated and found to be favourable for construction of such subsurface objects. With deeper exploration wells and new seismics this might turn out to the secondary option for geological storage of carbon dioxide in Bosnia and Herzegovina.
4.5.7 Country summary

In Table 4.10 is given a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database and storage capacity in the identified aquifer.

It can be concluded that Bosnia and Herzegovina lacks the geological storage capacity and this is due to the same reasons why the region of the Dinarides in Croatia had to be ruled out, predominance of carbonate sedimentary formations and high level of karstification and tectonic disturbance of their brittle layers.

Table 4.10: CO₂ emissions and storage capacity estimates in Bosnia-Herzegovina.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2001–2006</td>
<td>9</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Theoretical</td>
<td>197</td>
<td>296</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>N/A</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>N/A</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td>Theoretical</td>
<td>197</td>
<td>296</td>
</tr>
</tbody>
</table>
Figure 4.7: Map of CO₂ emissions, infrastructure and storage capacity in Bosnia-Herzegovina.
5 WP 2.4 COUNTRY UPDATES

5.1 Germany

The German updates affect the CO₂ storage potential in aquifers and natural gas fields.

Regarding aquifers, the CO₂ storage potential of saline aquifers in the German North Sea sector has been evaluated for the first time. Therefore, the potential storage structures have been identified and mapped. Then, the CO₂ storage capacity has been estimated for each structure. For the German onshore aquifers however, no updates of the GESTCO results have been made.

Regarding natural gas fields, the GESTCO data have been updated using the published numbers of cumulative natural gas production until the end of the year 2005 (see section 5.1.2).

5.1.1 Capacity estimation in aquifers

For every identified aquifer structure the CO₂ storage capacity has been estimated. The general assessment methodology is described in D24 (“storage capacity standards”). The used formula here is a slightly modified version, as described in D24:

\[ M_{CO₂t} = A \times NT \times \phi \times \rho_{CO₂r} \times S_{eff} \]

where:

- \( M_{CO₂t} \): "trap" storage capacity
- \( A \): area of aquifer in trap
- \( NT \): cumulative sandstone thickness in trap (net thickness)
- \( \phi \): average reservoir porosity of aquifer in trap
- \( \rho_{CO₂r} \): CO₂ density
- \( S_{eff} \): storage efficiency factor (for trap volume)

The calculations have been made twice for each structure: One approach for the database and one rather conservative approach with a different efficiency factor.

First approach (for the database)

For this approach, no error ranges have been used for the parameters. For the CO₂ density, a value of 700 kg/m³ was assumed for all estimations (Straaten, 1996 and Müller et al., 2003). The storage efficiency factor was assumed as 20 % (as in D24: open aquifer, low quality reservoir). The regional estimate is the sum of the storage capacities of all identified traps. This results in a CO₂ storage capacity of 6336 Mt. A subsequent error consideration produced an error range between 4000 and 8700 Mt for the result.

Second approach (conservative estimate)

For the second approach, estimated errors have been included in the calculations for all parameters. In order to estimate the uncertainties of the calculated storage capacities, Monte-Carlo-Simulations have been used. For the parameters A, NT and \( \phi \) a normal error distribution pattern was assumed. For the CO₂ density, a value of 625 ± 75 kg/m³ (standard deviation) was assumed for all estimations. The most important issue for the second calculation approach is a reduced (more conservative) storage efficiency factor. We assumed efficiencies in a range between 5 and 20 % with a triangular distribution pattern and a median value of ca. 10 %. The sum of the storage
capacities of all the identified structures results in a CO₂ storage capacity of 2901 Mt (error range: 1879–4495 Mt) for the German North Sea sector.

Overall, the CO₂ storage capacity has been calculated twice for the identified 262 structures. The results are summarized in Table 5.1. Generally, most of the structures are rather small. According to the database approach, 27 structures provide a storage capacity of more than 50 Mt CO₂.

According to the conservative approach, only 12 structures exceed that threshold. The most traps were found in aquifers of Middle Bunter (Lower Triassic) and Keuper (Upper Triassic) age. According to the CO₂ storage capacity, the Middle Bunter aquifers provide the bulk of storage potential in the German North Sea sector.

### Table 5.1: Summary of storage capacity estimates (database and conservative estimations) in aquifer structures of the German North Sea sector.

<table>
<thead>
<tr>
<th>Stratigraphic unit</th>
<th>Number of traps</th>
<th>CO₂ Storage capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Rotliegend</td>
<td>53</td>
<td>112.4</td>
</tr>
<tr>
<td>Middle Bunter</td>
<td>99</td>
<td>2147.5</td>
</tr>
<tr>
<td>Keuper</td>
<td>98</td>
<td>511.9</td>
</tr>
<tr>
<td>Jurassic</td>
<td>9</td>
<td>120.4</td>
</tr>
<tr>
<td>Middle Eocene</td>
<td>3</td>
<td>8.44</td>
</tr>
<tr>
<td><strong>Total storage capacity estimate</strong></td>
<td><strong>262</strong></td>
<td><strong>2901</strong></td>
</tr>
</tbody>
</table>

### 5.1.2 Capacity estimation in hydrocarbon fields

The CO₂ storage capacity in German oil and gas fields was assessed as part of the GESTCO project (Schuppers et al., 2003). In GeoCapacity this assessment has been updated only for natural gas fields because they promise sufficient CO₂ storage potential for the reductions of national CO₂ emissions. The assessment methodology (as in D24 storage capacity standards) has not been changed but new estimates have been calculated using the published numbers of cumulative natural gas production until the end of the year 2005 (LBEG, 2006).

The storage capacity of the German natural gas fields has been estimated on the basis of the formula from the GESTCO project (Schuppers et al., 2003), assuming a 1:1 volumetric replacement ratio between natural gas and CO₂:

\[
M_{\text{CO}_2} = \rho_{\text{CO}_2} \times UR_p \times \text{FVN}
\]

where:

- \( M_{\text{CO}_2} \): storage capacity substituting natural gas
- \( \rho_{\text{CO}_2} \): CO₂ density at reservoir conditions
- \( UR_p \): proven ultimate recoverable gas
- \( \text{FVN} \): gas formation volume factor

For the German database however, no real proven ultimate reserves are published. Therefore only the published cumulative production numbers had to be the starting point for the calculation.
of the storage capacity. Then a portion of the expected remaining reserves was estimated on the basis of the published data.

Each of the 39 aggregated gas fields considered for CO₂ storage has produced more than 2 \times 10^9 m^3 of gas at standard state condition. The accumulated gas recovery from these fields up to January 1st 2006 was 773 \times 10^9 m^3. The total storage capacity calculated from the produced gas is ca. 2.18 Gt of CO₂, including abandoned fields. Taking into account the ratio of probable and proven gas reserves to the total accumulated gas production in Germany (1.29), the total CO₂ storage potential would increase to approximately 2.8 Gt.

5.1.3 Capacity estimation in coal fields
The GESTCO data about the CO₂ storage potential in coal fields has not been updated for the GeoCapacity project. Information about the CO₂ storage capacity in unmineable coal beds in Germany can be obtained from the BGR contribution to the GESTCO report (May, 2003).

5.1.4 Country summary
This country summary comprises storage capacity in aquifers and natural gas fields, because these two options provide the bulk of CO₂ storage potential in Germany. Hence, for the GeoCapacity project the GESTCO results have been updated only for these two options.

The GESTCO results about the CO₂ storage in oil fields and coal fields have not been updated. Oil fields are omitted, because they do not provide a considerable share to the reductions of German CO₂ emissions. The storage of CO₂ in deep unmineable coal seams is considered to be very unlikely in Germany because of unresolved technical obstacles and the prevailing geological conditions. Therefore these two options are not integrated in this country summary, but they are included in the GeoCapacity database.

Regarding aquifers, the CO₂ storage capacity in the German North Sea sector has been evaluated for the first time. The estimation for the GeoCapacity database resulted in a storage capacity of 6330 Mt CO₂ (error range: 4000–8700 Mt). A second estimation with a reduced storage efficiency factor (conservative estimate) resulted in a capacity of 2900 Mt (error range: 1879–4495 Mt). The theoretical storage capacity in aquifers for onshore Germany, which is listed in Table 5.2, was not a part of the GeoCapacity project and represents an estimation by BGR on the basis of regional studies (May et al., 2005). Yet, the results of this estimation are included in the GeoCapacity database. The CO₂ storage capacity of German deep sedimentary basins has been estimated according to the areal extent of the basins and specific storage capacities per unit area. Based on regional studies specific storage capacities of 0.08 Mt/km² (smaller basins) and 0.12 Mt/km² (North German Basin) were applied. Accordingly, the CO₂ storage capacity for onshore Germany is expected to be ca. 20000 ± 8000 Mt. An additional conservative estimation has not been made.

The storage capacity in natural gas fields was estimated on the basis of the accumulated gas production until the end of 2005 for the biggest 39 gas fields in Germany. The total storage capacity calculated from the produced gas is 2180 Mt of CO₂, including abandoned fields (conservative estimate). Including the estimated remaining reserves, the CO₂ storage capacity is expected to be ca. 2800 Mt.
Table 5.2: CO₂ emissions and storage capacity estimates in Germany.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2004</td>
<td>465</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2004</td>
<td>864</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers (onshore)</td>
<td>Theoretical</td>
<td>-</td>
<td>20000 (12000–28000)*</td>
</tr>
<tr>
<td>Storage capacity in aquifers (German North Sea sector)</td>
<td>Theoretical</td>
<td>2900 (1879–4495)</td>
<td>6330 (4000–8700)</td>
</tr>
<tr>
<td>Storage capacity in natural gas fields</td>
<td></td>
<td>2180</td>
<td>2800</td>
</tr>
</tbody>
</table>

*May et al., 2005
Figure 5.1: Map of CO₂ emissions, infrastructure and storage capacity in Germany.
5.1.5 Luxemburg

BGR has evaluated the CO₂ storage potential in Luxemburg. In the following, the results are shortly described.

Saline Aquifers in Luxemburg
Only in the south-west of Luxemburg there perhaps is a slight chance to meet aquifers deep enough for CO₂ storage purposes, which means deeper than 800 m. From Dittrich (1984, 1993) there can be deduced depths of about 800 m for the uppermost Bunter Sandstone (Voltzia sandstone) in that area whereas Lucius (1951) has published a standardised profile with depths of about 700 m for the base of the Rotliegend. After Robelin & Matray (2003) the top of the Buntsandstein reached depths up to 500 m below sea level, which means up to 800 m below valley grounds. On the other hand, in the geological map of France (BRGM 1996) the top of the basement is given in the depth of 500 m b.s.l. which means that the Buntsandstein must be found less deep. There are no structural maps or well data available to get more detailed information. Therefore, as things are now there is no CO₂ storage potential in Luxemburg.

Coal fields and hydrocarbon fields in Luxemburg
There are no coal or hydrocarbon fields in Luxemburg.
5.2 The Netherlands

5.2.1 Geological description, aquifers

The total estimated capacity for storage in deep saline aquifers is about 440 Mt. When only the economically viable traps with capacities of more than 10 Mt are considered the onshore capacity is reduced to about 340 Mt, meaning that these very small traps hold almost 100 Mt storage capacity. The map (Figure 5.4) shows that most of the traps are located in the southern and western part of the country and offshore. Most of the capacity is present in relative deep traps in Rotliegend (RO) or Triassic (RB/RN) aquifers.

A frequency distribution plot of storage capacity in onshore aquifers (Figure 5.2) shows that there are many small aquifer traps, whereas the amount of large traps (> 50 Mt) is zero. Only 8 medium-sized trap structures with capacities larger than 15 Mt have been identified. Together these medium traps represent storage capacity of no more than about 160 Mt. Unfortunately, due to the absence of mapped aquifer trap structures in the offshore area a size classification for the offshore is not possible.

![Frequency distribution of storage capacity in onshore aquifer traps in the Netherlands.](image)

The storage capacity values reported here are based on the assumption that storage is limited by the pressure increase associated with injecting CO₂, with the integrity of the seal as the leading parameter controlling the safe and secure containment of CO₂. However, pressure increase could be managed by producing brine from the aquifer. In theory, if the produced volume equals the injected volume, average pressure increase in the aquifer would be zero and the storage capacity would be limited only by trap volume. This concept is not included, as its feasibility and efficacy must be assessed for each site separately.
5.2.2 Capacity estimation in aquifers

Potential structural and or stratigraphical trap locations for underground CO₂ storage in saline aquifers have been selected from geological maps. The selection of distinct stratigraphical aquifers is given in the next section. The locations, depth and thickness of potential saline aquifer traps for CO₂ storage are based on the most recent regional geological maps of the deep subsurface of the Netherlands, for an example see Figure 5.3. The presence or absence of faults is important to identify the aquifer trap as an ‘open’ or ‘closed’ system, where an open trap enables pressure release during CO₂ injection into the aquifer system. This pressure release is not possible in a closed trap. A trap was characterized as ‘open’ when the contours of the trap were not fully identified by faults. In the case of a ‘closed’ aquifer trap, the trap is completely defined by faults, offsetting the aquifer. From the aquifer layers, rock properties have been used to calculate the storage capacity per trap. The final selection of traps follows rules and boundary conditions:

- Aquifers are part of a geological structure in order to control the position of the injected CO₂.
- Aquifers are covered at the top by a sealing layer to prevent the CO₂ from migrating to the surface.
- The porosity of the aquifers is at least 10%.
- The permeability of the aquifer is at least 200 mD.
- The thickness of the aquifer is at least 10 m.
- The aquifer has a depth of at least 800 m below surface. At a temperature of 35 °C and a fluid pressure of 8 MPa the CO₂ is in supercritical state. In The Netherlands, these conditions correspond with a depth of about 800 m.
- When a potential trap structure has a spatial overlap with an oil or gas field the structure is not selected in this study due to foreseen flow interference and legislative consequences.

\[ V_{CO₂} = A \times d \times \phi \times f_{se} \times NG \times \rho \]

Where:
A: area (m$^2$)  
d: average aquifer thickness (m)  
$\phi$: porosity (-)  
f_{sc}: storage efficiency (-)  
NG: net-gross fraction (-)  
$\rho$: CO$_2$ density (kg/m$^3$)

The unit of $V_{CO_2}$ is Mt.

For the storage efficiency factor (the part of the pore space that can be filled with CO$_2$) of aquifers the following factors have been used:

- For ‘closed’ aquifer traps the storage efficiency is 0.02 (2%).
- For ‘open’ aquifer traps the storage efficiency is 0.06 (6%).
- For aquifer traps that cannot be clearly categorized the storage efficiency factor is 0.04 (4%).
- Net/Gross (N/G): fraction of porous permeable rock of the aquifer (often: sandstone thickness/total aquifer thickness).
- Porosity data are taken from previous studies.
- The density of CO$_2$ is taken as a constant value of 700 kg/m$^3$.

### 5.2.3 Capacity estimation in hydrocarbon fields

The main parameters to determine the CO$_2$ storage capacity of a depleted gas field are: the ultimate gas recovery volume, the gas expansion factor and the CO$_2$ density:

$$SC_{CO_2} = \left( \frac{V_{UR(stp)}}{E_g} \right) \times \rho_{CO_2}$$

Where:

- $SC_{CO_2}$: CO$_2$ storage capacity in [Mt]
- $V_{UR(stp)}$: Volume of ultimate gas recovered at standard conditions [10$^9$ m$^3$]
- $E_g$: Gas expansion factor
- $\rho_{CO_2}$: Density of CO$_2$ at reservoir conditions [in kg/m$^3$]

In trying to determine these parameters several problems can be identified. The main uncertainty in calculating the CO$_2$ storage capacity per field lies in the indirect way the ultimate gas recoveries per field are derived. This is caused by the fact that the values for ultimate recovery and historical cumulative production per individual field, from before 2003$^1$, are confidential in The Netherlands. It is therefore not possible to estimate UR figures based on these historic production data, which would probably be the most accurate and thus preferred method.

### 5.2.4 Capacity estimation in coal fields

Unmineable coal seams can be used to store CO$_2$, because in theory injected CO$_2$ would adsorb to the coal surface (van Bergen et al., 2001). During the storage process the coal seams release

---

$^1$ 2003 was the year when the new mining law took effect in The Netherlands. Some operators have published historical production figures in the production planning reports (WIPLA’s of 2003/2004). For the bulk of the gas fields however, these figures are not published.
methane (CH₄), which was previously adsorbed to the coal surface? This methane can then be produced; this process is called enhanced coal bed methane (ECBM) recovery. The technical feasibility strongly depends on the permeability of the coal layers. Here again the revenues of the methane can be used to offset the cost of the CO₂ storage.

The potential storage capacity in coal seams in the Netherlands has been studied thoroughly in a study for NOVEM (TNO-NITG, 2000). It was assumed that the storage capacity is fully described by adsorption of CO₂ in exchange for desorption of methane (the ECBM concept). The underlying methods and assumptions for calculating the storage capacity will not be described in detail here, only a brief summary will be given.

The geological inventory study on coal bearing sediments shows that within the depth range which is considered suitable for CO₂ storage (800–2000 m) these sediments are present in Southern Limburg, The Achterhoek/Twente area, the Peel area and in Zeeland/West Brabant. In the Southern Limburg area, the coal mine concession areas were excluded from the inventory, in other words only unmined coal areas were addressed.

After estimating the average coal seam thicknesses in these regions using available well data, a calculation of the Gas in Place volume was done:

\[
\text{GIP} = A \times H \times \rho_c \times G_c
\]

With:

- GIP: Gas in Place volume (10⁶ m³)
- A: Area (km²)
- H: cumulative thickness of the coal (m)
- \(\rho_c\): density of coal (t/m³)
- Gc: Gas content of the coal (m³ gas/ ton coal), following Langmuir adsorption and dependent on pressure and temperature.

The storable amount of CO₂ (CO₂S) was then calculated by:

\[
\text{CO₂S} = \text{GIP} \times C \times R \times \text{ER} \times \rho_{\text{CO₂}}
\]

With:

- C: an estimated completion factor, the fraction of the coal layers that will be used for ECBM (-)
- F: recovery factor, the part of the gas within the layers that will be produced (-)
- ER: the exchange ratio of CO₂ for methane (-); in theory ER = 2.
- \(\rho_{\text{CO₂}}\): the density of CO₂.

The parameters within these equations have large uncertainties, due to lack of real, measured data. Therefore in the NOVEM study a Monte-Carlo approach was used to determine probability distributions of expected storage capacities. Recent advances in knowledge on the ECBM technology (a.o. the RECOPOP study) however suggest using only the conservative capacity estimations (the P90 values) (Pers. comm. van Bergen).
5.2.5 Country summary

Table 5.3 shows the total storage capacity in aquifers, hydrocarbon fields and coal fields in The Netherlands. The distribution of the storage locations is shown in Figure 5.4. The estimates in the database represent the sum of all reservoirs listed in the GeoCapacity database, while the conservative estimates represent the following:
- for aquifers: only the larger aquifers (> 10 Mt) were included;
- for hydrocarbon fields: based on a recent detailed inventory, executed on a field level and taking into account possible re-use of infrastructure, a storage capacity estimate of the offshore Netherlands was obtained. The ‘success ratio’ between available storage capacity and capacity likely to be used was about 50%. This value was extended to include onshore capacity, using 50% ‘success ratio’ also for onshore fields.
- The conservative coal storage capacity listed is the lower end of the estimated range of storage capacity, with the note that the current view is that without significant financial incentives storage in coal is probably not economically feasible.

Table 5.3: CO2 emissions and storage capacity estimates in the Netherlands.

<table>
<thead>
<tr>
<th>CO2 emissions</th>
<th>Year(s)</th>
<th>Average CO2 emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 emissions from large point sources in database</td>
<td>2004</td>
<td>92</td>
</tr>
<tr>
<td>Total CO2 emissions</td>
<td>2003</td>
<td>180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO2 storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Theoretical</td>
<td>340</td>
<td>430</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Effective</td>
<td>1700</td>
<td>2700</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>Theoretical</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>2340</td>
<td>3630</td>
</tr>
</tbody>
</table>
Figure 5.4: Map of CO₂ emissions, infrastructure and storage capacity in the Netherlands.
5.3 France

5.3.1 Geological description, aquifers

Dogger
The Middle Jurassic aquifer is the result of deposition of a broad carbonate platform. With a thickness of 200–300m it is bounded above by the Callovian–Oxfordian argillites and by the Liassic shales below. The Callovian cap rock was studied in detail in coeval Bure Clay, in the east of the basin, for the purpose of nuclear waste disposal. The carbonate facies are interrupted by the NW–SE "Sillon marneux" (marly trough). From west to east of the trough, as well as vertically in the depositional sequence the facies become more proximal and more confined with the following facies: Alternances (outer shelf), Oolithe Blanche (white oolite, barrier), and Comblanchian (lagoon). This evolution corresponds to a westward progradation with a correlative distribution of the poro-permeability in the grainstone facies. At the top the Dalle Nacrée is the last carbonate unit in the eastern area, prior deposition of the Callovian–Oxfordian marls. The main reservoir corresponds to an assemblage of oolitic limestone of Upper Bathonian (Oolithe Blanche) and of Lower Callovian age (Dalle nacrée). Locally, in the centre of the basin, the comblanchian facies, generally tight, may exhibit good reservoir properties related to strongly digenitised areas (dolomitisation and dissolution). The secondary reservoir, of Bajocian age, consists of bioclastic limestone. The transmissivity is generally ~ 1 - 5 Darcy.m, increasing towards the basin centre. The total thickness of the Dogger ranges commonly between 90 and 350m. The cumulative thickness of grainstone facies in the different reservoirs is up to ~150m. The top of the main reservoir is from less than 1000m up to more than 1500m (Figure 5.5).

Figure 5.5: Structure map of the top Dogger reservoir (elevation m asl).
Triassic
The reservoir potential of the Triassic is related to the paleogeographic evolution and can be broken down into two large clastic units (Figure 5.6): the Lower Triassic sandstone (Buntsandstein) in the east (Lorraine province in France), and the Upper Triassic sandstone (Keuper) in the west (west of a line connecting Rheims-Sens-Nevers).

The Buntsandstein reservoir is the main aquifer in the eastern province for drinking water supply (‘GTI’ or Lower Triassic Sandstones). The reservoir consists of a wedge-shaped alluvial fan which exhibits a decreasing thickness and permeability westward. Meanwhile the effective porosity decreases like the grain size and the salinity increases. The transmissivity varies consequently.

In the central area of the Paris Basin, the other potential storage potentials in the Triassic are from bottom to top: the Donnemarie Sandstone: (Muschelkalk to Middle Keuper), the Chaunoy Sandstone (Middle Keuper) and the Rhaetian Sandstone. The two fluvial bodies (Chaunoy and Donnemarie) are multilayer reservoirs entirely sealed by anhydritic clay. They extend over ~320km in length and 180 Km in width, with an extent of ~100Km towards the north of Paris and 220Km towards the south. The top elevation of the upper fluvial reservoir (Chaunoy Sandstone) ranges between ±500 and ±2250m (AMSL) and is almost entirely compatible with the requested depth of storage. The top elevation of the lower fluvial reservoir (Donnemarie Sandstone) ranges between 1000 and 2750 m. The cumulative thickness of the two reservoirs ranges between 50 and 300m. They exhibit high salinities ranging between 30 and 180g/l.

Figure 5.6: Extent, structure (m asl) and thickness of the Triassic reservoirs.
A new GeoCapacity target in the north-west of the Paris Basin: the Liassic reservoir

In the Normandy region of the north-west France, south of the English Channel, a Liassic reservoir was described during geothermal investigation in the Paris Basin (Maget, 1983) now in the GeoCapacity GIS (Figure 5.7). It consists of carbonate (oolitic limestone), sandy limestone and sandstone of Hettangian and Sinemurian age capped by overlapping marls of late Liassic age forming the cap-rock. The effective reservoir facies covers an area of about 180x120km. The top of the reservoir is dipping to the south-east from elevation ÷500m (asl) in the north to ÷1900m in the south. For a ground surface around 100m, the major portion of the reservoir is deeper than the critical depth of 800m. The reservoir forms a saddle on the NW–SE ‘Pays de Bray anticline’, marked by the Jurassic outcrops. The maximum thickness is about 30m in the Beauvais area. The porosity and permeability measurements on core give values from 0.2% to 36.6% and from 0.1 to 5035 mD, respectively.

![Figure 5.7: Thickness, facies and structure (m asl) of the Liassic reservoir.](image)

Due to lack of other data, the basin synthesis by Baudrimont and Dubois (SNEA(P), 1977) is the only public comprehensive reference document available at the appropriate scale for preliminary reservoir maps. The specific input to GeoCapacity was to transform the printed maps to GIS feature classes by using the right projection and selecting the pertinent features. Therefore, eight facies maps displaying the distribution of possible reservoir were provided: Lower Liassic Mid Jurassic, (2 maps), Upper Jurassic, Valanginian, ‘Urgonian’, Upper Gargasian, Upper Turonian.

5.3.2 Capacity estimation in aquifers

**Dogger aquifer**

In the GESTCO project, the storage efficiency was 6% and the density of CO₂, 0.48. The difference between the amounts estimated for the identified traps and the aquifer at large scale are huge, demonstrating the need for large structures in front of the CO₂ productions of the integrated plants. The volumetric estimation was based on a rough processing of digital depth and thickness maps. The trapped volume is estimated 0.2%, assuming that the largest traps were filled with hydrocarbons and that most of the hydrocarbon structures have now been found.

**Triassic aquifer**

The reservoir depth, temperature and pressure range respectively between 1500 and 3000m, 70 and 120°C and 200–300 bars. The volumetric evaluation of the reservoir coupled with statistical processing of the reservoir properties deduced from the borehole data provided a quite realistic...
evaluation of the storage capacity. In GESTCO, the storage efficiency was 6% and the CO₂
density 0.7. The trapped volume was assumed 3% of the total storage capacity.

**Liassic aquifer**

Volumetric calculations of the pore volume for K>20mD, Phi>16% and z<700m asl were
performed through a numerical model with discrete Phi, K and thickness distribution. Arbitrary
storage efficiencies were subsequently applied to reduce the total volume to more realistic
values. Uncertainties on injection prognosis are related to reservoir heterogeneity of hydraulic
properties:

- This reservoir preliminary assessment is based on few well data.
- Core data indicate large variations in petrophysics and injectivity may be low.
- The reservoir modelling is based on heterogeneous and scarce data for petrophysics.
- Details of structure and effects of faults are not included in the model.

### 5.3.3 Capacity estimation in hydrocarbon fields

Hydrocarbon exploration in France started before the II World War. The hydrocarbons are
produced by the two main sedimentary basins: the Paris basin and the Aquitaine basin.
The annual French oil production stayed low along the 50 last years. From 1968 to 2007, it
ranged from 1 to 3 Mt; the annual gas production decreased regularly from 8 to 1 billion cum
since the end of the 70's (Figure 5.8) because of the depleting of the giant Lacq gas field in the
southern Aquitaine basin.

![Figure 5.8: French hydrocarbon annual production (1968–2007), DGEMP-BEPH, 2008.](image)

The French oil production peaked in 1989. Few EOR projects were carried out. The most
commented example was the Coulommes field case in 1984, where 2600 t of CO₂ were injected
with a noted result. Nowadays, a total of 76 hydrocarbon fields are on production: 64 oil fields
and 12 gas fields:

- The crude oil production is parted between the Paris basin (42 fields) and the Aquitaine basin
  (18 fields). A residual oil production remains in Alsace graben (4 fields). The others basins
  are devoid of discovered commercial oil accumulation,
- The natural gas production is concentrated in the south-western part of the Aquitaine basin:
  the Adour sub-basin, near the city of Pau. The remaining production is related to coal mine
  methane in the Nord-Pas-de-Calais area.
The CO₂ storage capacity in French oil and gas fields was assessed as part of the GESTCO project. In GeoCapacity, this assessment has been updated with 69 fields which were added to previously GESTCO database. The CO₂ storage capacity was assessed by using a thermodynamical model based on the following steps:

1. Miscibility Test
2. Oil recovery and CO₂ storage calculation under miscible conditions
3. CO₂ storage without oil production.

The sequence of events considered is first the oil recovery, followed by the CO₂ storage stage without oil production. The choice of this sequence is considered as the easiest and operationally most logical in case of a CO₂ storage operation in an oil reservoir. Refer to GeoCapacity Work Package 3 D17 for more details about the model used. As illustrated in Table 5.4, the total estimated CO₂ storage capacity for the French hydrocarbon fields amounts to 1008 Mt.

Table 5.4: Storage capacity estimation for hydrocarbon fields in France.

<table>
<thead>
<tr>
<th>Area</th>
<th>CO₂ storage capacity (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquitaine Gas</td>
<td>383.3</td>
</tr>
<tr>
<td>Aquitaine Oil</td>
<td>283.8</td>
</tr>
<tr>
<td>Alsace</td>
<td>0.3</td>
</tr>
<tr>
<td>Paris Basin in Gestco project</td>
<td>240.2</td>
</tr>
<tr>
<td>Paris Basin added in GeoCapacity Project</td>
<td>100.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1007.6</strong></td>
</tr>
</tbody>
</table>

5.3.4 Country summary

The Paris Basin, is the most advanced considering the CCS objective, having the advantage to exhibit large reservoir systems together in siliciclastic and in carbonate contexts (Figure 5.9). The programme GEOCARBONE funded by National Research Agency (ANR) explores storage possibilities in the south-east of Paris from regional and thematic points of view. New objectives, previously investigated for geothermal energy, can be explored. Other possibilities are likely to exist in the north and north-east of the basin, for instance, the Liassic Reservoir.

![Main reservoirs of the Paris Basin (W–E cross section, BRGM)](image)
In the Aquitaine Basin the gas/petroleum systems are the most investigated domains (Parentis Basin and Lacq gas field).

Ancient syntheses and explorations of coal fields were performed in France at the beginning of the eighties.Extent and injection points of the coal fields were mapped, however, except very punctual studies, no tentative evaluation of the ECBM potential was made.

The South-East Basin is not yet explored from this point of view. Located between Alps, Massif Central and Pyrenees, it is tectonically complex. Petroleum exploration operated in the sixties and seventies was abandoned. In spite of ancient basin syntheses, very few information on structure, geometry and facies distribution of reservoirs and seals is available. This is the reason why BRGM has undertaken in 2008 a new own research project, CO₂SE, with the objective to fill this lack of knowledge.

Table 5.5: CO₂ emissions and storage capacity estimates in France.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>1990–2004*</td>
<td>131</td>
</tr>
<tr>
<td>* For more 70% of data, the years of report are 2001, 2003 and 2004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Theoretical</td>
<td>7922</td>
<td>27136</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Effective</td>
<td>770</td>
<td>1008</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total storage capacity estimate</strong></td>
<td>-</td>
<td><strong>8692</strong></td>
<td><strong>28144</strong></td>
</tr>
</tbody>
</table>

Table 5.5 give the total CO₂ emissions and storage capacities. Due to existing uncertainties on injectivity and hydrodynamics, small values of storage efficiency must be used in order to be more realistic. The conservative estimation in aquifers takes into account factors of 2% for open aquifers, 1%, for the semi-open (restricted) aquifer, and 0.1% for the Keuper closed aquifers (TNO table in deliverable D24, WP4).

- Figure 5.10 gives the map of the major CO₂ sources, transport routes and sinks mapped so far in France.
Figure 5.10: Map of CO$_2$ emissions, infrastructure and storage capacity in France.
5.4 Greece

5.4.1 Capacity estimation in aquifers

The assessment of CO₂ storage capacity in deep saline aquifers in Greece has been carried out in three Tertiary sedimentary basins (Prinos, W. Thessaloniki and Messohellenic) in various levels of the pyramid. At first for the three basins an estimation has been performed for the whole basin storage capacity. After that some local estimations have been carried out for the W. Thessaloniki basin based on the evaluation of some individual structures have been determined by seismic and borehole data. For both cases the methodology used was that described in the GeoCapacity deliverable D24 storage capacity standards using the formula:

\[ M_{\text{CO}_2t} = A \times h \times NG \times \phi \times \rho_{\text{CO}_2r} \times S_{\text{eff}} \]

where:

- \( M_{\text{CO}_2t} \): storage capacity
- \( A \): area of aquifer
- \( h \): average height of aquifer
- \( NG \): average net to gross ratio of aquifer (best estimate)
- \( \phi \): average reservoir porosity of aquifer (best estimate)
- \( \rho_{\text{CO}_2r} \): CO₂ density at reservoir conditions (best estimate)
- \( S_{\text{eff}} \): storage efficiency factor

The area of the basins, for the basin estimations, has been determined based on the geological maps of them and delimited by the extent of the porous formation at depths greater than 800 m. The area of the structures has been determined based on contour maps of stratigraphic horizons near or at the top of the reservoir formation. In some cases the calculation of the volumes has been carried out based on the isopach maps of the porous formations.

Thickness, net to gross ratio and porosity have been evaluated using data from exploration wells drilled on the structure or extrapolating information from wells on nearby structures.

The CO₂ density varies with depth as a function of pressure and temperature and has been estimated using available data from the literature on the geothermal gradient of each area or trap and the hydrostatic pressure.

For the estimations in the basin scale a conservative efficiency factor was used ranging from 3–6% according to the quality of the reservoir.

For the estimation of individual structures or traps the aquifer systems surrounding and connected to the reservoir formations has been assumed to be open (unconfined) aquifers. Based on the “rule-of-thumb approach” described for open and semi-closed aquifers in GeoCapacity deliverable D24 Storage capacity standards, a storage efficiency factor of 30–40% has been assumed corresponding to open high quality reservoirs.
5.4.2 Capacity estimation in hydrocarbon fields

The assessment of CO₂ storage capacity in Greek hydrocarbon fields is based on evaluation of 17 individual fields on stream from 2001. The capacity estimates for 6 fields have been calculated according to the methodology described for hydrocarbon fields in GeoCapacity deliverable D24 Storage capacity standards, using the formula:

\[ M_{\text{CO₂}} = \rho_{\text{CO₂r}} \times UR_p \times B \]

where:

- \( M_{\text{CO₂}} \): hydrocarbon field storage capacity
- \( \rho_{\text{CO₂r}} \): CO₂ density at reservoir conditions (best estimate)
- \( UR_p \): proven ultimate recoverable oil or gas
- \( B \): oil or gas formation volume factor

The CO₂ density varies with depth as a function of pressure and temperature and has been estimated using available data.

\( UR_p \) is the sum of the cumulative production and the proven reserves and is given as the sum of produced volumes and the low estimate for reserves for each field as published.

CO₂ replacement of oil and gas, respectively, has been calculated separately. The formation volume factor for oil varies regionally depending on the oil type and a fixed formation volume factor of 1.2 has been used for the oil replacement. The formation volume factor used for gas varies with depth as a function of pressure and temperature.

The storage capacity of the Greek hydrocarbon fields has been estimated assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO₂. We have chosen not to distinguish between effective and theoretical storage capacity for hydrocarbon fields. The data for the hydrocarbon fields of Greece come from published sources.

A number of 1 producing, 1 exhausted and 4 non-producing hydrocarbon fields have been assessed and the total CO₂ storage capacity of the 6 Greek fields has been estimated to 70 Mt. This is a significant increase compared to the estimation made in the framework of the GESTCO project which is due to the new data made available for oil fields (mainly Kallirachi) in the wide Prinos sedimentary basin. In two of them (Prinos and South Kavala) the reservoirs are located into the Miocene sands. Fractured and karstified limestones constitute the reservoir of the Epanomi and Katakolon non producing fields. The storage potential for CO₂ of the onshore Epanomi gas field is low and it already contains a large amount of primary CO₂. The onshore East Katakolon gas field is also small.

5.4.3 Capacity estimation in coal fields

Greece has lignite fields only which are extensively mined for power generation. Their geological setting is on intramontane Tertiary basins and they occur in depths up to 800 m. in highly fractured rock sequences. Their mining will continue in high intensity since they cover more than 60% of the country’s electricity production. Therefore no CO₂ capacity estimation has been carried out for the lignite deposits.
5.4.4 Country summary

In Table 5.6 below is given a summary of CO₂ emissions of Greece from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions) and storage capacity in aquifers and hydrocarbon.

Table 5.6: CO₂ emissions and storage capacity estimates in Greece.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2005</td>
<td>69</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2005</td>
<td>110</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Effective</td>
<td>184</td>
<td>184</td>
</tr>
<tr>
<td>Storage capacity in aquifers</td>
<td>theoretical</td>
<td>1936</td>
<td>1936</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Effective</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>N/A</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total storage capacity estimate</td>
<td></td>
<td>2190</td>
<td>2190</td>
</tr>
</tbody>
</table>
Figure 5.11: Map of CO₂ emissions, infrastructure and storage capacity in Greece.
5.5 United Kingdom

5.5.1 Capacity estimation in aquifers

Storage capacities for apparently closed structures in the Bunter Sandstone Formation and the Ormskirk Sandstone Formation were estimated from small-scale maps of the top of these formations which do not provide sufficiently detailed information to determine the structural integrity of the individual structural closures. Information on the individual aquifer structures is summarized in D11/D12. It is assumed that all structures will be filled to spill point and that no structures will leak. No account was taken of any regional pore fluid pressure increase that might result from large-scale injection of CO₂ into the formation. The volumes of the closed structures were calculated using ArcView 3.2a and EarthVision 5.1. The CO₂ density was calculated from an equation of state. The geothermal gradient used was 25°C km⁻¹ and the pressure gradient used was 1.1 bar m⁻¹. An average surface temperature of 10°C and porosity of 15% were assumed. Also, for each structure a maximum saturation (S_eff) of 40% of the pore volume is assumed. The storage capacity was calculated in tonnes of CO₂ using the formula:

\[ M_{\text{CO}_2} = V \times \rho_{\text{CO}_2} \times S_{\text{eff}} \]

where:

- \( M_{\text{CO}_2} \): CO₂ storage capacity (t)
- \( V \): total pore volume (m³)
- \( \rho_{\text{CO}_2} \): density of CO₂ at reservoir conditions (t/m³)
- \( S_{\text{eff}} \): storage efficiency factor

The results of this analysis are summarized in Table 5.7. The estimated storage capacity for all UK saline aquifer structures in these areas is up to 14935 Mt CO₂. This includes all Bunter Sandstone Formation structures in the UK sector of the Southern North Sea and Ormskirk Sandstone Formation structures in the East Irish Sea. In practice it is likely that some of these sites may not be suitable for storing CO₂. If the potential in the East Irish Sea is discounted and only half the potential in the southern North Sea is considered due to the reservoir not being properly sealed then the storage capacity of the aquifer structures is reduced to approximately 7100 Mt CO₂. This is of course speculative and the integrity of the structures would need to be investigated further to determine their tightness.

5.5.2 Capacity estimation in hydrocarbon fields

Oil fields

The methodology used is outlined below. The most up to date data, collated from DTI (2000), Abbotts (1991) and Gluyas and Hitchins (2003), has been used to estimate the storage capacities. The CO₂ storage capacity of the UK’s oil fields has been estimated by assuming that a percentage of the pore space in a field will be filled with CO₂ using the following approach:

1. Assume that a percentage of the space occupied by the recoverable reserves of the field is available for CO₂ storage, then
2. Calculate the mass of CO₂ that could fill that pore volume at the initial (pre-production) reservoir temperature and pressure. For an oil field that did not originally have a gas cap, the calculation can be expressed as:
\[ M_{\text{CO}_2} = V_{\text{oil(stp)}} \times B_o \times \rho_{\text{CO}_2} \]

Where:

- \( M_{\text{CO}_2} \): CO\(_2\) storage capacity (t)
- \( \text{stp} \): standard temperature and pressure
- \( V_{\text{oil(stp)}} \): volume of ultimately recoverable oil at stp (m\(^3\))
- \( B_o \): oil formation volume factor
- \( \rho_{\text{CO}_2} \): density of CO\(_2\) at reservoir conditions (t/m\(^3\))

The oil formation volume factor is the ratio between a volume of oil and the dissolved gas that it contains at reservoir temperature and pressure and the volume of the oil alone at standard temperature and pressure.

The density of CO\(_2\) at reservoir conditions was calculated from an equation of state (Span & Wagner 1996).

This approach was used by Van der Straaten et al. (1996), who point out that the potential CO\(_2\) storage capacity of oil fields actually depends on how they will be exploited and thus largely on what percentage of the pore space occupied by the Ultimately Recoverable Reserves (URR) will be filled with CO\(_2\) at the final reservoir pressure.

Following Van der Straaten et al. (1996), the storage capacities assume that 100% of the underground volume of the initially recoverable reserves could be replaced by CO\(_2\). Estimates produced in this way could be considered to be less than rigorous because they do not involve any assessment of the geology of the individual fields. They should probably be considered as “theoretical capacity” estimates in terms of the Bachu et al. (2007) resource classification. In reality, the potential in the UK offshore oil fields probably ranges from approximately 1.175 Gt CO\(_2\) to approximately 3.5 Gt CO\(_2\) (Holloway et al., 2006).

**Gas Fields and Gas/Condensate Fields**

The methodology used to estimate the storage capacity of the UK’s gas and gas/condensate fields is based on the principle that a variable proportion of the pore space occupied by the recoverable reserves will be available for CO\(_2\) storage, depending mainly on the reservoir drive mechanism (e.g. Bachu & Shaw 2003). The mass of CO\(_2\) that would occupy the pore space in each field formerly occupied by its recoverable reserves of natural gas is calculated according to the following formula:

\[ M_{\text{CO}_2} = V_{\text{gas(stp)}} \times B_g \times \rho_{\text{CO}_2} \]

Where:

- \( M_{\text{CO}_2} \): CO\(_2\) storage capacity (t)
- \( \text{stp} \): standard temperature and pressure
- \( V_{\text{gas(stp)}} \): volume of ultimately recoverable gas at stp (m\(^3\))
- \( B_g \): gas formation volume factor (from stp to reservoir conditions)
- \( \rho_{\text{CO}_2} \): density of CO\(_2\) at reservoir conditions (t/m\(^3\))
The density of \( \text{CO}_2 \) at reservoir conditions was calculated from an equation of state (Span and Wagner 1996).

The above figure is then discounted to allow for factors that may reduce the amount of pore space in the reservoir that could be filled with \( \text{CO}_2 \). Water invasion into the reservoir during (and after) gas production is considered to be the main factor that will affect the amount of \( \text{CO}_2 \) that can be injected back into the gas field. This can most accurately be estimated by using a detailed numerical reservoir simulation. Unfortunately no reservoir simulations were available for this study. In the absence of simulations, the following factors, similar to those used by Bachu & Shaw (2003) in their study of the \( \text{CO}_2 \) storage capacity of the oil and gas fields of Alberta, were used to discount the \( \text{CO}_2 \) storage capacity calculated using the equation for gas fields:

1. In gas fields where depletion drive dominates, i.e. those where the wells are opened up and the pressure in the gas field simply depletes as it would if the gas were being produced from a sealed tank, it is assumed that 90% of the pore space could be occupied by \( \text{CO}_2 \).
2. In gas fields where water drive dominates, i.e. those where water encroaches into the pore space formerly occupied by the produced natural gas reserves, it is assumed that 65% of the pore space could be occupied by \( \text{CO}_2 \).

Ultimately Recoverable Reserves (URR) and Gas Expansion Factor (Bg) were taken from DTI (2000), Abbotts (1991) and Gluyas and Hichens (2003). \( \text{CO}_2 \) density has been calculated using the initial reservoir pressure and initial reservoir temperature, which were taken from DTI (2000), Abbotts (1991) and Gluyas and Hichens (2003) and drive mechanisms were taken from Abbotts (1991) and Gluyas and Hichens (2003). Where the drive mechanism was unpublished, the following assumptions were made: in Leman Sandstone reservoirs the drive mechanism is assumed to be depletion drive, in Triassic or Carboniferous reservoirs the drive mechanism is (conservatively) assumed to be water drive.

**Discussion**

The total storage capacity for the UK hydrocarbon fields is 9900 Mt. In practice it is likely that storing \( \text{CO}_2 \) in fields below a certain size would be uneconomic. For example, if all fields with storage capacities of less than 50 Mt \( \text{CO}_2 \) were excluded, the total storage capacity would be 7300 Mt.

### 5.5.3 Capacity estimation in coal fields

**Coal mines**

The underground volume of British coal mines is very large but most of the abandoned mines become flooded after a few years, rendering them unsuitable for \( \text{CO}_2 \) storage. Moreover UK coal mines are unlikely to be gas tight, due to subsidence cracks induced above the mine workings.

**Coal seams**

The shallower UK coal seams have been extensively mined and are thus unsuitable for \( \text{CO}_2 \) storage. The deeper UK coal seams are widely thought to have low porosity (this is confirmed by the fact that no economic coalbed methane production has yet been established in the UK) and therefore \( \text{CO}_2 \) storage in them would not be economic in the foreseeable future. Moreover they face conflicts of interest with industries that propose to use the coal as a fuel, e.g. by deep mining or underground coal gasification. Therefore there is considered to be no storage potential at present and no figures are available for the total storage volumes.
5.5.4 Country summary

A summary of CO$_2$ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO$_2$ emissions) and storage capacity in aquifers and hydrocarbon fields is given in Table 5.7. Figure 5.12 shows the data for the UK included in the GeoCapacity database.

Table 5.7: CO$_2$ emissions and storage capacity estimates in the UK.

<table>
<thead>
<tr>
<th>CO$_2$ emissions</th>
<th>Year(s)</th>
<th>Average CO$_2$ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ emissions from large point sources in database</td>
<td>2003–2005</td>
<td>258</td>
</tr>
<tr>
<td>Total CO$_2$ emissions</td>
<td></td>
<td>555</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO$_2$ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Theoretical</td>
<td>7100</td>
<td>14935</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>Effective/Theoretical</td>
<td>7300</td>
<td>9887</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total storage capacity estimate</strong></td>
<td>Effective/Theoretical</td>
<td>14400</td>
<td>24822</td>
</tr>
</tbody>
</table>


Figure 5.12: Map of CO₂ emissions, infrastructure and storage capacity in the UK.
5.6  Denmark

5.6.1  Capacity estimation in aquifers

The assessment of CO₂ storage capacity in deep saline aquifers in Denmark is based on evaluation of 11 individual structural traps. The capacity estimates in the GeoCapacity database for the 11 structures have been calculated according to the methodology described for deep saline aquifers in GeoCapacity deliverable D24 Storage capacity standards, using the formula:

\[ M_{\text{CO}_2} = A \times h \times NG \times \phi \times \rho_{\text{CO}_2r} \times S_{\text{eff}} \]

where:

- \( M_{\text{CO}_2} \): “trap” storage capacity
- \( A \): area of aquifer in trap
- \( h \): average height of aquifer in trap
- \( NG \): average net to gross ratio of aquifer in trap (best estimate)
- \( \phi \): average reservoir porosity of aquifer in trap (best estimate)
- \( \rho_{\text{CO}_2r} \): CO₂ density at reservoir conditions (best estimate)
- \( S_{\text{eff}} \): storage efficiency factor (for trap volume)

The area of the structures has been determined based on contour maps of stratigraphic horizons near or at the top of the reservoir formation.

Thickness, net to gross ratio and porosity have been evaluated using data from exploration wells drilled on the structure or extrapolating information from wells on nearby structures.

The CO₂ density varies with depth as a function of pressure and temperature and has been estimated using the Calsep 2001 PVTsim software.

The aquifer systems surrounding and connected to the reservoir formations in the individual traps has been assumed to be open (unconfined) aquifers. Based on the “rule-of-thumb approach” described for open and semi-closed aquifers in GeoCapacity deliverable D24 Storage capacity standards, a storage efficiency factor of 40 % has been assumed corresponding to open high quality reservoirs. This results in a total effective storage capacity of 16672 Mt CO₂ for the 11 structural traps.

A more conservative estimate has been calculated in this report for comparison with the estimates in the database. The conservative estimates have been calculated assuming that the aquifer systems surrounding and connected to the reservoir formations in the trap structures are closed (confined) aquifers. The storage efficiency factor has been determined using the “table approach” described for closed aquifers in GeoCapacity deliverable D24 Storage capacity standards, assuming a total compressibility \((c_{\text{pore}}+c_{\text{fluid}})\) of \(10^{-4}\) bar⁻¹, hydrostatic pressure, an allowable average pressure increase of 10 % and total aquifer volume 50 times the trap aquifer volume. For the 11 structural traps the calculated conservative storage efficiency factors range between 5 % and 10 % resulting in a total effective storage capacity of 2553 Mt CO₂.
5.6.2 Capacity estimation in hydrocarbon fields

The assessment of CO₂ storage capacity in Danish hydrocarbon fields is based on evaluation of 17 individual fields on stream from 2001. The capacity estimates in the GeoCapacity database for the 17 fields have been calculated according to the methodology described for hydrocarbon fields in GeoCapacity deliverable D24 Storage capacity standards, using the formula:

\[ M_{\text{CO}_2} = \rho_{\text{CO}_2} \times \text{UR}_p \times B \]

where:

- \( M_{\text{CO}_2} \): hydrocarbon field storage capacity
- \( \rho_{\text{CO}_2} \): CO₂ density at reservoir conditions (best estimate)
- URₚ: proven ultimate recoverable oil or gas
- B: oil or gas formation volume factor

The CO₂ density varies with depth as a function of pressure and temperature and has been estimated using the Calsep 2001 PVTsim software.

\( \text{UR}_p \) is the sum of the cumulative production and the proven reserves and is given as the sum of produced volumes and the low estimate for reserves for each field as published by the Danish Energy Authorities for 2005.

CO₂ replacement of oil and gas, respectively, has been calculated separately. The formation volume factor for oil varies regionally depending on the oil type and a fixed formation volume factor of 1.2 has been used for the oil replacement. The formation volume factor used for gas varies with depth as a function of pressure and temperature.

The storage capacity of the Danish hydrocarbon fields has been estimated assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO₂. This results in a total storage capacity of 810 Mt CO₂ for the 17 fields. We have chosen not to distinguish between effective and theoretical storage capacity for hydrocarbon fields.

A more conservative estimate has been calculated in this report for comparison with the estimates in the database. The conservative estimates have been calculated assuming that only 25 % of the produced hydrocarbons can be replaced by CO₂ and amounts to 203 Mt CO₂ for the 17 fields. The fact that most of the fields are chalk reservoirs may jeopardize their potential for storage and more research on chalk and carbonate as potential storage reservoirs is needed.

Due to confidentiality of data the outline of the Danish hydrocarbon fields have been slightly modified before import to the GeoCapacity database.

5.6.3 Capacity estimation in coal fields

Denmark has no coal fields and no evaluation has therefore been carried out.

5.6.4 Country summary

In Table 5.8 below is given a summary of CO₂ emissions from large stationary point sources included in the GeoCapacity database (supplemented with total CO₂ emissions) and storage
capacity in aquifers and hydrocarbon. Figure 5.13 shows the data for Denmark included in the GeoCapacity database.

Table 5.8: CO₂ emissions and storage capacity estimates in Denmark.

<table>
<thead>
<tr>
<th>CO₂ emissions</th>
<th>Year(s)</th>
<th>Average CO₂ emissions (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions from large point sources in database</td>
<td>2000–2005</td>
<td>28</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>2000–2005</td>
<td>52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CO₂ storage capacity</th>
<th>Pyramid class</th>
<th>Conservative estimate (Mt)</th>
<th>Estimate in database (Mt)</th>
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<tbody>
<tr>
<td>Storage capacity in aquifers</td>
<td>Effective</td>
<td>2553</td>
<td>16672</td>
</tr>
<tr>
<td>Storage capacity in hydrocarbon fields</td>
<td>N/A</td>
<td>203</td>
<td>810</td>
</tr>
<tr>
<td>Storage capacity in coal fields</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total storage capacity estimate</strong></td>
<td>Effective</td>
<td><strong>2756</strong></td>
<td><strong>17482</strong></td>
</tr>
</tbody>
</table>
Figure 5.13: Map of CO₂ emissions, infrastructure and storage capacity in Denmark.
6 EUROPEAN SUMMARY

The results of the GeoCapacity project are the first detailed pan-European assessment of CO₂ storage capacity. Some of the main achievements of GeoCapacity are:

- We have established a CCS inventory of Europe based on a GIS platform
- The work could be the base for a future CO₂ storage atlas of Europe
- We have contributed to guidelines for assessment of geological storage capacity, site selection criteria and methodology for ranking
- We have pioneered CCS work in many European countries and China

In the summary tables for individual countries in the sections above the total storage capacity estimates in the GeoCapacity GIS database is given. The GIS database include a total storage capacity of 360000 Mt with 326000 Mt in deep saline aquifers, 32000 Mt in depleted hydrocarbon fields and 2000 Mt in unmineable coal beds. 116000 Mt is onshore storage capacity and 244000 Mt is offshore storage capacity. Some of the estimated storage capacity is associated with geological trap structures, but a large part is in regional deep saline aquifers without identification of specific trap structures. It is also worth mentioning; that almost 200000 Mt of the total storage capacity in the database is located offshore Norway and that these estimates are dating back to the GESTCO project in 2003 and have not been updated in the GeoCapacity project.

In the country summary tables are also provided more cautious and conservative estimates for each country and in the European summary given in Table 6.1 below are used only the conservative estimates as they probably give the most realistic picture of storage capacity that can be realized in Europe. For Norway and Belgium which were not updated as part of the GeoCapacity project the conservative estimates has been estimated from the GESTCO values included in the database using the same ratio between database and conservative estimates as for Denmark.

The sum of the conservative storage capacity estimates in Table 6.1 is 95724 Mt CO₂ in deep saline aquifers, 20222 Mt in depleted hydrocarbon fields and 1089 Mt in unmineable coal beds. This totals 117035 Mt CO₂ of conservative European storage capacity of which approx. 25 % is offshore Norway in mainly deep saline aquifers. These figures must be compared to a total of 1893 Mt of CO₂ emissions from large point sources emitting more than 0.1 Mt/year. Thus the conservative storage capacity estimate of 117035 Mt CO₂ corresponds to 62 years of storage of the 1893 Mt yearly emissions of CO₂ from large point sources emitting more than 0.1 Mt/year.

In Figure 6.1 to Figure 6.5 below are shown regional source-sink maps for:

- Northwest Europe
- Northeast Europe
- Central-East Europe
- Southwest Europe
- Southeast Europe

The maps are produced from the GIS database and its content of large emission point sources, storage possibilities and pipeline infrastructure.
Table 6.1: European summary of CO₂ emissions and storage capacity estimates.

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual total CO₂ emissions (Mt)</th>
<th>Annual CO₂ emissions from large point sources (Mt)</th>
<th>CO₂ storage capacity in deep saline aquifers (Mt)</th>
<th>CO₂ storage capacity in hydrocarbon fields (Mt)</th>
<th>CO₂ storage capacity in coal fields (Mt)</th>
</tr>
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<tbody>
<tr>
<td>Slovakia</td>
<td>46</td>
<td>23</td>
<td>1716</td>
<td>-</td>
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<tr>
<td>Estonia</td>
<td>21</td>
<td>12</td>
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<td>Latvia</td>
<td>4</td>
<td>2</td>
<td>404</td>
<td>-</td>
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<tr>
<td>Lithuania</td>
<td>18</td>
<td>6</td>
<td>30</td>
<td>7</td>
<td>-</td>
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<tr>
<td>Poland</td>
<td>325</td>
<td>188</td>
<td>1761</td>
<td>764</td>
<td>415</td>
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<tr>
<td>Czech Republic</td>
<td>128</td>
<td>78</td>
<td>766</td>
<td>33</td>
<td>54</td>
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<tr>
<td>Hungary</td>
<td>79</td>
<td>23</td>
<td>140</td>
<td>389</td>
<td>87</td>
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<tr>
<td>Romania</td>
<td>74</td>
<td>67</td>
<td>7500</td>
<td>1500</td>
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<tr>
<td>Bulgaria</td>
<td>52</td>
<td>42</td>
<td>2100</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>Albania</td>
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<td>0</td>
<td>20</td>
<td>111</td>
<td>-</td>
</tr>
<tr>
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<td>6</td>
<td>4</td>
<td>390</td>
<td>-</td>
<td>-</td>
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<td>23</td>
<td>5</td>
<td>2710</td>
<td>189</td>
<td>-</td>
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<td>Spain</td>
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<td>158</td>
<td>14000</td>
<td>34</td>
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<td>140</td>
<td>4669</td>
<td>1810</td>
<td>71</td>
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<tr>
<td>Slovenia</td>
<td>20</td>
<td>7</td>
<td>92</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Bosnia-Herzegovina</td>
<td>-</td>
<td>9</td>
<td>197</td>
<td>-</td>
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<tr>
<td>Germany</td>
<td>864</td>
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<tr>
<td>Norway</td>
<td>-</td>
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<td>26031</td>
<td>3157</td>
<td>-</td>
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<td>Belgium</td>
<td>-</td>
<td>58</td>
<td>199</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-</td>
<td>1893</td>
<td>95724</td>
<td>20222</td>
<td>1089</td>
</tr>
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</table>
Figure 6.1: Map of CO$_2$ emissions, infrastructure and storage capacity in Northwest Europe.
Figure 6.2: Map of CO₂ emissions, infrastructure and storage capacity in Northeast Europe.
Figure 6.3: Map of CO$_2$ emissions, infrastructure and storage capacity in Central-East Europe.
Figure 6.4: Map of CO₂ emissions, infrastructure and storage capacity in Southwest Europe.
Figure 6.5: Map of CO$_2$ emissions, infrastructure and storage capacity in Southeast Europe.
REFERENCES


BRGM, 1996: Carte géologique de la France au millionième. – 6ème édition.


Lucius, M., 1951: Leitlinien der Geologie des Luxemburger Sedimentationsraumes. – 54 S.


May, F., 2003: CO₂ storage capacity in unmineable coal beds in Germany. – GESTCO Project report, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.


