A CO_2GeoNet Initiative

ENOS D6.8 | v11-final

Study on new pilot and demonstration project opportunities for CO2 geological storage onshore in Europe

Date	31.03.2020
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Number of pages	31
Number of appendices	6
Project name	ENOS
Project website	http://www.enos-project.eu
Project number	Grant Agreement No 653718

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653718

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Executive Summary

Existing pilot and demonstration sites enhance confidence in the ability of geological formations to safely store CO_2 on a regional basis, and local demonstration of CO_2 Capture and Storage (CCS) technology will encourage further project development. So far, onshore storage has been tested and demonstrated only at a few pilot sites in the EU (i.e. Ketzin, Lacq-Rousse, and recently Hontomín), which is deemed insufficient. An earlier ZEP/CGS Europe study identified several promising opportunities for possible onshore storage pilots across Europe, based on proposals by partners with 19 potential onshore locations for pilot projects. There was a limited assessment of the probability of these pilot sites moving forward, which, as the CCS landscape has changed rapidly, makes development of a new set of plans a necessity.

ENOS Task 6.3. followed up with these efforts and approached the European CCS community with a request to submit proposals for new onshore CO_2 storage pilots with the aim to provide funding for several conceptual case studies based on selected proposals. Altogether 8 pilot project proposals were submitted, of which six have been selected for further development and funding. Based on this, six conceptual case studies have been elaborated:

- Sava Depression in Croatia
- Havnsø in Denmark
- Kenderes in Hungary
- Vilkyciai in Lithuania
- Dziwie in Poland
- Brădești in Romania

The portfolio of the suggested pilots has excellent geographical spread – if implemented, the new projects will bring CCS knowledge and practical experience to European regions with limited development of the technology so far, including the South-Eastern and Central Europe and the Baltic Sea region. All these regions have large CCS deployment potential lying in numbers of emission-intensive facilities in both energy and other industrial sectors. In addition to testing and verification of the technology in local conditions, the pilots will also serve as an unsubstitutable element of practical demonstration of the CCS technology to local, national and regional stakeholders, starting from politicians and policy makers, through regulators, industry representatives and research community, to local population, general public and media.

Implementation of the pilots would also unlock the geological storage potential of important supra-regional geological structures with promising properties and prospects of further development, like the Pannonian Basin, the Baltic Basin, the Moesian Platform, as well as the Danish basin and the Central Poland area. All of these regions have seen historically significant hydrocarbon production and their thick sedimentary successions render large potential for CO_2 geological storage. The chosen locations are also either in connection with CO_2-EOR possibilities (like in Lithuania or Croatia), or try to make use of the existing deep wells in the gas or oil fields that are either depleted or soon to be depleted (in Romania and Hungary). A possibility to study synergy with deep geothermal project is indicated in the Hungarian project proposal. The most favourable geological conditions to demonstrate the safe storage in structurally defined aquifers are presented in the Polish and Danish case studies. Geological conditions for significant upscaling are demonstrated in the case studies from Denmark, Lithuania, Romania and Hungary. The Croatian case study works with three possible scenarios; involving an ongoing CO_2-EOR project and two small depleted oil fields.

In addition, a number of common success factors have been identified that have facilitated and enabled the success of international CO_2 storage pilots worldwide. These include:

- the potential for upscaling, which might be achieved in a number of different ways depending on the specific objectives and conditions of the project, following the successful implementation of the pilot;
- the designation of a “project champion” - an appropriate lead institute or organisation that has the mandate, financial resources and capabilities to assemble a consortium with the needed skills;
- a detailed plan for engagement with a potentially wide range of different stakeholder groups, supported by an analytical understanding of the needs of each group, and a dedicated resource for implementation;
- clear policy support, which is backed up by a robust governance structure and decision-making process together with best practice project management, to ensure regulatory support and compliance across all stages and activities within the project;
- a clear plan for implementation that will allow the pre-defined and pre-agreed objectives of the pilot to be fully achieved;
- a cost-effective CO_2 supply,
- a well-defined geological structure which may exploit existing infrastructure as appropriate and the definition of comprehensive and fit-for-purpose baseline conditions.

The proposed pilot project conceptual studies have been assessed with respect to the identified success factors to identify their strong and week points.

1 Introduction

Europe is currently experiencing a new wave of interest in CCS technology, induced by adoption of the European Green Deal and related re-assessment of both European and national decarbonisation policies, as well as by the increasing price of CO_2 emission allowances. Representatives of both energy sector and other emission-intensive industries are developing new emission reduction strategies, in which CCS more and more frequently plays an important role.

Main focus in this respect is now put on development of big industrial clusters around the North Sea, allowing industrial-scale solutions supported by abundant offshore storage opportunities. It is clear that first big CCS projects to happen in Europe will be based on this concept and will happen in the North Sea area. It must be, however, taken into account that CCS will have to play its role in other parts of Europe as well, including those where offshore storage opportunities are limited. Also here, CCS is the only currently available solution for reducing process CO_2 emissions in cement, iron & steel and chemical industries and provides opportunities for production of “blue” hydrogen or application of carbon-negative BECCS (bio-energy with CCS). To be able to meet the demand of local industries, onshore CO_2 storage sites must be identified and developed.

Experience from overseas, especially form North America and Australia, shows that the best way to develop CCS as a new technology in a new geographical area is to take gradual, follow-up steps, starting from assessment of regional CO_2 storage potential, through small-scale and large-scale pilot projects to industrial-scale applications. The role of CO_2 storage pilots in this succession is unsubstitutable, as has been clearly demonstrated by the success of the Regional Carbon Sequestration Partnerships (RCSP) initiative in the USA[1]. The EU has now an excellent opportunity to replicate this approach, if the newly emerging initiatives to introduce, develop and deploy CCS in the areas of Southern, Central and Eastern Europe through new CCS pilot projects are accepted and sufficiently supported. Many activities of ENOS project are dedicated to back up these new initiatives.

An interesting finding illustrating the importance of CO_2 storage pilots has been made in ENOS WP5 that deals with coordination with local communities living around possible new CO_2 storage sites. The group-work-based results show that the citizens clearly prefer a step by step approach towards large scale implementation of the CCS technology, emphasizing the importance of a step by step learning process, starting with small scale pilot projects without immediate large-scale application of the technology (quoting one of the participants: “large projects - large mistakes; small projects - small mistakes”).

ENOS Task 6.3 is fully devoted to the topic of CO_2 storage pilots. Within the Task, a study focusing on onshore pilot project opportunities across Europe was planned, aiming to give an overview of the potential onshore sites in different EU countries. The goal was to address different geological settings and wide geographical spread, including regions with little CCS activity to date, in addition to those that have already been explored and assessed to a higher level. The study is further aimed at identification of factors that have helped lead to a successful pilot or demonstration project and giving a look at other sites where there is a good chance that success could be replicated. Similarity of geological settings and other technical factors (e.g. CO_2 sources, infrastructures etc.) to existing successful pilot projects can help to identify regions likely to be favourable for future pilot projects and/or regions with potential to scale up to demonstration scale.

[1] https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/regional-carbon-sequestration-partnerships-initiative

2 CO_2 storage pilots onshore Europe – past, present and future

2.1 Status quo

In spite of the relatively high number of CO_2 storage pilot projects reported worldwide with 18 in deep saline aquifers and 4 in depleted oil and gas fields (Cook et al, 2014) [2], the experience with CO_2 storage in Europe is relatively limited.

CO_2 storage has only been tested in onshore Europe in three small-scale pilot projects so far:

- Ketzin in Germany where CO_2 (mostly food-grade gas purchased on the market) has been stored in a relatively shallow (~ 650 m) sandstone aquifer for prevailingly research purposes;
- Lacq-Rousse in France, which has been the only integrated CCS project in the EU so far, executed by the French oil & gas major Total; the storage site was an extremely deep (~ 4.5 km) depleted gas field located in dolomite reservoir rocks. The goals of the project were to demonstrate the technology, acquire operating experience, develop methodologies and increase knowledge;
- Hontomín in Spain where a limited amount of food-grade CO_2 purchased on the market has been injected in a tight brine-filled carbonate reservoir at ca. 1500 m depth; it is a typical research pilot project.

While Ketzin and Lacq-Rousse projects have already been completed and the injection sites closed, the Hontomín site is still technically available but set now in a suspended mode with unclear prospects. All the other subsurface CO_2 injection projects carried out or under preparation in continental Europe have either been very small-scale (e.g. the ECBM experiment at Kaniów in Poland), or very shallow, representing thus rather leakage experiments (e.g. Svelvik in Norway).

CO_2 injection into oilfields for the purpose of Enhanced Oil Recovery has been performed at industrial scale in Hungary, Turkey, and Croatia; these activities have, however, fully focused on additional oil production and have not dealt with CO_2 storage so far. CO_2 injection experiments were also recently performed in 3 oilfield wells in Lithuania within the preparatory phase of the Minijos Nafta Clean Energy Project that aims at unlocking a CO_2 storage potential of about 200 mil. tonnes in this area by implementation of CO_2-EOR followed by subsequent CO_2 storage (Haselton, 2019).

It is obvious that this experience is insufficient and Europe needs new CO_2 storage pilots that will support CCS deployment, especially in those parts of the continent where these activities have not really developed up to now. This is reflected in the EU Strategic Energy Technology Implementation Plan for CCS which has defined a target for at least three new storage pilots by the mid-2020s[3].

2.2 CGS Europe study

The earlier EU FP7 project CGS Europe[4] made a first step towards identification of possible candidate geological structures across Europe that would be suitable for setting up new CO_2 storage pilot projects. The report "Opportunities for CO_2 storage pilot projects across Europe" (Martinez et al., 2013) provides an overview of 29 potential pilot project sites in 16 European countries. There were altogether 22

[2] The CO_2RE database (https://co2re.co/FacilityData) maintained by the Global CCS Institute indicates 19 operational pilot and demonstration CCS facilities that include a CO_2 storage part at the end of March 2020
[3] https://setis.ec.europa.eu/system/files/set_plan_ccus_implementation_plan.pdf
[4] http://www.cgseurope.net/

onshore sites described (in Bulgaria, the Czech Republic, Denmark, France, Hungary Italy, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Spain, Turkey and the UK), the rest were offshore objects. The most numerous targeted storage structures were aquifers (15), then EOR operations or depleted oil or gas fields (10), 3 were described as field labs (one in UK and two in Norway) and one even did not have a defined storage target as it was a concept to make use of the capture plant at Mongstad in Norway.

Diverse geological settings were described with reservoirs in sandstones and sands (21) and carbonate rocks (4), even coal sealed by clays, shales or marls. The storage targets depth spanned from 750 to 3000 m, with some experimental sites (field labs) with 12-20-100 m depth. Partners then forecasted budgets in the span of 2-100 mil. €, but mostly between 20 and 40 mil. €.

CGS Europe partners reported in 2013 a general lack of funding schemes to develop these projects. In this aspect, a viable self-financing model for geological storage is still expected today. Engagement of research programmes, national and regional funding and industry was and still remains a necessity. Having in mind that this report included estimates of storage capacity in the range of 20 kt up to 460 Mt CO_2, with many between 50 and 100 Mt, the potential value of this underexplored resource in Europe was already documented. The favourable natural conditions exist, scientific community is interested, and the technology is demonstrated worldwide in each cycle at a higher level of confidence, but the incentives to industry are lacking. That was the conclusion of the study then and it mostly stays valid today, because, apart from a few EU-funded projects and sporadic CO_2-EOR activities by the oil companies (which are focusing on increasing the oil production and not on geological storage), there were no major developments in the past 7 years in Europe.

2.3 ENOS Task 6.3 – way to new CO_2 storage pilots

Work on finding new prospective CO_2 storage pilots onshore Europe commenced at the beginning of the ENOS project. In the beginning it was closely connected with the analysis of the research priorities for onshore CO_2 geological storage (ENOS Task 6.2), practically building on the outcomes of the ENOS Open Workshop „Research priorities and future pilots" that took place at the CO_2GeoNet Open Forum in Venice in 2017. As a result of this workshop, four different types of storage objects and three injection pilot concepts were identified to be the most interesting to further investigate in this phase.

The first storage characteristic to be explored is if we can find locations where both the intergranular porosity of the reservoir exists parallel to some sections with fracture porosity (i.e. the dual porosity situations), so that the effect of such a heterogeneity of a reservoir on CO_2 plume migration with implications on safety and capacity might be better studied. The second type of characteristic that came into focus are the depleted hydrocarbon fields. There are many depleted oil and gas reservoirs in sedimentary basins throughout continental Europe, they are usually not far from CO_2 sources and have potential to be converted to geological storages of CO_2. The third type of objects are regional saline aquifers (much in the same regions as depleted HC fields) but with considerably different problems to study in comparison with depleted HC fields. Saline aquifers do not have many old wells that terminate within them to provide access to the pore space (though may have wells that pass through them where underlying and overlying oil and gas fields are exploited) and the pressure has not been reduced by exploitation, which means that the main issue here is if they are possibly open or closed regional units. For this the parameter that will most significantly influence the CO_2 storage resource estimates is the pressure increase. The fourth and last type was generally described as "active hydrocarbon fields", which means using the reservoirs that are still in production and gradually converting them into storages by firstly commencing CO_2-EOR/EGR operations that would mean some CO_2 retention while still producing, and then converting these objects into geological storages in the second stage.

At the same time, three CO_2 storage pilot concepts were identified as being the most relevant for further development in the near future. The first one is called "Enhanced hydrocarbon pilot" which reflects the fact that it might attract attention of some oil companies that are presently developing EOR projects (including CO_2-EOR), or are planning to do so, and try to integrate these projects with pilot studies focusing on CO_2 storage, which in such a situation would have a significant upscaling potential. The second concept was called "CCS – geothermal energy synergies", which considers a niche option where deep geothermal energy projects will soon see growth with the possibility to use CO_2 either as cushion gas or to facilitate the energy transport process itself. The last concept was called "Flexible storage", thinking of all the other possibilities that might be attractive in various settings, for example in combination of CO_2 storage with underground storage of natural gas or hydrogen.

In order to cover a portfolio of various geological settings and have a good geographical spread of future pilots, an elaborate questionnaire was prepared by an ENOS T6.3 working group (led by BGS) to approach the European CCS community with a request to propose new CO_2 storage pilots onshore Europe. The option to support elaboration of a conceptual case study for selected proposals in the second stage of the work was part of the announcement. The questionnaire was broadly distributed using the contact list of CO_2GeoNet and within the ENOS participating institutes directly. There were not as many replies received as expected; either the questions were too demanding, or the perceived use of CO_2 prospects was low back in 2017. In total, 8 submissions were received from 6 countries:

- Velika Ciglena (Croatia)
- Voloder & Mramor Brdo (Croatia)
- Jutland (Denmark)
- Kenderes (Hungary)
- Vaškai (Lithuania)
- Vilkyciai (Lithuania)
- Dziwie (Poland)
- Thornton (UK)

A set of weighted criteria was jointly prepared by the T6.3 team to evaluate the received proposals. The particular aspects of the described plans for pilots were grouped into 5 categories (Table 1). Three of these categories were given the biggest impact – 'Geological description' with a maximum of 39 points, 'National support and context' with 36 and 'Scientific and other benefits' with maximally 30 out of the total sum of 120 points.

Table 1: Evaluation criteria of individual CO_2 storage pilot proposals

Category	Comment	Max. score
Location	Evaluates the potential for CCS growth in a county or region, and the track record of the contributor.	12
Geological description	Evaluates the types of storage, confidence and understanding of traps, together with the potential for upscaling.	39
National support and context	Evaluates the quality of preparatory work already undertaken, potential for linking to wider regional low-carbon energy systems and national policy and regulatory support.	36
Scientific and other benefits	Evaluates the scientific and local impacts, the quality of the proposed consortium and level of stakeholder engagement.	30
Additional comments	Evaluates additional information supplied by the proposer.	3
		120

Each institute in the working group had one person responsible to study all submissions and give scores with instructions to consider only what was explained in the questionnaire, and to bear in mind that the pilots can have two main purposes – testing the site (with the upscaling potential) and testing the methods (research potential). This joint exercise by BGS, CGS, GeoEcoMar, IGME, UNIZG, and TTUGI resulted not only in a summary evaluation table, but also in a discussion about discrepancies in evaluators' scores (the responses by the evaluators differed for just a few criteria, not significantly). As a result, the views on how closely the plans are related to research priorities and also to the national priorities were harmonized. In the end, not only the ranking based on the evaluation procedure, but also the possibility to involve different storage objects and the best possible geographical spread across Europe were considered. The possibility to fund two case studies from one country was excluded. The summary of evaluation scores is shown in Fig. 1.

Figure 1. Summary of average evaluation scores of individual CO_2 storage pilot proposals

The evaluation resulted in letters offering financial support for elaboration of a conceptual case study sent to the proposers of Thornton (UK), Velika Ciglena (HR), Vilkyciai (LT), Dziwie (PL), Kenderes (HU) and Jutland (DK) future pilot projects. Thornton would be a purely research-oriented project, Velika Ciglena a study on using CO_2 in a geothermal power plant, Vikyciai an injection of CO_2 in a depleted oil reservoir while Dziwie and Kenderes are aquifer structures. This set would represent a very good portfolio of various pilot types in diverse geological settings.

Unfortunately, these plans subsequently had to be modified. Firstly, the Thornton contributors backed up, so the elaboration of a study was not possible, and secondly the Velika Ciglena geothermal plant project was not proceeding quite according to the schedule in the final phase of development, so its investors (a private company) also decided to step out of the negotiations on the subcontract.

This left only 4 valid candidates to start the subcontracting procedure and the evaluation results had to be considered once again. It was decided to replace the Croatian Velika Ciglena project with the secondly ranked one (Voloder & Mramor Brdo), focusing on two depleted oil fields. To replace Thornton, another call for future pilots was made within the ENOS partnership, and the Brădești project from Romania was selected. There was a minor change in Denmark, too. The original Jutland project proposal was substituted with another location – Havnsø, which is a structurally defined aquifer. Since the potential subcontractors for preparing the Brădești and Havnsø studies are members of the ENOS consortium (having status of the CO_2GeoNet-linked third parties), no subcontracts were applicable here. Funding of these two case studies was made possible by modification of the ENOS budget (within its CO_2GeoNet part), approved by the ENOS Management board and the EC. UNIZG-RGNF then proceeded with negotiations with the other 4 potential contributors, which resulted in four subcontracts signed in spring/summer 2019.

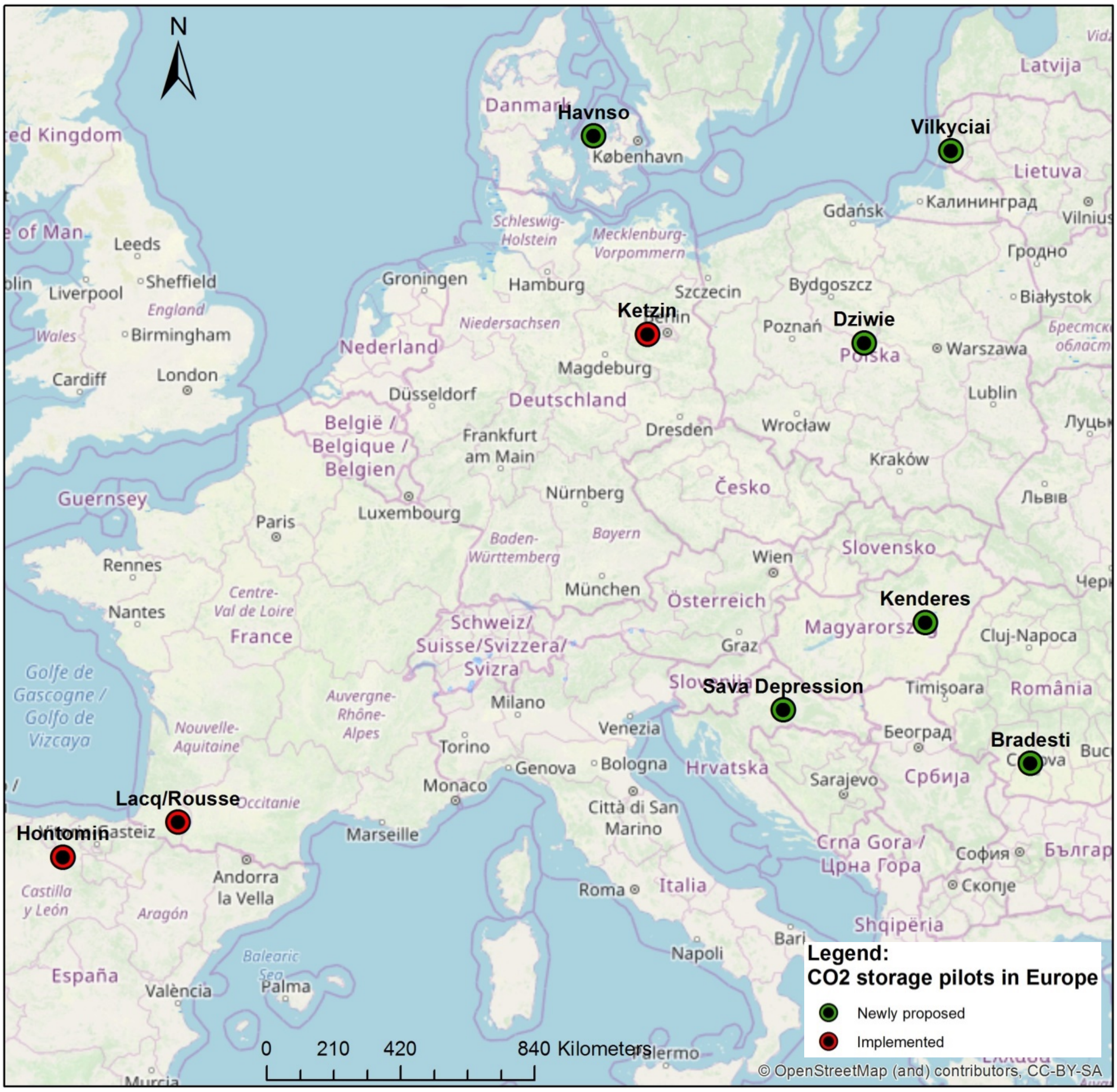

Figure 2. Map of implemented and newly proposed CO_2 storage pilot projects onshore Europe

All studies were submitted in time and their contents were subjected to technical review by selected Task team members. Comments were sent and the contributors made corrections accordingly, so the work delivered by both the sub-contractors and project partners has delivered the expected results in full extent.

It can be summed up that despite not all of the initial plans from 2017 regarding storage site types and pilot project concepts have been met, modifications resulted in minor differences – there are no purely research pilots, and no geothermal-related projects either. However, there remained a portfolio of different geological settings and a very good geographical spread from Denmark over Lithuania and Poland to Hungary, Romania and Croatia (see Fig. 2). Also, there are the two types of objects – aquifers and depleted hydrocarbon fields that can be investigated. Naturally, these “Conceptual studies” are in various phases of development and, from a variety of reasons, they also have different upscaling potential or perspective. This will be explained in the next chapters.

3 Portfolio of geological settings

3.1 Geology of realised European CO_2 storage pilots

The three successfully implemented European onshore storage pilots targeted very diverse geologies, generally quite special and not very typical for expected future storage sites.

In *Ketzin*, 25 km west of Berlin, the CO_2 was injected (2008 - 2013) into a 40 metre thick saline sandstone formation with brine salinity of about 240 g/l (Zimmer et al., 2011), represented by the Triassic Stuttgart Formation, at a relatively shallow depth of about 630-650 metres below ground level. CO_2 storage reservoir was formed as an anticlinal structure by salt tectonics (Lüth et al., 2011). The storage sandstones in the Stuttgart Formation have porosity of 13 to 26%. A permeability of 50 to 100 mD was demonstrated in hydraulic tests; permeability measured on core samples is from 500 to more than 1000 mD. Storage reservoir is covered by about 165 m thick primary seal composed of claystones. Above the primary cap rock of the CO_2 storage, at a depth of about 250 to 400 m, there is sandstone from the Jurassic Period, which was formerly used as storage for city gas and natural gas. This layer in turn is covered by a cap rock about 80 to 90 m thick, made of Tertiary Rupelian clay. This clay plays an especially important role as a groundwater barrier, preventing the salinization of the usable groundwater near the surface. Together with the anticlinal structure, this multibarrier system ensures that the CO_2 migrates in a controlled and limited way.

The small depleted gas field of *Rousse* used in the Lacq-Rousse pilot project is a deep isolated Upper Jurassic horst draped and overlaid by a very thick Campanian to Eocene series of marls, shales and silts, named “Flysh”, deposited in the Pyrenean foredeep basin. The dolomite reservoir is situated at a relatively big depth of 4200 m. Its initial pressure and temperature were 485 bars and 150°C; main reservoir properties are 3% porosity and permeability of 1-5 mD. The reservoir has been drilled and produced for more than 30 years by only one single well Rousse-1, which was transformed in a CO_2 injection well in March 2009. The storage site of Rousse is located in a rural and non-populated area, five kilometres to the South of the town of Pau (Monne et al., 2015).

In *Hontomín* the principal reservoir/seal pair is formed by Lower Jurassic carbonate rocks (limestones and dolostones) sealed by marls and black shales. The rocks at around 1.500 m depth take the form of a structural dome (5x3 km^2), where the main seal is the Marly Lias and Pozazal Formations and the reservoir is the Sopeña Formation. The study area has undergone a very complex tectono-sedimentary evolution, which developed fractures under successive deformation stages. The reservoir has a high level of fracturing and it is compartmentalised into geological blocks, but this does not affect the seal integrity. It is filled with brine of ca. 20g/l salinity. Secondary porosity based on fractures represents the main pore volume for CO_2 storage. The challenge is the low injectivity of the reservoir, corresponding to low permeability values (0.015 – 1.8 mD according to the results of hydraulic injection tests). The permeability changes with injection pressure (Ortiz et al., 2015).

3.2 Geological setting of the selected future pilot projects

The studies acquired in Task 6.3 cover different geological settings and have a geographical spread from Denmark over Lithuania to Poland, Hungary, Romania and Croatia. Generally they consider two types of objects – aquifers and depleted hydrocarbon fields.

Future pilot project at Havnsø (Kalundborg, Denmark)

This pilot study is oriented at the domal closure 15 km NE of Kalundborg. The reservoir is situated in the well-studied Gassum Formation, and interpretation of subsurface geology is built on the previous investigations for underground natural gas storage. The model can therefore be considered as quite well substantiated with data, augmented by interpretations from the actual gas storage at the nearby Stenlille structure. Apart from geology, reservoir simulation, reservoir and caprock characterization and risk assessment are important issues in the case study. In regional geological setting, the structure lies between one large uplifted structure - Ringkøbing-Fyn High to the SW, and one large subsidence area - Sorgenfrei-Tornquist Zone in the NE. The tectonic unit between them is the Danish basin, which principal favourable characteristic is that it contains several salt diapirs forming four-dip domal closures in the overburden sedimentary column. In many places both the reservoir and cap rocks are preserved in such structures and here it is the Gassum Sandstone Formation (Upper Triassic) covered with marine claystones of the Lower Jurassic Fjerritslev Formation.

In the *Havnsø* area the Gassum formation properties are extrapolated from the nearby Stenlille structure (100 m of net sand with average porosity of 22% and permeability of 500 mD), while the apical part of the structure is at depth of 1500 m with a spill point around 1850 m. The structure covers 166 km^2, and the missing element here is that actual measurements of the reservoir pressure and temperature were not taken at the site, so the regional values were used for storage capacity estimates. The proposed injection concept includes drilling of one deviated and then partly horizontal well into the flank of the mildly inclined faultless structure, with an estimated injection rate of 6 Mt/year, making this structure highly prospective for up-scaling (see Larsen et al, 2007). The only element that still remains to be investigated in detail is the sealing; the Fjerritslev formation at Havnsø does not have quite the same lithology as in the Stenlille structure where its claystones proved to be tight. At Havnsø, the same seal is actually made by a 260 m thick section of marine mudstones and their sealing properties still have to be tested. With just a few faults on the location, low seismicity and multiple seals in the column above the reservoir, this should not present a major problem. It is mainly the matter of how the geological storage complex will be defined. With an estimated capacity of 926 Mt the future pilot at *Havnsø* becomes the most prospective location with excellent upscaling potential.

Future pilot project at Vilkyciai (Klaipeda, Lithuania)

The example of the *Vilkyciai* oil field is important for Lithuania because there are similar reservoirs in the country, and also the phenomenon called the Gargzdai Residual Oil Zone (ROZ). Such zones have a residual oil saturation of 40 - 60 % and this resource can only be used if CO_2 is injected into the reservoir formation.

The *Vilkyciai* oil field is situated in the central part of the Baltic basin, in the southern part of the Gargzdai uplift, where the basement is maximally 2 km deep and the mentioned ROZ is developed where the Phanerozoic sedimentary column is the deepest. It affects the deepest Cambrian reservoirs in western Lithuania. Top of the Middle Cambrian reservoir (quartz sandstone with some shale) is here at a depth of 1931 m while in the deepest part at 2088 m. Reservoir thickness is 66 - 75 m, and the structural closure itself is around 50 m . Cap rock is a Middle Cambrian, 750 m thick shale. This means that this should be a safe location for geological storage but there is a problem with relatively small permeability of 0.1 - 50 mD. Since the ROZ underlies the reservoir and all the wells were drilled through it, the injection concept is simple and straightforward – inject into ROZ using some of the already completed wells (to be selected by Minijos Nafta, the exploitation licence holder and partner in this proposal). No detailed estimates of storage/retention/production capacity have been made so far.

Future pilot project at Dziwie (Kłodawa, Poland)

The saline aquifer structure of Dziwie has already been partly investigated in the scope of the Polish CCS demonstration project Bełchatów, part of the EU CCS Flagship Programme. Its location is SW of the Teisseyre-Tornquist tectonic zone in central Poland. Reservoir rocks are Lower Jurassic heterolithic sandstones at 1300 m depth that are 132 m thick and have average porosity of 20% and permeability of 200-500 mD. Caprock is made of 110 m thick Lower Jurassic claystones and mudstones with some heterogenous intercalations. The planned injection amount is 27 kt CO_2 in 24 months.

Future pilot project at Kenderes (Jász-Nagykun-Szolnok county, Hungary)

This pilot project study includes an object in eastern Hungary, in the Great Hungarian Plain. It lies in the Mecsek geotectonic unit (part of Tisia), south of the Mid-Hungarian Lineament. Regional structural trend is NE-SW with major tectonic elements of reverse faults and nappes in the deep subsurface, the complex Neogene basement structures are covered with a thick-sequence sedimentary basin fill. The chosen potential storage object is one of the Lower Pannonian gas reservoirs that are all stratigraphic traps that developed through combination of lithology variation induced by the depositional-system and subsequent differential compaction. The reservoir lithology variations make a highly complex unit with many stratigraphic traps. To make things even more complicated, sandstone bodies are also separated by WNW-ESE faults. Phase boundaries are practically sub-horizontal. The composition of the natural gas varies in each reservoir. Hydrocarbon content is 46.53 - 83.22 % whereas carbon dioxide content falls between 0.3 and 32.45 %. Existence of CO_2 saturation is regarded as a favourable element in terms of storage safety.

The depth of the reservoirs at *Kenderes* is in the 1200 - 1700 m range, the areal extent is 15.3 km^2, and average porosity 27%. Two storage estimation concepts were tried – one based on cumulative production, and another based on injection of dissolved CO_2. In the first case, under assumption that most of the previous gas saturated pore volume could be substituted with CO_2, the capacity of more than 10 Mt CO_2 is reached, more than enough for the 3-year pilot of 33.000 t/yr under the current regulations. In the second case, there is a concept of injecting dissolved CO_2, which may have potential for coupling with geothermal projects (e.g. CO_2-Dissolved concept[5]).

Future pilot project at Brădești (Oltenia, Romania)

One of the oil fields in SW Romania has been selected for proposing a project with EOR and associated CO_2 storage in a smaller anticline south of the actual oil structure – called the South Brădești storage structure – a structurally defined aquifer at 1640 m depth. Regional geological setting is such that both structures lie in the western part of the Moesian Platform characterized by E-W trending faults and regional uplifts and depocentres between them. These regional structures are locally intersected with faults striking N-S (or NW-SE) and also those striking E-W. Between them we can find the Lom Depression - the most important subsided unit in the investigated area. The sedimentary cover of the Moesian platform ranges from Cambrian to Pliocene and is subdivided into four major sedimentation cycles.

The *Brădești hydrocarbon field* has three major reservoir units – Triassic, Dogger and Sarmatian, ranging in depth from 2580 to 2200 m and with effective thickness of 10 to 40 m. Their lithology and reservoir properties are quite similar – limestones and siliceous sandstones with average porosity of 15 - 16 % and permeability in the range of 150 to 350 mD. Pressure is close to hydrostatic but locally depleted,

[5] http://co2-dissolved.brgm.fr/

especially in the deepest (Triassic) reservoir, the most important commercial object. Structure of the Brădești oil field is a heavily faulted monocline which is not very favourable for both production and storage due to the complexity of traps.

The *South Brădești storage complex* has a different model. Injection is planned in the Sarmatian sequence of coarse-grained sandstones covered with Sarmatian shales. In places where the entire sequence pinches out on the Pre-Tertiary paleo-relief, structural-stratigraphic traps can be formed. The sealing part of the Sarmatian extends from top of the reservoir to the top of Sarmatian, which is at 1150 - 1200 m depth at the location. The top of the reservoir is at 1640 m, with the average porosity 15% and estimated storage capacity of 23.8 Mt of CO_2 in supercritical state. No injectivity analysis or detailed modelling data have been prepared in this phase.

Future pilot project in the Sava Depression (Moslavina, Croatia)

This is an example of a possible future integrated project with several scenarios that might be developed in a region with several depleted oil and gas fields. The Sava Depression is a regional tectonic trench with an NW-SE strike in continental Croatia. Along its northern border there were numerous oil discoveries with around 20 oil and gas reservoirs in the small W-E striking anticlines. The main reservoir rocks are Upper Miocene sandstones that form several vertically stacked sandstone bodies, while Upper Miocene calcite marls and Pliocene clayey marls form numerous cap rock intervals.

Two of such fields were selected for more detailed evaluation of their storage potential due to their vicinity to the source (15 - 19 km) and the fact that they are not in production now. Geological models of these fields – *Voloder* and *Mramor Brdo* presented in the study are based on publicly available data. It should be noted that the public input data do not include the latest pieces of knowledge ("vintage" maps). In addition, the models do not represent all of the reservoirs in the two fields. There are more data available, but some were not made public. In consequence, the actual storage capacity at these sites is surely larger. The *Voloder* field reservoir has one structural trap (anticline with two peaks) in the SW part and another trap in the downthrown block at the regional NW-SE trending fault. These reservoirs have porosity of 16.5 - 17.2 mD, they are close to 1900 m depth, with average thickness of 20 m. Much the same situation is in the *Mramor Brdo* field where reservoirs were defined but the model is burdened by complex geology – structural traps, pinch-outs and fault-associated traps are mapped. Porosity ranges from 21.5 to 27.4 %, the average depth is between 920 and 1350 m, and layer thickness from 25 to 32 m.

A strong side of this study is that three different injection scenarios were analysed – using CO_2 in the existing large CO_2-EOR operation at the Ivanić field 45 km away (Scenario 1), using the Voloder and Mramor Brdo fields as the main pilot storage objects with a slower injection rate (Scenario 2a) and a faster injection rate (Scenario 2b). In both of the two last scenarios the total storage capacity is estimated at 1.2 Mt CO_2, but the scenario with a larger injection rate is more economical. Any of these might be feasible and all have upscaling potential especially because they have a stable source of 180.000 t of pure CO_2 per year in the neighbouring fertilizer factory (Petrokemija Kutina).

Summary

Out of the 6 conceptual studies altogether:

- two are structurally defined aquifers (in Denmark and in Poland),
- one is an aquifer with a structural-stratigraphic trap, adjacent to an oil field (in Romania),
- one is oriented to only partly depleted gas field, with some CO_2 saturation already but with no structural trapping defined and relying on a dispersion of CO_2 through a complex and heterogeneous sedimentary body (in Hungary),

- one is aimed to testing of the CO_2-EOR potential of a regional residual oil zone (in Lithuania),
- and the last one presents an idea of a multi-faceted future pilot combining two small depleted oil fields and a large ongoing CO_2-EOR project in their vicinity (in Croatia).

In all cases there is sufficient intergranular porosity at favourable depth range and all reservoirs have documented thick seal formations, except partly the Hungarian and Croatian examples from the Pannonian basin.

In any case, each of these locations deserves a more detailed study of the future storage complex, advantages of one over the other will, however, not come from geology but from economics (EOR, CO_2 source, transport routes) or legal impediments like the one that appeared in Lithuania in 2019[6].

[6] In November 2019, the Lithuanian parliament approved a bill prohibiting any injection of CO_2 into the underground, starting from July 2020.

4 CO_2 sources

Securing a suitable source of CO_2 for injection has been a critical issue for all the onshore CO_2 storage pilot projects in Europe so far. The typical requirements of a storage pilot usually represent tens of thousands of tonnes of CO_2, which is deemed a sufficient amount to test the technology and perform methodological research, especially in the area of monitoring of the CO_2 stored (e.g. plume tracking). Such amounts of CO_2 normally exceed the amounts handled in small-scale CO_2 capture pilot projects, and even the use of CO_2 from larger-scale capture pilots is not straightforward because the capture pilots usually do not involve purification and compression stages and the captured gas is vented to the atmosphere. One of the reasons of this state has been the way how the CCS pilots in Europe have been funded: usually, there have been separate projects for CO_2 capture and separate ones for CO_2 storage, without any request for integration. The lack of a reasonable CO_2 source was one of the main reasons why many of the CO_2 storage pilot project concepts developed in Europe in the past 10 – 15 years have not materialised.

Looking at the three successful European CO_2 storage pilots that reached the realisation phase, we can see two different approaches. The first one, used for Ketzin and Hontomín pilots, lies in purchasing food-grade CO_2 on the market, from companies selling CO_2 to beverage and other industries. This approach is costly, even if discounts based on relatively big quantities of CO_2 purchased are applied, and the costs of “investment” into the CO_2 to be stored represent a significant part of the overall project budget. The other approach, applied in the case of the Lacq-Rousse project (and to a small extent in the latest phase of Ketzin), is realisation of an integrated pilot project involving all three parts of the CCS technology chain, i.e. capture, transport and storage. A brief overview of the approach used at the three European onshore storage pilots is provided below.

CO_2 injection at *Ketzin* began on June 30, 2008 and ended on August 29, 2013. During this period, a total amount of 67 kt of CO_2 was injected. The CO_2 used was mainly of food-grade quality (purity > 99.9%), delivered by Linde AG. In addition, ca. 1.5 kt of captured CO_2 from the Vattenfall oxyfuel pilot plant Schwarze Pumpe (power plant CO_2 with purity > 99.7%) was used from May to June 2011. In July and August 2013, a co-injection experiment with CO_2 and N_2 was performed to test and demonstrate the technical feasibility of a continuous impure CO_2 injection scenario. A total of 613 tons CO_2 and 32 tons N_2 were continuously mixed on site and injected resulting in an average CO_2 to N_2 mass ratio of approximately 95 to 5. The CO_2 was delivered in liquid state by road trucks to the Ketzin pilot site and stored in two intermediate storage tanks at about -18°C and 18 bars on site. Prior to injection, the CO_2 was pre-conditioned: Plunger pumps raised the pressure to the necessary injection pressure and CO_2 was pre-heated to 45°C by ambient air heaters and an electrical heater in order to avoid liquid-vapour phase transition of the injected CO_2 and associated pressure build-up within the reservoir. The CO_2 was then transported via a short pipeline to the injection well Ktzi 201. Typical injection rates ranged between 1,400 and 3,250 kg CO_2/h with a maximum monthly injection rate of 2,300 tons (Martens et al. 2014).

The *Lacq-Rousse* pilot is an exceptional case of a full-chain integrated CCS pilot project, designed, funded and carried out by the French oil & gas major Total. The project included conversion of a steam boiler into an oxy-fuel combustion unit of a 30 MW_{th} scale, CO_2 capture, treatment, dehydration, compression, transport and storage. The CO_2 captured at the Lacq gas production and treatment plant was compressed up to 27 bars, dried and transported in gaseous phase via an existing pipeline to the depleted gas field of Rousse, 29 kilometres away where it was injected into the deep depleted gas reservoir of the Mano Dolomite formation at a depth of 4,500 m below ground. The injection started in January 2010 and lasted for 39 months; in total 51,340 tonnes of CO_2 were injected (Monne et al. 2015).

The *Hontomín* pilot project has been completely relying on food-grade CO_2 purchased on the market, which is costly and turned out to be one of the barriers hindering the project from larger-scale CO_2 storage testing. Between 2015 and 2018, 3,400 tonnes of CO_2 were injected. The CO_2 was injected in liquid phase, mostly for testing of different injection strategies and combined with brine injection (de Dios et al. 2019). Since 2018 CO_2 injection has been put on hold.

The approach of the six newly proposed storage pilot case studies to the CO_2 source question is diverse. It needs to be mentioned that the primary focus of the studies is CO_2 storage and the attention paid to the CO_2 source issue is, hence, rather limited. Nevertheless, when (preliminary) assessing the feasibility of individual case studies, the connection of the planned storage pilot with a suitable CO_2 source becomes crucial.

In this respect, two of the case studies assume storing CO_2 from prospective CO_2 emission sources representing industries and technologies that can be branded strategic for the development and deployment of CCS in Europe. As such, CO_2 capture projects at these installations might gain broad political and hopefully also financial support not only nationally, but also on the European level.

The first of these two studies is the Danish Havnsø pilot project, which aims at storing CO_2 emissions from the nearby Asnæs Power Plant where one of the blocks is now being converted to fire biomass. This provides an excellent opportunity to develop a project demonstrating BECCS (bio-energy with carbon capture and storage), a carbon-negative technology that will be crucial for achievement of the target of “no net emissions of greenhouse gases in 2050” as suggested in the European Green Deal[7].

The Croatian Sava Depression case deals with emissions from the ammonia production plant in the Petrokemija factory in Kutina. With its high CO_2 content in the flue gas stream (92.5 %), this type of CO_2 source is one of the most favourable ones for CO_2 capture. The high CO_2 concentration allows for relatively low capture costs. Moreover, the chemical industry is (together with cement and iron & steel production) a typical example of emission-intensive industries with difficult-to-decarbonise technological processes where CO_2 is, to a large extent, an integral part of process emissions. To contribute to decarbonisation of these industries is now the largely acknowledged main role of CCS in Europe.

The other four case studies are rather less concrete and more ambiguous concerning possible sources of CO_2 emissions to be stored.

The Hungarian Kenderes pilot project plans to rely on CO_2 purchased on the market in the initial phase, or, optionally, use CO_2 produced from natural reservoirs by the national oil company MOL that has been using it for CO_2-EOR operations in the country since 1970s. The project, however, provides an upscaling opportunity, for which up to 10 various emission sources (both energy production and industrial facilities) have been mapped.

The Vilkyciai pilot project in Lithuania counts on CO_2 from a fertilizer and chemical materials producing factory – the JSC Azotas LT plant in Jonava. Its distance from the storage site is, however, quite big – ca. 200 km, which would significantly increase the transport costs.

In the Polish Dziwie case study, the source of CO_2 is unclear, even though opportunities exist to use CO_2 emitted by two chemical plants located nearby. Similarly, there is no clear source of CO_2 for the Brădești pilot project in Romania; here, the nearby Ișalnita lignite-fired power plant can be considered suitable, provided a pilot capture facility handling a slip-stream of the total massive power plant exhaust (containing 2Mt CO_2 annually) is built, which might prove costly. Nevertheless, according to Romanian

[7] https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

national energy strategy, lignite is envisioned to play an important role in the country energy mix in decades to come, providing stability of the energy supply, and CCS is recognized as an important measure to decarbonize the energy sector. It is also worth mentioning that the owner of Ișalnița, the Oltenia Energy Complex is committed to continue the production of energy from coal and to deploy CCS. In addition, three other power plants and two chemical factories were also identified as possible CO_2 sources in the vicinity.

Generally none of the case studies can rely on any existing CO_2 infrastructure, except the Croatian Sava Depression case where one of the scenarios assumes integration of the CO_2 stream into existing CO_2-EOR operations performed by the INA oil company. In this scenario, two existing gas pipelines could possibly be re-used, and the existing CO_2 injection facilities at the Ivanic oilfield could be utilised.

5 Success factors

Reviews of past, active and proposed pilot projects, including those concepts for new pilots in the ENOS project summarised above, have identified a range of factors that have ensured their success. Before these are described below, however, it is worth considering how we define a successful storage pilot. The success of a pilot might be viewed in a number of different ways and reflect the range of objectives for which it was designed. Here we consider measures of success to include a range of indicators:

- Achieving the permitting, construction and injection, and in some cases, closure of the project, to meet the original objectives of the project is perhaps an obvious measure of success. Nevertheless the financial, organisational, policy, developer and regulatory support needed to achieve this can remain a significant barrier to success if not all obtained and maintained throughout the project.
- The most successful pilots are considered those that lead to further CO_2 storage development.
- Increased confidence amongst wider stakeholder groups is an important measure of success.

5.1 Objectives of Pilot projects

At the highest level, CO_2 storage pilots are expected to lead to further storage development, the extent of which will reflect the maturity of CCS policy and the knowledge, capacity and support amongst stakeholders within the country or region. Pilot CO_2 storage projects can have a number of different aims, which can be related and complementary:

- To act as a bridge to further CO_2 storage through:
  - Increased injection at the same site
  - Additional injection within the same geological formation
- To increase knowledge and capacity amongst stakeholders, including storage operators and project developers, policy makers, regulators.
- To increase understanding and dialogue with local communities, as a prelude to wider and larger storage.
- To provide a facility for further research, thereby increasing expertise, experience and knowledge amongst the academic, research institutional and project developer communities.
- To decrease financial risks.

5.2 Potential for upscaling

The most successful CO_2 storage pilot projects have enabled the subsequent expansion of CO_2 storage. This expansion can take a number of forms, reflecting the range of objectives being pursued at the pilot but a key success factor is the definition of the potential for future continued development beyond the initial pilot. In some cases, where an objective of the pilot has been to build knowledge, understanding, expertise and experience in CO_2 storage, both within the project development team and wider community, there is an explicit attempt to include a wide group in the project design, construction and operation. This needs to be supported by further inclusive and open approach to undertaking research where, whilst often predominantly focussed on national capabilities, the most successful projects embed international collaboration throughout as well. Pilot projects that have very successfully embraced this approach include the Otway Project in Victoria, Australia, Nagaoka in Japan and the Frio Project in Texas, USA.

At Otway, the pilot was conceived to develop capability, experience and confidence in CO_2 storage both among the Australian research community and wider stakeholders in the state and national levels.

Additionally, through all stages of the project, international collaboration was encouraged and successfully implemented via direct joint research initiatives, with groups in North America and Europe, as well as through international peer review and advisory boards. These multiple research streams, which covered both new technological innovation, demonstration of effective monitoring capabilities, and research on fundamental reservoir processes were coordinated by the CO_2 Cooperative Research Centre, which was dedicated to the construction, operation and funding of the pilot. During the initial three phases of operation, from 2007 to 2015, the Otway project stored 65,000 tonnes of CO_2 in both a depleted gas field and an adjacent saline aquifer. A further injection of 15,000 tonnes was injected in 2015-2016. During this time a comprehensive research program demonstrated effective monitoring of the site using commercially mature and new monitoring technologies (e.g. Jenkins et al, 2012). Through the open collaborative approach between academia, industry and state and commonwealth agencies, the Otway pilot enabled an expansion and upscaling of CO_2 storage in Australia with the development of a number of storage programmes in eastern (the CarbonNet Program) and western (the South West Hub Carbon Capture and Storage project) Australia, as well as the Gorgon CCS project which is currently the largest CCS project in terms of CO_2 to be permanently stored, globally.

Storage pilots can also be used to demonstrate the potential for further larger deployment in a specific formation. Defining this potential for further upscaling is an important success factor and enables decision makers to undertake initial proving of the safety, costs and feasibility of injection at a modest scale without commitment to full-scale projects. Taking this initial step of developing a pilot to establish the potential storage capacity and injectivity of a specific target formation can therefore be extremely valuable, and designing the pilot project to demonstrate this can be a key to success. Here the potential for upscaling is particularly important in regions where there is no previous experience of CCS or previous testing of the target formations. There are a number of examples of CO_2 storage pilots that have been designed to achieve this aim and include the Decatur project in Illinois (Gollakota and McDonald, 2014), the Aquistore project in Alberta and pilot concepts developed within the ENOS project, the Havnsø Pilot in Denmark and the Dziwie Pilot in Poland. Illinois Basin Decatur Project successfully demonstrated safe, cost-effective CO_2 storage in the Mt Simon Sandstone saline aquifer through the injection of 1 Mt CO_2, through a partnership of the Illinois State Geological Survey, Archer Daniels and the Kentucky and Indiana State Geological Surveys (Greenberg, 2014 and references therein). This has established the Mt Simon Sandstone as a primary target for other CO_2 storage projects in the region, which will increase the storage amounts significantly.

5.3 Project champions and teams

As with all major infrastructure projects, a key success factor is the identification of a project champion that has the appropriate authority, resources and funding to build a consortium, create supply chains, control project design and implementation and communicate with the range of stakeholder groups that must be involved in the successful project. In many cases, the project champion is a public research institute (e.g. GFZ at Ketzin, Illinois State Geological Survey at Decatur, Bureau of Economic Geology at Frio). However, in some cases a government agency or separate entity has developed the project (e.g. Japan CCS Co at Nagaoka, CO_2 CRC at Otway, Petroleum Technology Research Centre at Aquistore in Saskatchewan). In all cases each project owner has assembled a consortium of industrial engineering and geotechnical companies to design, construct and operate the facilities. In a few cases, individual commercial organisations have developed the pilot project, e.g. Total at Lacq-Rousse, France (Monne et.al., 2015). In all cases, public money from national and/or regional research and development programmes is required to support the institutional and commercial investments. These project champions undertake funding, commissioning or client roles themselves. In the currently developed ENOS pilots, roles and responsibilities have not been defined as it is too early in the conceptual design process and stakeholder engagement processes. A key role will be to assemble the scientific team, with the necessary range of skills from engineering, geology, public engagement, project management, finance and many other areas.

5.4 Policy Support and Governance

Storage pilots can be conceived as national projects in many countries. Therefore a national policy that defines the steps a country intends to take to assess the feasibility and then implement CCS is often a necessary first step. However, the development of smaller, more-research-focussed pilot projects can contribute to the development of these policies. Consistent, clear and sustained policy support, including the availability of public funding, is a key factor in successful projects. It is unlikely that in many countries CO_2 storage pilots will be successful without this support (an exception might be the Lacq-Rousse pilot in France). The policy support will be required at the national and local scale to enable permitting for construction, health and safety, and injection, addressing long-term liability issues, and in some cases enabling the in-kind and commercial co-investments that might be needed. Almost all pilot projects have required some financial support from public/societal programmes. In order for pilot projects to proceed, budgets, with funding in place with adequate coverage for contingencies, must be agreed.

The governance structure and lines of responsibility must be clearly defined to allow a robust decision-making process. This naturally requires a detailed plan, with clear milestones and an agreed realistic, and flexible project time frame. Good practice in project management will be fundamental to the success of any project, especially one that is specifically designed to strengthen and test capabilities and experience in a new operation such as CO_2 storage. In addition to the other elements of good practice described here, the basis for all key decisions must be clearly documented and best practice should be followed at all times for all health, safety and environmental protocols and operations.

Agreement on future liability issues and the associated stage gate decision-points needed during key project milestones must be achieved to enable project start. This will include the need for clear protocols for commencing, suspending and concluding injection, well closure and abandonment. At a high level, key project milestones are likely to include, inter alia: final project design, permission to inject, final investment decision, start of construction, start of injection, end of injection and site closure.

Ensuring and maintaining fully engaged regulators has also been shown (Cook et al., 2014) to be very important to the successful delivery of storage pilots. This naturally requires regulations and key performance indicators to be in place, which, in turn, requires clear policy steer from policy-makers. One significant benefit of storage pilots, especially if conducted as research facilities, can of course be to provide significant opportunities to ‘learn by doing’ for the regulatory agencies, as well as for the wider stakeholders.

5.5 Increasing stakeholder confidence

A clear benefit of CO_2 storage pilots is their potential to increase knowledge, understanding, awareness and confidence in CO_2 storage amongst many stakeholder groups. The range of stakeholders relevant to the pilot will be large and will naturally reflect the objectives of the project. Successful projects undertake a robust analysis of their stakeholders, to understand their needs and to help develop appropriate methods of engagement and dialogue. A clear, strategic, proactive engagement plan is fundamental to the success of CO_2 storage pilots. As most pilots are onshore, this is particularly important with local communities as the “social licence” to operate can be decisive in enabling the success of these pilots. Furthermore the metrics by which a pilot will be considered successful may be different for different stakeholder groups and will comprise both qualitative and quantitative metrics.

The opportunity to demonstrate the safety and technical feasibility of CO_2 storage to wider stakeholder groups is a common objective of many pilots and in fact is the primary motivation for the development of most CO_2 storage pilots. In addition to the technical results and proof of storage, demonstrating the safe operation of an active facility has great power to impart in visitors knowledge and confidence in CO_2 storage. This requires a careful, targeted, detailed, analytical stakeholder engagement plan that is consistently implemented throughout the project lifetime. The most successful projects have dedicated and expert resources to implement these plans.

A key factor in the successful stakeholder engagement is transparency in the disclosure of monitoring results with new technologies enabling real-time publication of monitoring results. Furthermore an open-access database could be developed for all scientific, operational and other project information supported by a clear protocol for data collection, dissemination and curation, being implemented at a very early stage.

In addition, the engagement process might highlight job opportunities and increased economic stimulus for the benefit of local communities – an important factor in the development of the Hontomín and the Lacq-Rousse pilot projects which offered direct and indirect support for local economic development and for future use for a depleted gas field.

5.6 Decreasing financial risks

An important factor in enabling the success of a storage pilot is the decrease in financial risks. This might be achieved through establishing routes through the permitting, policy, insurance, investment and funding decision-making processes. In addition financial risks may be reduced through gaining experience in the technologies and identifying future cost-savings (e.g. in approaches to MMV, cheaper materials, improved operations, cheaper infrastructure) as well as innovation to increase efficiencies. All of the proposed ENOS pilots include some element of financial risk-reduction.

5.7 Technical success factors

Key technical factors that have enabled successful pilots include the following:

- Clear technical objectives must be developed at the beginning of the project and must be communicated widely across relevant stakeholder groups (Cook et al., 2014). From these scientific objectives a strategy for achieving them can then be developed, costed and implemented following a robust decision-making process. The Dziwie, Havnsø and Sava Depression pilot projects provide particularly clearly developed objectives at this stage of their project concept development.
- The availability of a cheap, consistent supply of CO_2 can enable a project to operate at lower costs. Whilst not an absolute fundamental requirement, where the objective of the pilot is to demonstrate cost-effective CCS, then using CO_2 captured from an industrial or power station source will be of significant benefit. If the CO_2 source is relatively close as has been the case in a number of pilots, this can further reduce transport costs, especially where volumes are relatively low and transport by truck is the preferred delivery option. For example, Decatur uses CO_2 captured from bio-ethanol production, Aquistore uses CO_2 captured from the nearby Boundary Dam coal-fired power station. The Havsnø pilot has identified a nearby power-station source of CO_2. In contrast, although a source of CO_2 is identified for the Vilkyciai pilot, the 200km distance to the storage site would make transport costs a very significant and possibly prohibitive cost for

the pilot. However there have been successful projects that have tested injection using commercially-purchased CO_2 (e.g. Ketzin) or naturally occurring CO_2 produced from nearby fields (e.g. Otway).
In some cases there may be a requirement to use food-grade CO_2 as a precaution to protect aquifers or the environment. In the future, it might be expected that CO_2 captured from nearby industrial of fossil-power sources will be used and the identification and support of these emitters that will allow low-cost capture and transport of CO_2 is likely to be increasingly important to demonstrating CCS as a viable climate-mitigation option, rather than to demonstrate safe injection or conduct further process research. An initial proof of injection using commercially available (food-grade) CO_2 might be undertaken (as undertaken at Ketzin amongst others), which could be upscaled in a second phase to CO_2 injection from industrial or fossil-power sources – this is being considered at the Kenderes pilot for example.

- Typically CO_2 injection at a pilot project is best achieved with injection into a well-defined geological structure. This has a number of benefits, including the potential to limit the amount of CO_2 being injected to achieve the project objectives (and thereby reduce costs), to enable safe storage into a well-defined and containing structure to enable permitting and to more effectively achieve the scientific objectives of the pilot by verifying geological models, verifying reservoir and caprock responses and testing injection and monitoring technologies more quickly.
  All the ENOS proposed pilots have identified specific geological structures which are expected to contain the injected CO_2. However the degree of confidence in the containment at this stage reflects the amount of pre-existing data that is available and has been interpreted. Havsnø, Dziwie, Kenderes and the Sava Depression concepts have all identified geological structures that have enabled or could enable future construction of a parameterised geological model which would allow simulations to explore potential dynamic storage capacities (matched to capture rates), and potential containment risks.

- As discussed above, whilst a pilot project might be specifically designed to build knowledge and awareness with stakeholders of CCS concepts, undertaking storage pilots in areas with pre-existing hydrocarbon activity might be an advantage. This will be particularly the case for pilots that plan to undertake enhanced oil recovery (EOR) via CO_2 injection into active and mature oil fields. The Vilkyciai, Sava Depression and Brădești Pilot project concepts developed for the ENOS project, all plan to take benefit of both utilising the CO_2 for EOR which may offset some costs and of developing a pilot in a community with some familiarity of, and support for, oil and gas operations. Of course, where these previous oil and gas operations have not been a positive experience for local communities, the potential introduction of a CO_2 storage pilot may not be welcome or supported.

- Utilising either active or depleted oil and gas fields may have other advantages including:
  - the potential to reuse existing infrastructure such as wells and pipelines, thereby reducing costs,
  - proven containment potential through the retention of hydrocarbons,
  - the availability of data from exploration and production including seismic data, well logs, porosity and permeability data, reservoir and other geological models, fracture tests and production data, and
  - the potential for upscaling to other compartments in the same field, or other fields in the same formation.

  The Brădești, Vilkyciai, Kenderes and Sava Depression pilot concepts will all utilise depleted hydrocarbon fields.

- Successful storage pilots embed risk assessment and risk management within all aspects and during all stages of the project. This enables both informed decision-making as well as clear, auditable prioritisation of the technical design, construction, operation, monitoring and research being undertaken.

- Establishing appropriate baseline conditions prior to injection and indeed prior to construction is also seen as a key success factor by Cook et al (2014). The definition of baseline conditions provides reassurance to local communities and wider stakeholder groups, especially where these conditions can be communicated alongside other information during engagement activities.

6 Conclusions

The presented study evaluated six onshore sites throughout Europe that have the potential for developing future pilot CO_2 storage projects. The geographical spread of the suggested pilots is excellent (see Fig. 2) – if implemented, the new projects will bring CCS knowledge and practical experience to European regions where such considerations have been rather theoretical so far. These regions include in particular the South-Eastern and Central Europe and the Baltic Sea region; in all cases regions with large CCS deployment potential lying in numbers of emission-intensive facilities in both energy and other industrial sectors. In this respect, implementation of pilot projects in countries largely dependent on fossil fuels like Poland or Romania would be of utmost importance.

In addition to testing and verification of the technology in local conditions, the pilots will also serve as an irreplaceable element of practical demonstration of the CCS technology to local, national and regional stakeholders, starting from politicians and policy makers, through regulators, industry representatives and research community, to local populations, general public and media.

Implementation of the pilots would also unlock the geological storage potential of important supra-regional geological structures with promising reservoir properties and prospects of further development, like the Pannonian Basin, the Baltic Basin, the Moesian Platform as well as the Danish basin and the Central Poland area. All of these regions have seen historically significant hydrocarbon production and their thick sedimentary successions render large potential for CO_2 geological storage. The chosen locations are also either in connection with CO_2-EOR possibilities (like in Lithuania or Croatia), or try to make use of the existing deep wells in the gas or oil fields that are either depleted or soon to be depleted (in Romania and Hungary). Certain possibility to study synergy with deep geothermal project is hinted in the Hungarian project proposal., The most favourable geological conditions to demonstrate the safe storage in structurally defined aquifers are presented in the case studies from Denmark and Poland. Geological conditions for significant upscaling are demonstrated in Denmark, Lithuania, Romania and Hungary. In the Croatian study, there are three possible scenarios; the best way to go forward being to inject CO_2 as a part of the ongoing Ivanić CO_2-EOR project. Optionally, there is still a minimum of 1.2 Mt of realistic storage in the two small depleted oil fields that would rely on the steady inflow of CO_2 from a fertilizer plant in the vicinity.

To be successfully implemented, the proposed CO_2 storage pilots will need to have a suitable source of CO_2 to be stored. It is promising that two of the pilots (Havnsø in Denmark and Sava Depression in Croatia) have identified promising CO_2 sources representing technologies and industries considered strategic for the development and deployment of CCS in Europe – BECCS and CCS in chemical industry. Bringing these two project concepts into realisation might thus have a strategic impact on development of CCS in Europe as a whole. The other four case studies have not yet clearly specified the CO_2 source; in all cases, however, several suitable sources could be identified where CO_2 capture can be combined with proposed storage pilot.

A number of common factors can be recognised that have facilitated and enabled the success of international CO_2 storage pilots worldwide. These include the potential for upscaling, which might be achieved in a number of different ways depending on the specific objectives and conditions of the project, following the successful implementation of the pilot; the designation of an appropriate lead institute or organisation that has the mandate, financial resources and capabilities to assemble a consortium with the needed skills; a detailed plan for engagement with a potentially wide range of different stakeholder groups, supported by an analytical understanding of the needs of each group, and a dedicated resource for implementation; clear policy support, which is backed up by a robust governance structure and decision-making process together with best practice project management, to ensure regulatory support and compliance across all stages and activities within the project. In addition, a clear plan for implementation will allow the pre-defined and pre-agreed objectives of the pilot to be fully achieved. A well-developed project implementation plan will contain within it a number of technical success factors including, inter alia: a cost-effective CO_2 supply, a well-defined geological structure which may exploit existing infrastructure as appropriate and the definition of comprehensive and fit-for-purpose baseline conditions.

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List of Appendices

This deliverable is prepared as a part of ENOS project
More information about the project could be found at http://www.enos-project.eu

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The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653718

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Energetski institut Hrvoje Požar

CONCEPTUAL STUDY OF CO_2 STORAGE PILOT IN SAVA DEPRESSION OF PANNONIAN BASIN (CROATIA)

Zagreb, July 2019

Client:
UNIVERSITY OF ZAGREB
FACULTY OF MINING, GEOLOGY AND PETROLEUM ENGINEERING
Zagreb, Pierottijeva 6

Contract no.:
EIHP: UG-19-00020/1
Client: Class: 406-09/19-01/14
File No. 251-70-13-19-4

Title:

Conceptual Study of CO_2 Storage Pilot in Sava Depression of Pannonian Basin (Croatia)

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Zagreb, July 2019

CONTENTS

SCOPE OF THE STUDY

This Study is made as a part of the ENOS Project.

The task of the Project ENOS – Enabling Onshore CO_2 Storage in Europe is to provide advances in fostering CO_2 storage across Europe through developing, testing and demonstrating key technologies specifically adapted to onshore storage in the field. One of the main activities is to study possible new storage pilot sites in order to produce improved integrated research outcomes and increase stakeholder understanding and confidence in CO_2 storage.

ENOS strives to enhance the development of CO_2 storage onshore, close to CO_2 emission points. Several field pilots in various geological settings will be studied in detail and best practices that stakeholders can rely on will be produced. In this way, ENOS will help demonstrate that CO_2 storage is safe and environmentally sound and increase the confidence of stakeholders and the public in CCS as a viable mitigation option.

Here is a conceptual study of one of selected pilots where excess CO_2 from the petrochemical plant located in Croatia is meant to be transported to a nearby oil field and permanently stored. The study takes into account all aspects of collection, transport and geological storage of CO_2, potential impact of the pilot as well as risk assessment. The study also contains economic analyses of required activities considering investment costs and operational costs when applicable.

1. AIMS OF PILOT PROJECT

Technologies of carbon capture and storage (CCS) are recognised by specialist climate change bodies such as Intergovernmental Panel on Climate Change (IPCC) and IEA as the only technology able to decarbonise large industrial sectors, particularly the large industries such as steel, cement, fertiliser and petrochemical industries and help mitigation of international climate targets. Despite this, there are not nearly enough facilities coming onstream. To reach the Paris 2˚C target, more than 2,500 facilities need to be operating by 2040 (based on a facility with capture capacity of 1.5 million tonnes per annum (Mtpa) of CO_2) (Global CCS Institute, 2018). Recently, in the effort to decrease CO_2 emission to the atmosphere, carbon capture, utilization, and storage (CCUS) is becoming more and more interesting. Among possibilities for use of CO_2 captured from industrial sources are converting CO_2 into useful chemicals of commercial importance or utilizing CO_2 for oil extraction or remediation of alkaline industrial wastes, that can add economic value to this greenhouse gas. Carbon utilization and storage schemes can be classified by their capacity and permanence of storage, environmental consequences, and cost of implementation. Any viable system for storing carbon must be (1) effective and cost competitive, (2) stable as long-term storage, and (3) environmentally benign[1].

Pursuant to CCS Directive 2009/31/EC, a geological formation can only be selected as a storage site, following the screening criteria for safe storage of CO_2, if there is no significant risk of leakage, and no significant environmental or health risks exist. To identify and evaluate the risks associated to a potential storage site, a complete characterisation and assessment of the potential storage complex and surrounding area must be carried out, according to the best practices comprising: (1) Data collection to construct a 3-D static model of the reservoir, the caprock, and the surrounding area, including the hydraulically connected areas; (2) Building the 3-D static geological earth model, developing a range of scenarios for each parameter and calculating the appropriate confidence limits and the associated uncertainty; (3) Characterisation of the storage complex dynamic behaviour, the sensitivity characterisation

[1] https://www.aiche.org/ccusnetwork/what-ccus

and the risk assessment, through computerised simulations of CO_2 injection into the storage site (Barros et al., 2012).

Specifically, three fundamental features of a reservoir are crucial for development of the reservoir model and also to consider the reservoir as a potential storage site (Bachu, 2007; Bachu et al., 2007):

- Capacity - the space available in the reservoir for CO_2 storage depends on the reservoir the dimension (volumetrics) and pore space characterisation;
- Containment - existence of several CO_2 trapping mechanisms, namely a sealing layer or cap rock (and also other low permeability layers in the overburden);
- Injectivity - the rate of CO_2 injection in the reservoir is dependent on several reservoir characteristics especially the depth, the pressure but, above all, the permeability of the rock formation.

Still according to CCS Directive, the storage complex monitoring plan has to be establishing and updating (Barros et al., 2012). Pursuant to CCS Directive monitoring requirements, the plan must take into account: detection of CO_2 migration; detection of CO_2 leakage; quantification of effects on the surrounding environment, including the biosphere and all its resources particularly human populations. The monitoring plan must provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring. Besides the monitoring plan, a mitigation and corrective measures plan assesses the effectiveness of any corrective measures; updating the assessment of the safety and integrity of the storage complex in the short and long term, including the assessment of whether the stored CO_2 will be completely and permanently contained.

One of the aims of the ENOS project is to facilitate and accelerate the development of onshore CO_2 storages and this study is the first step towards achieving this goal in Croatia.

This study will cover a potential carbon capture utilization and storage pilot project involving a large industrial CO_2 emitter and one of the nearby oil fields as the potential storage site, either in depleted oil/gas field or as part of the ongoing EOR project.

The emitting industry is petrochemical company *Petrokemija* that has a surplus of CO_2 as a by-product of certain technological process which is only partially used in another process, while the rest of surplus CO_2 is released into the atmosphere.

The idea is to store this surplus of CO_2 in one of nearby depleted oil/gas fields (Voloder or Mramor Brdo) or to be used as a part of EOR project in Ivanić Grad.

Transport between the petrochemical plant and the oil/gas fields will be by pipeline or trucks, depending on the selected location. A favourable circumstance is existence of abandoned gas pipeline from Kutina to Ivanić Grad oil field, where *Ethane* plant with appropriate equipment is located.

This study will provide analysis of all the aspects of the project and its economic viability.

2. GEOLOGICAL MODELS FOR THE SELECTED RESERVOIRS OF THE VOLODER AND MRAMOR BRDO OIL FIELDS

2.1. Review of geology

The Sava depression is located in the Croatian part of the Pannonian Basin System, at its very southwestern margin (Figure 2.1). Development of the Pannonian Basin System started in the Early Miocene as a consequence of continental collision and subduction of the European Plate beneath the Apulian Plate. It is composed of several smaller deep depressions (sub-basins) separated by elevations of the basement rocks, such as the Sava depression (Grizelj et al., 2011).

The Sava depression is bordered with Dinarides and the Bosnian mountains on the right bank of the Sava river in the south and southwest, Medvednica in the northwest and the Moslavačka gora, Psunj and Krndija in the north. The central, flat part of Sava depression belongs to the valleys of the Sava, Lonja and Česma rivers with altitudes of 80 (in the east) up to 110 m (in the west). On the outer parts of the depression, the relief is more indented, and the landscape is more hilly with the altitude up to 200 m and more in the area of Vukomeričke gorice and Moslavačka, Petrova and Zrinska gora.

The most important feature of the Sava depression is its very complex tectonic structure. Two large stratigraphic units are distinguished within the basin. The older (Pre-Tertiary) complex consists mainly of the Palaeozoic igneous and metamorphic rocks, with a subordinate presence of Palaeozoic and Mesozoic sediments with a markedly complex structure – folds, faults and metamorphism, together with a pronounced lithologic heterogeneity. A younger complex includes Tertiary (mostly Neogene) and Quaternary rock formations (Troskot-Čorbić et al., 2009).

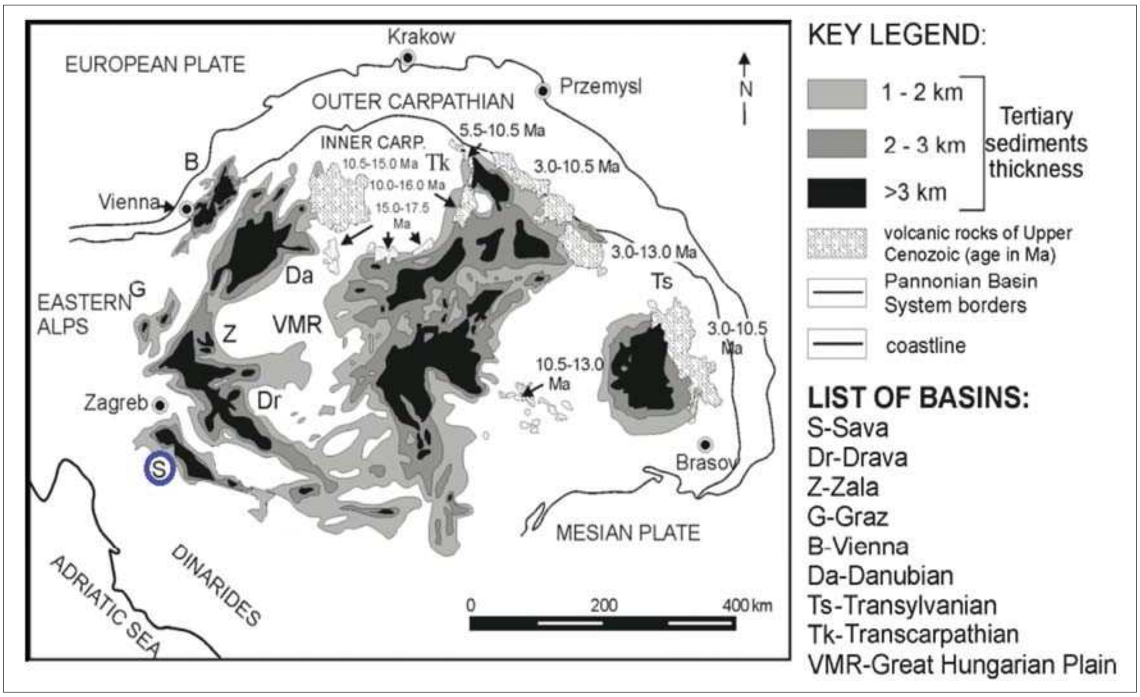

Figure 2.1. The geotectonic position of the Sava Depression in the Pannonian Basin System (Ivšinović, 2018; Malvić and Rusan, 2009)

Lithological units are described in detail by formations (Figure 2.2). Prečec Formation represents the 1st Neogene-Quaternary megacycle in Sava Depression, including Badenian and Sarmatian, and locally possible deposits of Lower Miocene. The sedimentary complex is extremely heterogeneous, comprising breccias, conglomerates, sandstones, siltstones, shales, marls, igneous rocks and limestones. The Prkos, Ivanić-Grad, Kloštar Ivanić and Široko Polje Formations belongs to 2nd megacycle and are represented mostly by a monotonic marl/sandstone sequence. The 3rd megacycle is represented by the Lonja Formation, composed mostly of unlithified sediments, i.e. sands, gravels, loess and some lignite (Ružić, 2015).

Altogether, there are about 20 hydrocarbon fields in the Sava Depression. They are all concentrated in the north-western part of the depression. The prevailing reservoir rock formations are the Pannonian and Pontian sandstones, but significant hydrocarbon accumulations have also been discovered in the weathered and fractured Palaeozoic igneous and metamorphic rocks (Troskot-Čorbić et al., 2009).

The hydrocarbon reservoirs in the Sava Depression are mostly in the secondary or tertiary recovery phase and some of them represent interesting candidates for the CO_2 storage objects.

Chosen potential storage objects are reservoirs of the two oil fields situated along the Northern marginal fault of the Sava depression. Regional strike of these structures is NW-SE and this fault pertains to a system of faults that represent the contact between the Moslavačka gora Mt. as a horst and an asymmetric tectonic graben of the Sava depression where a number of smaller hydrocarbon accumulations are discovered along its NE margin.

Description of the Voloder and Mramor Brdo oil fields reservoirs is based on the publicly available data - models given in the Study of environmental influence (Gaurina-Međimurec et al., 2015) and one Master thesis (Matošević, 1995).

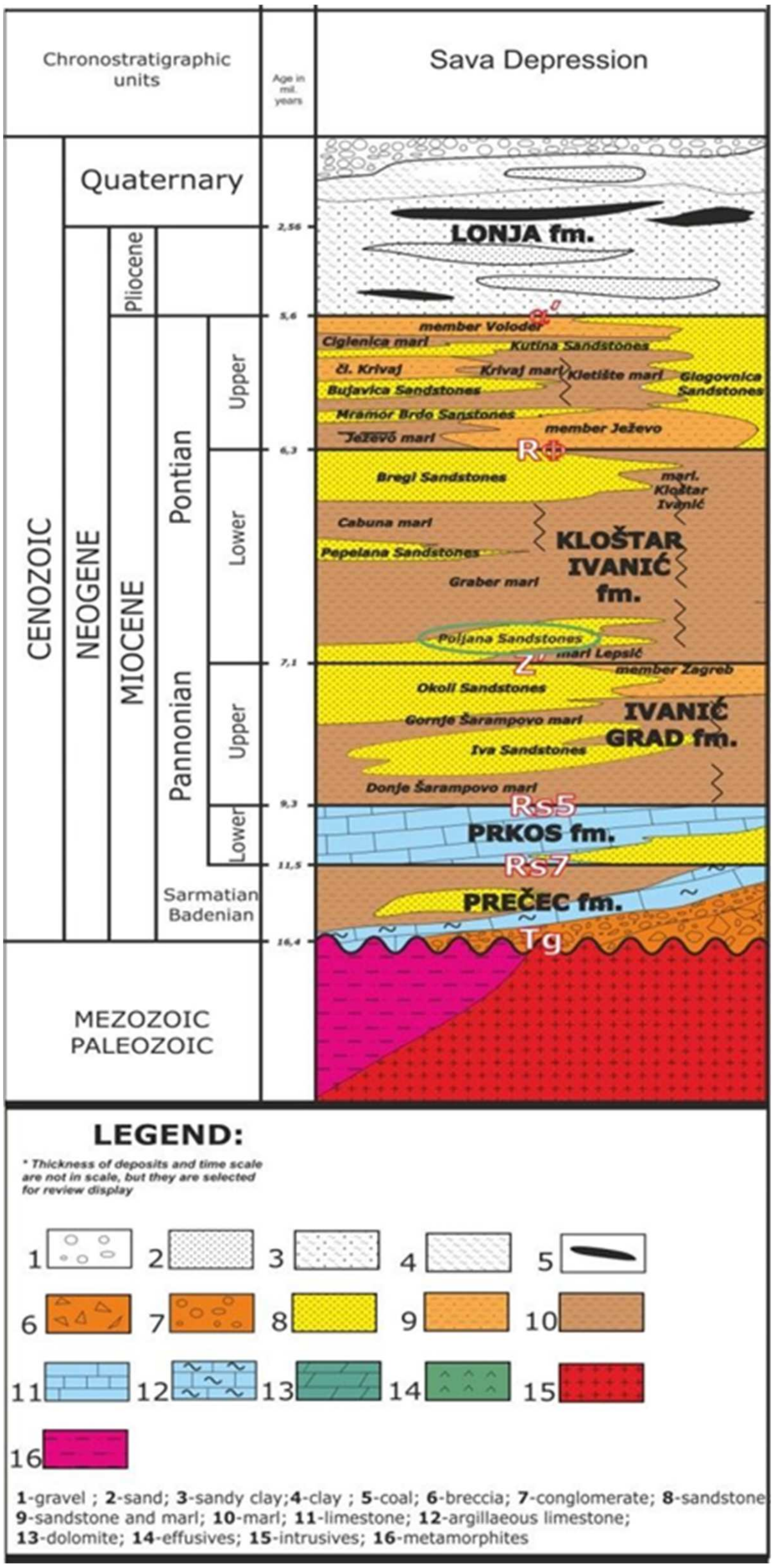

Figure 2.2 Chronostratigraphic and lithostratigraphic units in the Sava Depression (Velić, 2007; Cvetković, 2013; Podbojec and Cvetković, 2016)

2.2. Selected potential of CO_2 storage objects of Voloder oil field

Principal feature of the Voloder oil field structure is NE-SW striking marginal fault. The reservoirs are in the downthrown SW block and the ones that are described here as potential pilot storage objects pertain to the „A sandstone series" which lithostratigraphically corresponds to the Poljana Sandstones member of Kloštar Ivanić Formation (previously determined as of Lower Pontian age, now considered as Pliocene sandstones). The cross-section through the Voloder oil field is given in Figure 2.3.

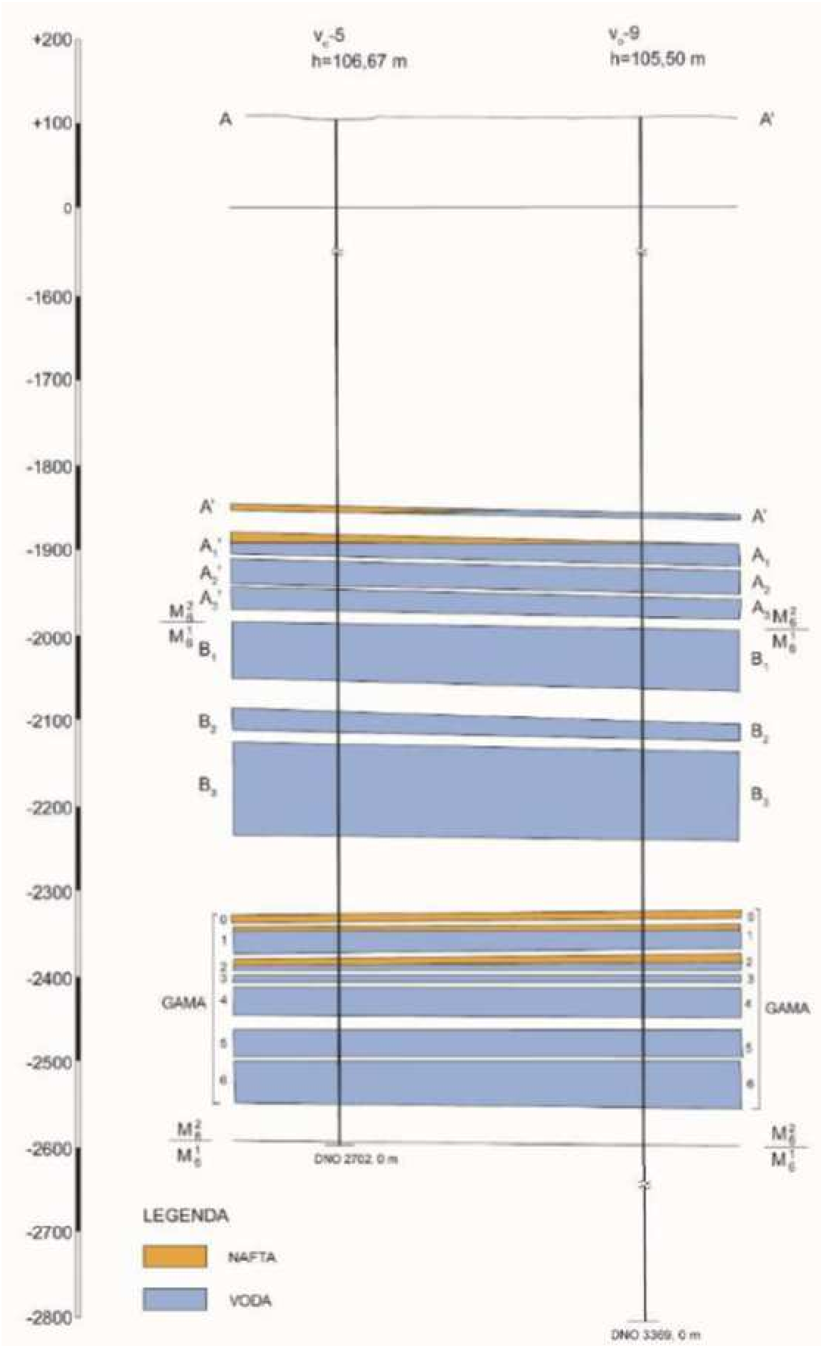

Figure 2.3 Cross-section through the Voloder oil field (Gaurina-Međimurec et al., 2015)

The mentioned sandstone reservoirs of the Voloder field are saturated with hydrocarbons, but the reserves were found to be non-commercial. Sandstones of A series have been drilled through by all but two wells within the Voloder oil field. Sandstones are mostly coarse-grained and well sorted. In the lower part they are well consolidated, in upper part they are partially consolidated and in the top part almost non-consolidated and fine-grained. Within the sandstones there are appearances of marl interlayers which are characterized by increase of compaction and clay content from lower part towards the top of the sequence.

Both selected potential storage objects represent traps of structural type. SW accumulation is a double anticline with the average absolute depth of -1885 m. NE accumulation is a structural nose, closed by a fault. The structural map on the top of production unit (sandstone layer) A1 is given in Figure 2.4. The characteristics of the potential storage objects are listed in Table 2.1.

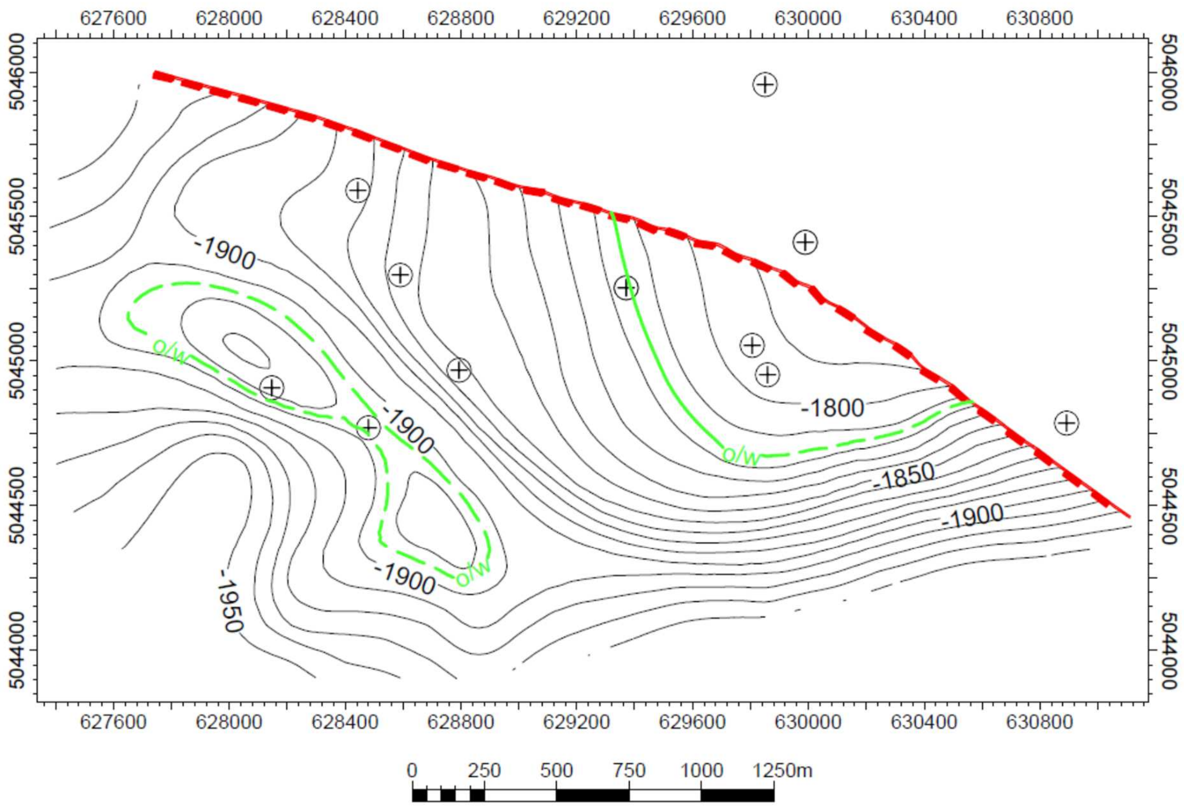

Figure 2.4 Structural map - top of production unit A1 (after Hernitz et al., 2000)

With the estimated average depth, porosity values of both reservoirs were calculated using correlation of porosity and depth as proposed by Jelić (1984). This regional correlation was established long ago, based on hundreds of core measurements from similar sandstones in Croatian part of the Pannonian basin. In this way estimated porosity values still must be taken with caution, since the proposed correlation is rather simplified as it implies mainly influence of compaction on porosity, neglecting other geological factors. Permeability was estimated using the permeability-porosity correlation that was developed for the sandstones of the same age in adjacent Stružec oil field (after Jüttner et al., 2000), as shown in Figure 2.5.

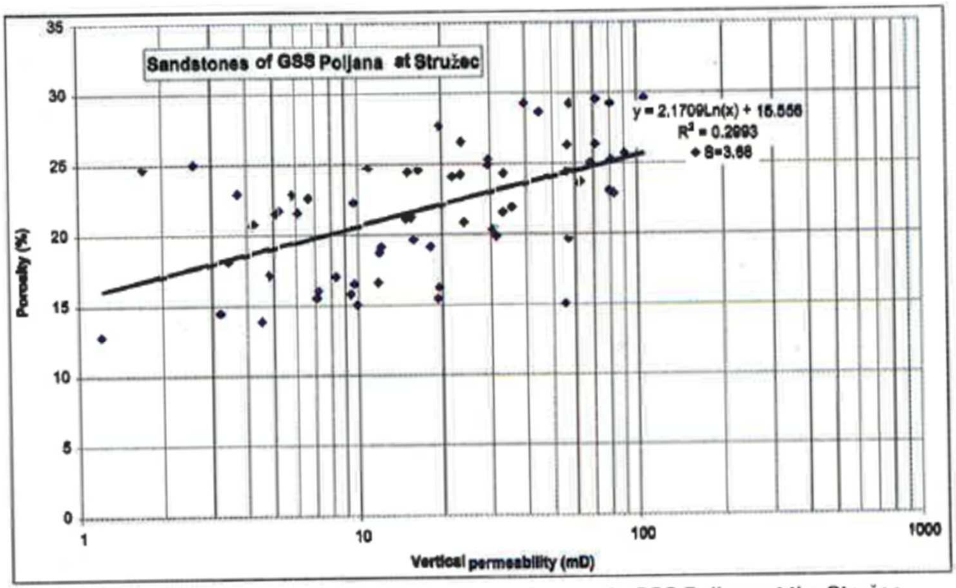

Fig. 11. Porosity vs. vertical permeability plot – sandstones in GSS Poljana at the Stružec field
Sl. 11. Odnos šupljikavosti i okomite propusnosti u pješčenjaku GSS Poljana iz ležišta polja Stružec

Figure 2.5 Correlation of porosity and vertical permeability of Poljana Sandstones at the Stružec field (from Jüttner et al., 2000)

Table 2.1 Voloder field reservoirs

Trap (reservoir)	Porosity (%)	Permeability (mD)	Average depth (m)	o/w contact (m)	Layer thickness (m)	Pore volume – HC saturated (m^3)	No of wells in a reservoir
SW	16.5	1.54	-1 885	-1 895	20	308 000	2
NE	17.2	2.13	-1 800	-1 815	20	1 206 000	3

It is worth mentioning that reservoirs of “gamma series” which are of Late Pannonian age can be regarded as more interesting storage objects on the Voloder field site, due to their size and capacity, but they are situated at depth of around 2 500 m which might make them uneconomical, and there are no publicly available data on pressure. It is certain that the pressure has dropped from the initial pressure during the production period that started in 1998, but the decrease cannot be estimated.

2.3. Selected potential of CO_2 storage objects of Mramor Brdo oil filed

Description of the Production unit C of the Mramor Brdo oil field was prepared based on Gaurina-Međimurec et al. (2015) and Matasović (1995).

Oil field is situated on the southern slopes of Moslavačka gora Mt. Main geological features are the two anticlines with very steep antincline limbs (>60°). This is because of the proximity to the main fault area (marginal fault system) in the norhtern part of the Sava Depression. The oil filed itself has four HC accumulations (A, B, C and P, Fig. 4). The described Production unit

C interval belongs to the Kloštar Ivanić Formation. It is comprised of series of sandstone layers from Poljana and Bregi Sandstones members wich are intercalated with marls of Brezine and Graberje units. The thickness of the accumulation is variable troughout the field and ranges from more than 260 m to less than 20 m. In some parts of the structure the sandstones are totally lacking in this interval. Sandstones are dominantly fine grained (0.063-0.125 mm mean grain diameter), they are lithic arenites with poor sorting.

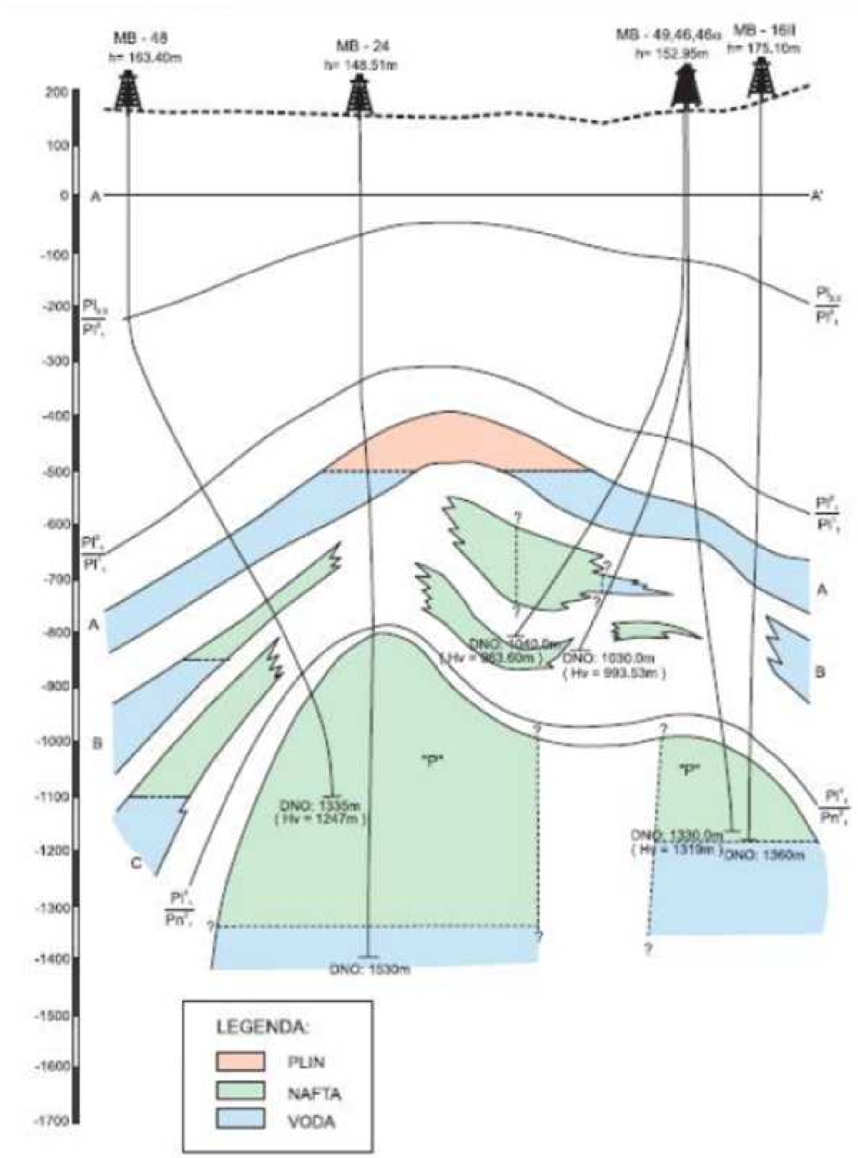

Figure 2.6 Schematic cross-section of the Mramor Brdo oil field (Gaurina-Međimurec et al., 2015)

According to the strucutral map on the top of the Production unit C (from Matošević, 1995), there are three separate oil accumulations/reservoirs (Figure 2.7). Northern accumulation is a dominantly structural trap with small part belonging to stratigraphic pinch out in the shallowest part of the reservoir north of the fault. Central accumulation is the largest by volume and is dominantly a structural trap caused by folding (anticline) with fault barrier on the norhtern flank and stratigraphic pinchout in the central and eastern part. Southern accumulation is a structural trap -structural nose closed by a fault on the eastern part (the here depicted “no reservoir rock area” is most likely a trace of another fault). The characteristics of all three potential storage objects are given in Table 2.2.

Production of oil from the Mramor Brdo oil field began in 1949 with cummulative recovery of approximately 21 % achieved.

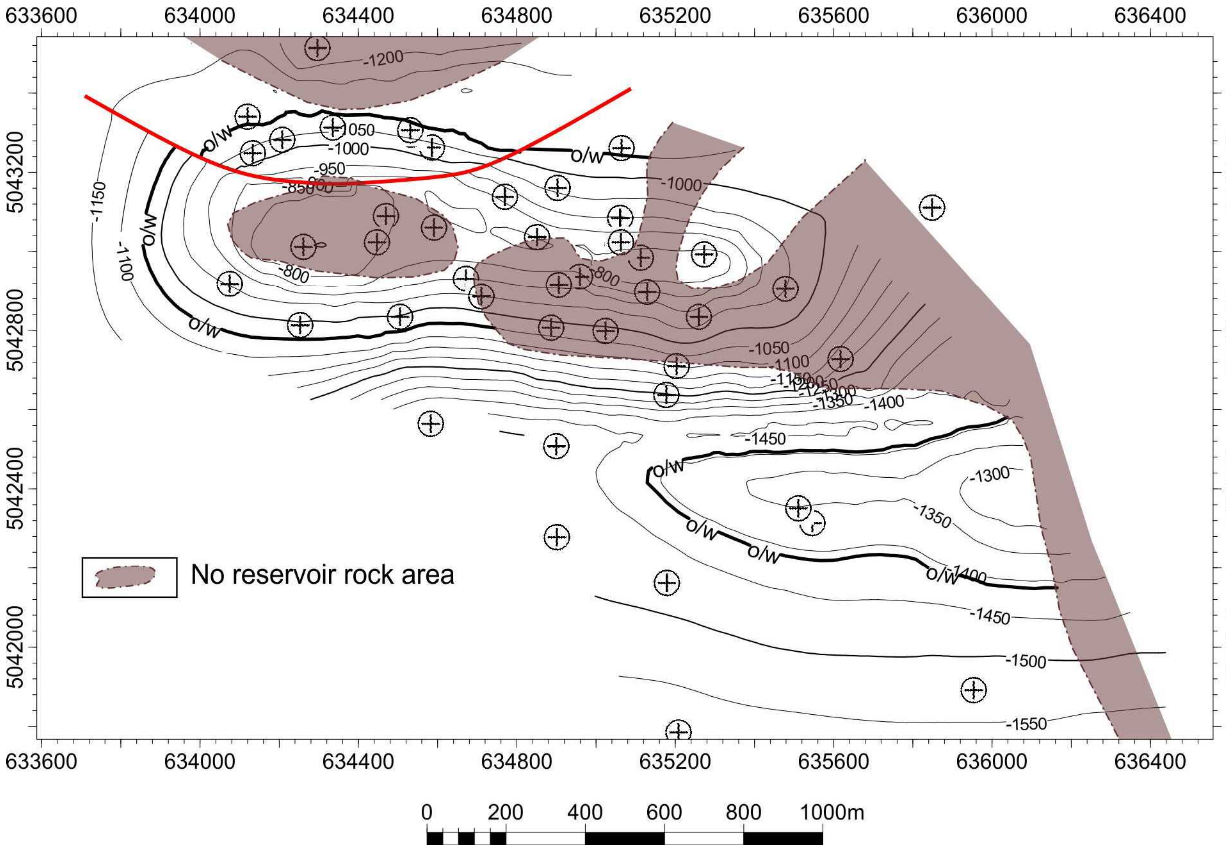

Figure 2.7 Structural map the top of Production unit C (from Matasović, 1995)

Table 2.2 Mramor Brdo field reservoirs

Trap (reservoir)	Porosity (%)	Permeability (mD)	Average depth (m)	o/w contact	Layer thickness (m)	Pore volume – HC saturated (m^3)	No of wells in reservoir
Northern	26.5	154.66	-980	-1 095	25	221 000	5
Central	27.4	234.11	-920	-1 050	32	1 871 000	9
Southern	21.5	15.46	-1 350	-1 410	32	588 500	2

2.4. Petrophysical and fluid data

Due to insufficient data for detailed 3D dynamic study, material balance equation (MBE) was used to assume capacities for CO_2 storage. The MBE is adequate for matching the produced volumes and general properties of a reservoir, with an assumption of homogeneous petrophysical and fluid properties (so called *box model*). Minimum required data for such analysis are:

- Reservoir pressure and temperature
- Average effective porosity
- Average absolute permeability
- Total reservoir volume (i.e. total volume of oil saturated rock above the water-oil contact)
- Reservoir depth
- Effective reservoir thickness (i.e. the average thickness of oil saturated hydrodynamic unit)
- Compressibility of rock, brine and oil
- Density of oil and gas (at standard conditions), formation volume factor and gas solution ratio at initial reservoir pressure and temperature
- PVT properties of oil and respective petroleum gas (gas composition, bubble point pressure and temperature, pressure dependent viscosities, densities, oil and gas formation volume factors and gas solution ratios)
- Relative permeability table for water-oil system and for gas-oil system.

Reservoir pressure is assumed as 1.05 hydrostatic pressure and temperature is calculated according to the regional average geothermal gradient (45°C/1 000 m). Porosity is given in Table 2.3. Due to the lack of laboratory data or well-test data, and by using the analogy from similar formations in the same region, reasonable assumption is that permeability can be correlated with porosity. Permeability data actually do not affect the total CO_2 storage capacity (or recoverable oil reserves estimates). It is only for dynamic observations that feasibility of oil recovery is better estimated if reservoir permeability is taken into an account.

Calculation included radial inflow equation, but that part only assumes the dynamics of oil recovery.

Fluid properties are calculated by correlations:

1. Glaso (1980) - for oil saturation pressure, formation volume factor and solution gas to oil ratio
2. Standing (1981) - for volumetric properties of gas (Z – factor)
3. Relative permeabilities re calculated by using generalized Brooks and Corey (1964) equation.

MBE is coupled with radial inflow equation, and later, algorithms developed within ESCOM project[2] were used to assess changes of recoveries and pressure versus time, and also to recommend the moment for CO_2-EOR, and to estimate additional oil recovery, and eventually the higher storage capacity from CO_2 utilisation and storage, compared to CO_2 storage after oil production.

[2] https://escom.rgn.hr

2.5. Analysis of CO_2 storage capacity sensitivity to average brine saturation in oil reservoir and oil recovery

The analysis results are summarized in Table 2.3.

Table 2.3. CO_2 storage capacity estimates for all selected reservoirs

Reservoirs	Initial oil saturation	CO_2-EOR	CO_2 storage (CO_2 injection rate = 0.3 Mt/year]		
		CO_2 retention (permanent storage) during CO_2 EOR [t]	Cumulative oil recovered [m³]	CO_2 stored [t]	time of injection [day]
Voloder SW	S_{oi} = 1	64 961.30	51 158.77	46 497.02	56.61
	S_{oi} = 0.75	49 210.70	38 756.64	35 225.01	42.89
	S_{oi} = 0.5	32 803.80	25 837.76	23 483.34	28.59
Voloder NE	S_{oi} = 1	245 810.10	199 740.86	175 400.73	213.55
	S_{oi} = 0.75	186 217.30	151 318.84	132 879.34	161.78
	S_{oi} = 0.5	124 141.50	100 879.22	88 586.23	107.85
Mramor Brdo - Southern	Soi = 1	96 351.50	85 189.79	57 130.71	69.56
	S_{oi} = 0.75	72 990.20	64 537.72	43 280.84	52.69
	S_{oi} = 0.5	48 655.50	43 025.15	28 853.89	35.13
Mramor Brdo - Central	S_{oi} = 1	219 483.50	256 439.09	74 257.96	90.41
	S_{oi} = 0.75	168 151.40	194 272.04	56 256.03	68.49
	S_{oi} = 0.5	109 479.30	129 514.69	37 504.02	45.66
Mramor Brdo - Northern	S_{oi} = 1	27 510.10	30 701.43	10 171.08	12.38
	S_{oi} = 0.75	20 837.60	23 258.66	7 705.36	9.38
	S_{oi} = 0.5	8 271.60	23 258.66	7 705.36	9.38
Total (all reservoirs)	S_{oi} = 1	654 116.50	623 229.94	363 457.49	442.51
	S_{oi} = 0.75	497 407.20	472 143.90	275 346.59	335.23
	S_{oi} = 0.5	323 351.70	322 515.48	186 132.84	226.62

It should be noted that the analysis was conducted only for those reservoirs where publicly available data exist. Both fields (Voloder and Mramor Brdo) contain more reservoirs with larger pore volumes (Table 2.2).

Linearity between the CO_2 storage capacity and initial oil saturation is presented in the following figures (Figure 2.8 and Figure 2.9).

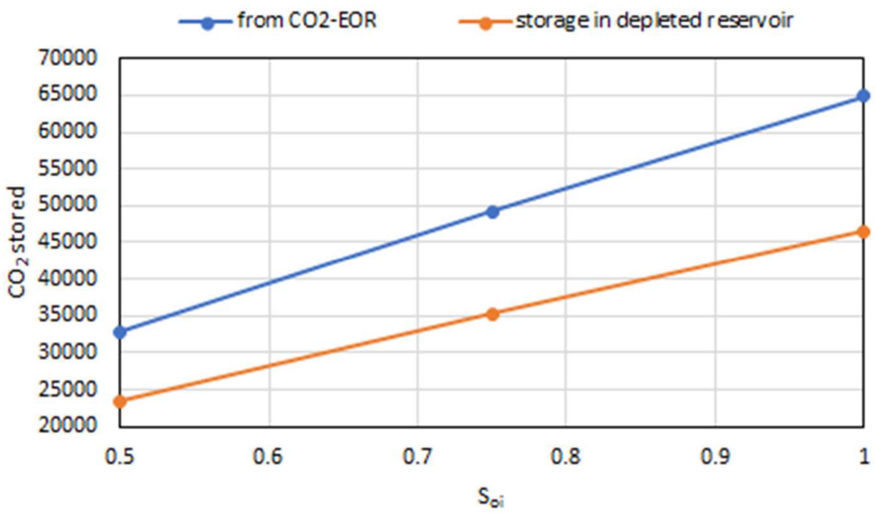

Figure 2.8 Example of S_{oi} vs CO_2 storage capacity linearity for Voloder SW

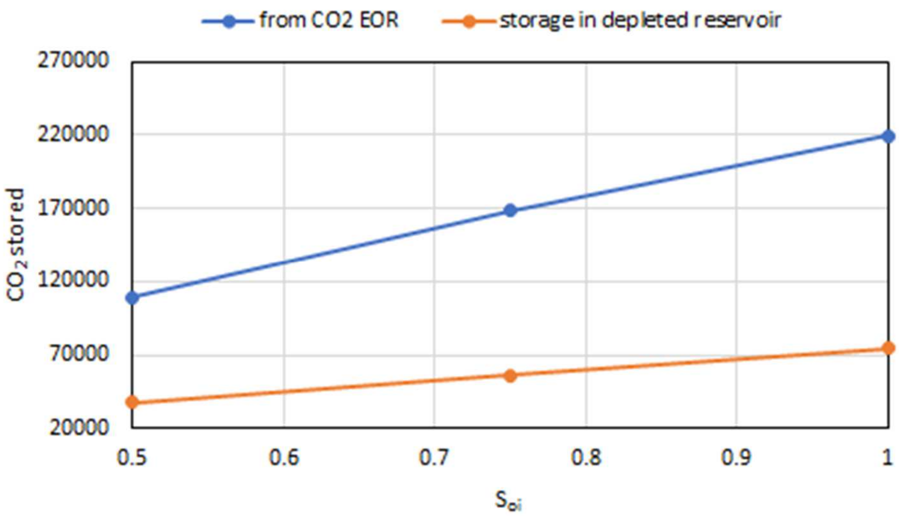

Figure 2.9 Example of S_{oi} vs CO_2 storage capacity linearity for Mramor Brdo - Central

Some examples of sensitivity of storage capacity estimates to fluid properties (Mramor Brdo Northern, S_{oi}=0.5) are given in Appendix 1. Petrophysical properties, like relative permeability table etc. should be at least matched with reservoir production data, to narrow ranges of possible values.

Sensitivity analysis for simultaneous change of a wide range of parameters (uniformly distributed) is performed for a given range of values (Figure 2.10):

- Initial oil saturation: Soi = [0.85, 0.8, 0.75, 0.7, 0.65, 0.6, 0.55, 0.5]
- Reservoir temperature (°C): Tr = [40, 45, 50, 55]
- Relative density of gas (air=1): gama_g = [0.62, 0.66, 0.7, 0.74]
- Relative density of oil (water=1): gama_o = [0.78, 0.82, 0.87, 0.92]
- Saturation (bubble point) pressure (bar, reservoir pressure = 102 bar): Pb = [95, 98, 102]

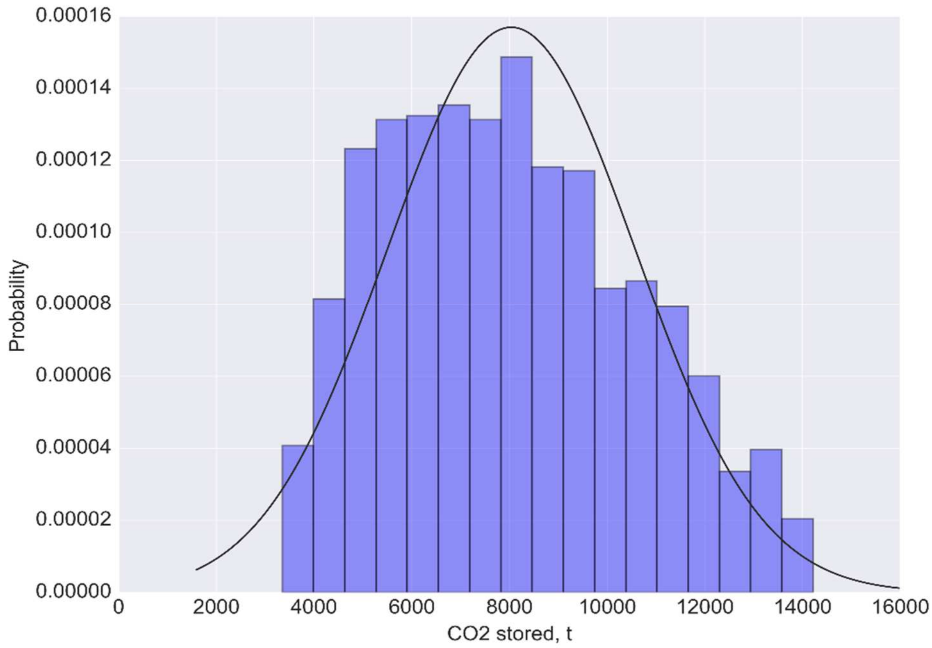

Figure 2.10 Probability of CO_2 storage capacity for different reservoir settings (Mramor Brdo - Northern, S_{oi}=0.5)

Figure 2.10 shows a wide range of possible storage capacities with maximum value of 14 216.4 t, and minimum value of 3 349.6 t. In this analysis, after 1 536 calculations, P values (P10=90th, P50=50th and P90=10th are percentiles) are: P10 = 11 616.9 t (optimistic), P50 = 7 853.8 t, and P10 = 4 813.3 t (pessimistic).

3. INJECTION PROJECT CONCEPT

After comprehensive analysis of possibilities to decrease CO_2 emissions to the atmosphere from the *Petrokemija* two nearby oil/gas reservoirs were taken into consideration as well as the ongoing project of EOR in the oil fields Ivanić and Žutica, situated a bit further away from the factory.

The project concepts are presented in the following chapters.

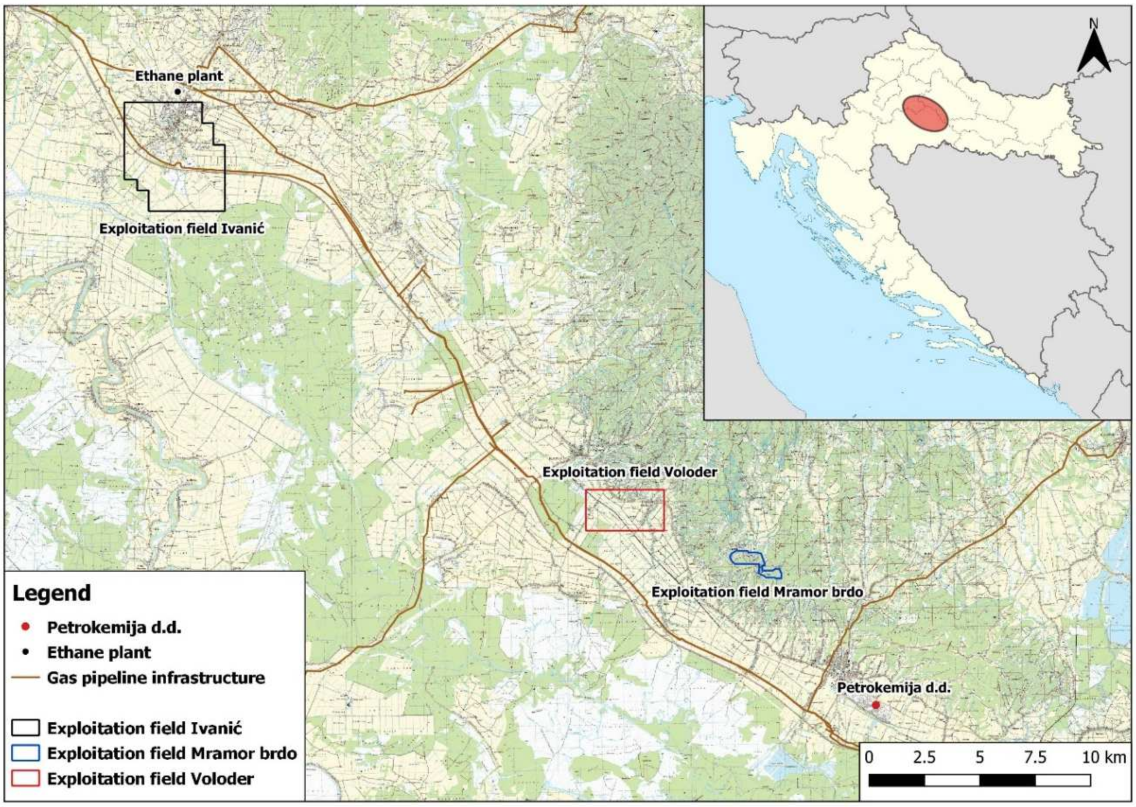

Figure 3.1 Situation map of CO_2 source and potential injection fields

3.1. CO_2 storage as part of the EOR project

Area of Sava depression is well known oil and gas production area for decades. One of the large oil fields is Ivanić, situated in the close vicinity of Ivanić Grad, a town located only 40 km east of Zagreb, and about 45 km from Kutina to the southeast. Citizens have learned to live with oil industry and actively participate in the field development for decades. About 10 years ago, EOR project was established at this oil field in order to enhance oil production by injecting CO_2 and water as a WAG process. For the purpose of that project, extensive explorations were done, and large number of monitoring devices were installed throughout the town in order to ensure the safety of the citizens.

Further developments at the oil production site requires additional amounts of CO_2. Therefore, having a CO_2 source close to the oil production site, along with some available infrastructure is definitely a benefit for all sides involved:

- for Petrochemical industry that can decrease its CO_2 emissions;
- for oil company that can get needed amounts of CO_2 for a reasonable price,
- for the local community that can prosper from new development in local industry, and
- for the country to decrease industrial CO_2 emissions and present one of the few CCUS projects in Europe and region.

The project design basis will include the major facilities provided as follows:

1. **CO_2 supply system** will be located in *Petrokemija*, at Ammonia production facility.
2. **Transport system** is comprised of 2 segment of CO_2 pipeline. Part of the pipeline that connects Ammonia production facility (cca 3 km) to the existing natural gas pipeline (currently not in operation) from Kutina to Ivanić *Ethane* facility near the Ivanić oil field. As both pipelines are not in use for some time they need to be tested and refurbished if needed. There is a need for build a short connecting pipeline (3 km) between the one within the *Petrokemija* Kutina factory and the gas pipeline point.
3. **Injection system** exists in the Ivanić field therefore will not require any specific work or activities.
4. **Monitoring system** exists and covers the area of the oil field Ivanić as well as whole City of Ivanić-Grad.

3.2. CO_2 storage in depleted oil and gas fields

A number of oil and gas fields, of various sizes were discovered and put in production in the Sava depression. Some of the smaller fields have already reached its economic viability and production has ceased. These are the objects that can be considered as a potential CO_2 storage sites, if the conditions in certain field are favourable for CO_2 injection.

In the scope of this project, two of oil fields, Voloder and Mramor Brdo, were analysed as potential CO_2 storage, as they are located near the petrochemical plant. They might serve as pilot sites, where additional research could be conducted, and according to the results sites might be put into operation. In case of favourable conditions, they might even upscale to demonstrational or industrial CO_2 storage sites.

The project design basis will include the major facilities provided as follows:

1. **CO_2 supply system** will be located in *Petrokemija*, at Ammonia production facility.
2. **Transport system** to the fields should be built, whereby part of the existing gas pipeline that is not currently in operation can be used.
3. **Injection system** would most probably include refurbishment of existing wells, sealing of wells that are not needed for the project, and additional testing.
4. **Monitoring system** needs to be designed, built and tested.

4. SOURCES OF CO_2

The petrochemicals industry has evolved out of oil and gas processing by adding value to low value by-products, which have limited use in the fuels industry. The industry produces a wide range of useful products, such as plastics, synthetic rubber, solvents, fertilisers, pharmaceuticals, additives, etc. which have important applications in almost all areas of modern society. The petrochemicals industry uses raw materials from refining and gas-processing and converts them into valuable products using a variety of chemical process technologies.

This pilot considers CO_2 emissions from Ammonia facility where natural gas is used as the main feedstock.

Ammonia (NH_3) is a stable, colourless gas at ordinary temperatures. It is very soluble in water, and its solubility decreases with increasing temperature. Ammonia is one of the largest chemicals manufactured from hydrocarbons. It is the main element in the value chain for producing fertilizers such as urea fertilizer, ammonium nitrates, ammonium phosphates, and a wide range of industrial applications, such as synthetic resins, polyurethanes, and refrigeration.

Ammonia is synthesized from hydrogen contained in natural gas and nitrogen contained in air, and urea is synthesized from ammonia and carbon dioxide coming from ammonia facility.

Annual CO_2 quantity available for injection amounted to 180 000 t. Average quality of CO_2 gas at the outlet of Ammonia plant is presented in the following table.

Table 4.1. Average quality of CO_2 gas available for injection

% (v/v)	Average value
CO_2	92,5
H_2O	6,6
H_2	0,70
CH_4	0,00
N_2	0,19
Ar	0,01

5. ASSESSMENT OF THE FEASIBILITY OF THE PROJECT

Two basic concepts of the feasibility of the CO_2 storage project has been analysed in this study. With the aim of assessing the profitability of the investment, an estimate of investment and operating costs were made for each of the analysed scenarios. The assessment of the profitability of the investment was carried out using a dynamic discounted cash flow (DCF) model. In addition to the defined input parameters such as the value of the investment, the amount of CO_2 injection, the operating costs, the price of the emission units, the calculations of the cost-effectiveness indicators such as the net present value (NPV), the pay-back period of the investment and the internal rate of return (IRR) are calculated.

Scenario 1 assumed the use of CO_2 within the existing EOR project in Ivanić Grad (described in Chapter 3.1). CO_2 produced on the Ammonia production plant (*Petrokemija*, Kutina) is transported by pipeline to *Ethane* plant in Ivanić Grad, where it is further compressed to 200 bar and liquefied and after that injected through existing wells in the scope of existing EOR project. Distance from CO_2 source in Kutina to compressor in Ivanić Grad is about 45 km. For the transport of CO_2, a part of an existing gas pipeline that is not currently in operation would be used, and one part of the new pipeline should be built.

Structure of the investment costs according to Scenario 1 is given in the next table. Investments do not include investing in injection wells since the injection of CO_2 will be carried out through the existing injection wells.

Table 5.1 Structure of the investment costs according to Scenario 1

	Investment costs (EUR)
Petrokemija location (Kutina)	
Compressor 0-5 bar	1 000 000
Compressor 5-30 bar; 200 000 m3/day	2 000 000
Dehydration	1 000 000
Auxiliary equipment	1 000 000
Construction work and materials	3 000 000
Pipelines	
Petrokemija - MRS Kutina (replacement)	1 000 000
MRS Kutina - Ethane Ivanić Grad (conversion)	3 000 000
Ethane location (Ivanić Grad)	
Compressor 25 - 200 bar	2 000 000
Construction work and materials	1 000 000
TOTAL	15 000 000

The average annual amount of CO_2 from *Petrokemija* that is available for injection equals to 180 000 tons. Scenario 1 envisages injection of a maximum available annual quantity of 180 000 tons over the observed lifetime of the project of 20 years (2021-2040). Based on the estimated amount of CO_2 available for the injection and the required equipment, assessment of operating costs was made as shown in the following table.

Table 5.2 Structure of the operational costs according to Scenario 1

Maintenance costs of pipeline	1 200	EUR/km/year
Maintenance costs of equipment	0.8%	%/investment
Number of employees	5	
Gross annual salary per employee	25 000	EUR/year
Energy cost	60	EUR/MWh
Petrokemija (2MW, 7500 hour/year)	900 000	EUR/year
Ethane (0,5MW, 7500 hour/year)	225 000	EUR/year
Charges related to wells	0.2%	%/investment
Charges related to pipeline	0.5	EUR/100t/km
Other variable costs	10.0%	%/(energy+maintenance+ employee costs)

Within the project feasibility analysis, it is assumed the use of own resources in the amount of 35% of the total investment costs and loans of 65% of the total investment with an annual interest rate of 5% and a repayment period of 10 years.

In cost-effective analysis, the avoidance of the CO_2 charge for the amount of CO_2 injected in the oil field is calculated as a revenue. For the needs of national energy-climate plans, the European Commission has prepared the recommended prices of emission units by 2050. Given that the current market prices of emission units show higher values than those recommended by the EC, corrections have been made and alternative price trend has been estimated by 2030. The prices of emission units used in the cost-benefit analysis are shown in the following figure.

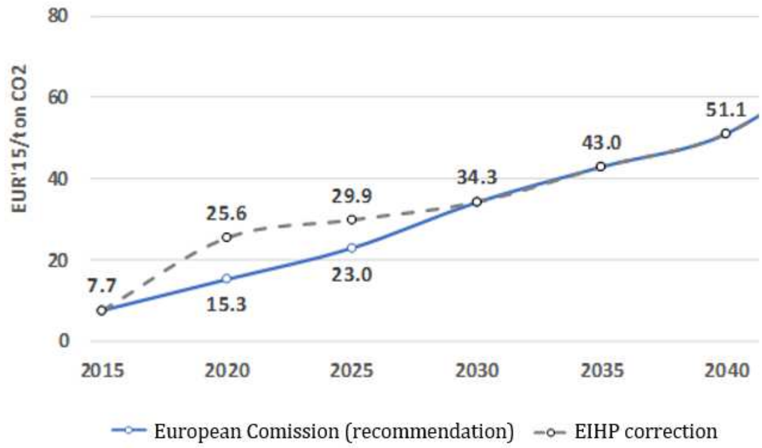

Figure 5.1 Expected prices of emission units by 2050
Source: EU Reference Scenario 2016 and EIHP analysis

Oil and gas revenues generated as a consequence of CO_2 injection were not taken into account given that at this stage of the project development there was not sufficient data for a high-quality estimate of these quantities.

Investment feasibility indicators calculated on the basis of previously presented input parameters are shown in the table below. The results obtained by the DCF method show that the payback period of the project equals to 5 years with the net present value of 17.3 million EUR. The internal rate of return of the project equals to 23%. The obtained results indicate that there is a basis for further detailed analysis of this investment scenario.

Table 5.3 Project feasibility indicators according to Scenario 1

IRR – Internal rate of return	23	%
Payback period	5	years
NPV - Net present value	17.3	Mill EUR

In addition to Scenario 1, storage of CO_2 in depleted oil field located near the CO_2 source are also analysed. This scenario was analysed through two different sub-scenarios (Scenario 2a and Scenario 2b).

Scenario 2a assumed storage of CO_2 in the Voloder and Mramor Brdo depleted oil fields (described in Chapter 3.1.). CO_2 produced on the Ammonia production plant (*Petrokemija*, Kutina) would be transported by pipeline to Voloder and Mramor Brdo fields, where it is further compressed to 200 bar and liquefied and after that injected through existing wells into the reservoir. The distance from the CO_2 source in Kutina to the injection wells in the Mramor Brdo field equals to about 15 km, and to the Voloder field about 19 km. For the transport of CO_2, a part of an existing gas pipeline that is not currently in operation would be used, and one part of the new pipeline should be built.

In accordance with available data, for the purpose of this study, the capacities of only part of the reservoirs in Voloder and Mramor Brdo were analysed in detail. Consistent with the results of analyses, the estimated capacity of the analysed reservoirs is approximately 275 000 t CO_2 (Table 2.3). Given the total size of the oil fields (compared to the analysed reservoirs), and taking into account all reservoir parameters, the total storage capacity was estimated to 1 200 000 t CO_2.

With the 20-year project lifetime, annual quantity of CO_2 injection is assumed to 60 000 tons. Over the first 3 years, CO_2 would have been injected in the Voloder field, and after that in the Mramor Brdo field. The planned first year of injection would be 2023, and the injection would last until 2042.

Structure of the investment costs according to Scenario 2a is given in the next table. The investments included equipping of already existing wells in Voloder and Mramor Brdo fields.

Table 5.4 Structure of the investment costs according to Scenario 2a

	Investment costs (EUR)
***Petrokemija* location (Kutina)**	
Compressor 0-5 bar	600 000
Compressor 5-30 bar; 100 000 m3/day	1 200 000
Dehydration	600 000
Auxiliary equipment	600 000
Construction work and materials	1 800 000
Pipelines	
Petrokemija - MRS Kutina (replacement)	650 000
MRS Kutina - *Ethane* Ivanić Grad (conversion – cca 35%)	960 000
Pipeline (MRS Kutina - Ivanić Grad) - Mramor Brdo	1 100 000
Pipeline (MRS Kutina - Ivanić Grad) - Voloder	650 000
Mramor Brdo location	
Compressor 25-200 bar	1 000 000
Construction work and materials	2 000 000
Injection well (equipping)	1 000 000
Voloder location	
Compressor 25-200 bar	1 000 000
Construction work and materials	2 000 000
Injection well (equipping)	1 300 000
TOTAL	**16 460 000**

The average amount of CO_2 from *Petrokemija* available for injection equals to 180 000 tons, but due to the limited total capacity of the field, the annual CO_2 injection of 60 000 t is assumed over the observed lifetime of the project of 20 years. Based on the estimated amount of CO_2 and necessary equipment, assessment of operating costs was made as shown in the following table.

Table 5.5 Structure of the operational costs according to Scenario 2a

Maintenance costs of pipeline	1 200	EUR/km/year
Maintenance costs of equipment	0.8%	%/investment
Number of employees	10	
Gross annual salary per employee	25 000	EUR/year
Energy cost	60	EUR/MWh
Petrokemija (0,8MW, 7500 hour/year)	360 000	EUR/year
Ethane (0,3MW, 7500 hour/year)	135 000	EUR/year
Charges related to wells	0.2%	%/investment
Charges related to pipeline	0.5	EUR/100t/km
Other variable costs	10.00%	%/(energy+maintenance+ employee costs)

Within the project feasibility analysis, it is assumed the use of own resources in the amount of 35% of the total investment costs and loans of 65% of the total investment with an annual interest rate of 5% and a repayment period of 10 years.

As a revenue in cost-effective analysis, the avoidance of the CO_2 charge that is injected in oil field is included. The prices of emission units used in the cost-benefit analysis are the same as in Scenario 1 (Figure 5.1).

Investment feasibility indicators calculated on the basis of previously presented input parameters are shown in the table below. The results obtained by the DCF method show that the payback period of the project equals to 18 years with a negative net present value of the project of -7.4 million EUR. The obtained results indicate that the project is not economically viable and that investing in the analysed option is not justified. The main reason for these results is the relatively small capacity of analysed fields, primarily the Voloder field, which, with the anticipated quantity of 60 000 t/year can be operational for only three years.

Table 5.6 Project feasibility indicators according to Scenario 2a

IRR – Internal rate of return	2	%
Payback period	18	years
NPV - Net present value	-7.4	Mill EUR

Given the negative results obtained for Scenario 2a, a new Scenario 2b was developed and analysed.

Scenario 2b envisages, like Scenario 2a, the storage of CO_2 in the Voloder and Mramor Brdo fields, but with a higher amount of annual CO_2 injection (80 000 t/year) with a total project lifetime of 15 years. The total amount of the investment as well as unit operating costs are equal to Scenario 2a.

The initial year of CO_2 injection was shifted to 2026, and the injection would have been completed by 2040. In this way, the implementation of the project was shifted to period of higher prices of emission units (Figure 5.1).

The result of the feasibility analysis according to Scenario 2b are more favourable in relation to Scenario 2a, but still with the negative net present value of the project. Payback period equals to 11 years, with a negative net present value of -2.2 million EUR. The internal rate of return of the project equals to only 7%.

Based on the results obtained for all three scenarios, it can be concluded that reservoir capacities, annual CO_2 injection capacity and price of emission units have a very important role in the overall profitability of such projects. It is also important to point out that the obtained results are a good basis for further and more detailed research is the way forward in implementation of such projects.

6. POTENTIAL IMPACT OF THIS PILOT

In the field of the geological storage of CO_2, a 'pilot' project is one that has a research objective and where less than 100 000 tons of CO_2 are injected into the subsurface, typically over a few years (Martinez et al., 2013). Although CO_2 geological storage is well advanced from a technological point of view, research based on real field sites is now strongly needed in order to maximize the efficiency of these technologies, to optimize the tools needed for monitoring and verification, and to be able to adapt to the specificity of local geological conditions. Pilot projects can thus benefit investment decisions for deployment of CO_2 capture and storage in the foreseeable future.

There are many processes involved when analysing the impact that proposed project will have on environment and a community. For CCS technology, we can mitigate these adverse impacts from three aspects: project planning, investment, and operation.

When analysing community impact of CO_2 geological storage projects, trust has been identified as a critical component for any project to be positively accepted in a community. This can be achieved with a team of project representative, technical experts, government and/or local community representative and environmental non-government organisational representative. Their goal should be to increase awareness and understanding of a proposed project and to facilitate ongoing communication and effective working relationships between project staff and the community as the project evolves.

In Kutina, the location of petrochemical plant, the project is not expected to have any impact on community, since the city lives with the factory for decades. Similar situation is in Ivanić Grad, which is quite near the Ivanić and Žutica oil fields, no impact is expected on the community since oil production and its development is ongoing for several decades and community is used to live near the production activities and facilities. The EOR project is already ongoing for several years, and the city is well equipped with a number of monitoring devices for CO_2 detection for population protection.

Environmental impact in the capture part of the project is limited to compressor leakage since CO_2 is collected from the CO_2 removal system (Benfield process) and needs no specific facility for capture.

Another impact in Kutina might be related to construction of pipeline, but that is highly dependable on the project details. The impact would be of limited time period, i.e. of the time of construction. As in Ivanić Grad, most facilities are already in place, impact connected to construction of compressor station is expected. In the area of Voloder and Mramor Brdo oil/gas fields the impact would be limited environmental impact of pipeline construction, for the well reconstruction or adjustment, and construction of compressor station if necessary. This impact will be temporary and limited to the area of construction only.

The greatest environmental risk associated with CCS relates to the long-term storage of the captured CO_2. Leakage of CO_2, either gradual or in a catastrophic leakage, could negate the initial environmental benefits of capturing and storing CO_2 emissions and may also have harmful effects on human health. On the other hand, CCS has the long-term potential to make a substantial positive impact on the amount of CO_2 emitted into the atmosphere by the stationary energy sector. Therefore, the potential risks need to be weighed against the potential benefits, and also the possible consequences of inactivity.

As already stated above, in the area of oil field Ivanić, in the scope of ongoing EOR project the potential leakage is highly covered with large number of installed monitoring devices, whereas in the areas of Mramor Brdo or Voloder oil/gas fields they should be installed.

Transport of CO_2 from *Petrokemija* to the storage site can be conducted by pipeline or by trucks. Even though pipeline transport is considered safer, road transport by trucks might be considered acceptable in cases of oil fields Voloder and Mramor Brdo that does not have a ready and strategic access to pipeline facilities or if the expected quantity of captured CO_2 would not justify the building of a new pipeline. Road transport may be considered for projects at a scale suitable for proving a concept, but it is unlikely to be adopted as the transport option for long-term large-scale projects.

There is always present some degree of risks and hazards to people during transport of CO_2 regardless of its destination (e.g., either to another industrial application as a commodity or to storage and final sequestration), if improperly handled.

This pilot is expected to have an important economic impact on both companies involved - *Petrokemija* as a provider of CO_2, and INA as end-user.

Petrokemija is currently paying the fee for CO_2 emissions counted from the volume of natural gas used in a factory. When the project becomes operational the emissions of CO_2 will decrease drastically. Therefore, *Petrokemija* should be exempted to some degree of paying CO_2 fee according to its avoided emissions.

Exploration and production company INA could benefit through having a chance to have a steady supply of CO_2, in the vicinity of its facilities where it can be used in EOR activities or stored for a certain fee. Furthermore, it will profile the company as a leader in CO_2 utilization and storage in this part of Europe, providing increased knowledge on the matter.

The impact is also expected in development of new projects in Croatia. Providing information to key stakeholders on project results and outcomes, will affect other organizations in the future to get involved and to include CCS in their business plans.

Transferring successful project results and initiatives to appropriate decision makers in regulated local, regional or national systems can contribute to improving future policy and practice so it can adapt to the needs of others and transfer to new areas of interest.

Transfer of results can contribute to:

- strengthening awareness
- spreading effect
- involvement of stakeholders and target groups
- exchange of solutions and skills
- impact on politics and practice
- developing new partnerships.

The results can affect the project, end users, associates, or policy makers, i.e relevant stakeholders including:

- positive effects on the reputation of participating organizations
- increased awareness of the subject, goal or area of work
- greater financial support from other donors or donors
- greater influence on politics and practice.
- potential adjustments of legal framework and regulations.

7. STAKEHOLDER MAPPING IN THE REGION

Stakeholders are all persons or groups or organisations that have interest or concern in a project. In this regard, stakeholders of a CCUS project in a region are specific companies as well as government and local communities.

CCUS projects are very complex and understanding public perceptions towards them and knowing how to effectively engage and communicate with relevant stakeholders is crucial to successfully deploying the technology. The life-cycle of a CCUS project contains many phases, different levels of development and varying stakeholder involvement. Understanding how to navigate through this life-cycle by appropriately involving stakeholders is important.

Stakeholders are sometimes divided into primary stakeholders, or those who have a direct stake in the project and its success, and secondary stakeholders, or those who may be very influential, but whose stake is more representational than direct[3].

Stakeholders	
Primary	Shareholders and investors Employees and managers Customers Local community Suppliers and other partners
Secondary	Government and regulators Civil institutions and associations Activist groups Media and academic Trade bodies Competitors General public

Government and community are secondary stakeholders, because they are more interested in the organization's impact on the community rather than having a direct stake in the

[3] https://www.stakeholdermap.com/primary-stakeholders.html

organization's success. They don't have any direct engagement with a company but can still be influential.

Stakeholders regarding this project are listed in the following table.

Table 7.1 Stakeholder table

Stakeholder		Group	Individual	Level of interest			Level of influence		
				Low	Med	High	Low	Med	High
Primary	Petrokemija	Stakeholders and investors; Supplyers and other partners	CEO; Head of Ammonia unit; Employees			√			√
Primary	INA	Stakeholders and investors; Customers	CEO; CO_2 project manager			√			√
Primary	Local Community	Local Community	Mayor, Local residents; Business owners	√					√
Secondary	Ministry of environment and energy	Government and regulators	Minister of environment and energy			√		√	
Secondary	Environmental Protection and Energy Efficiency Fund	Civil institutions and associations	Representatives of the environment sector			√			√
Secondary	Environmental protection groups	Activist groups	Activists			√		√	
Secondary	Journals, TV, radio	Media	Journalists			√		√	
Secondary	University, schools	Academics	Teachers; Academics, Scientists		√			√	
Secondary	Public	General public	Citizens	√					√

The interest and influence of particular stakeholder is presented in the stakeholder map below (Figure 7.1).

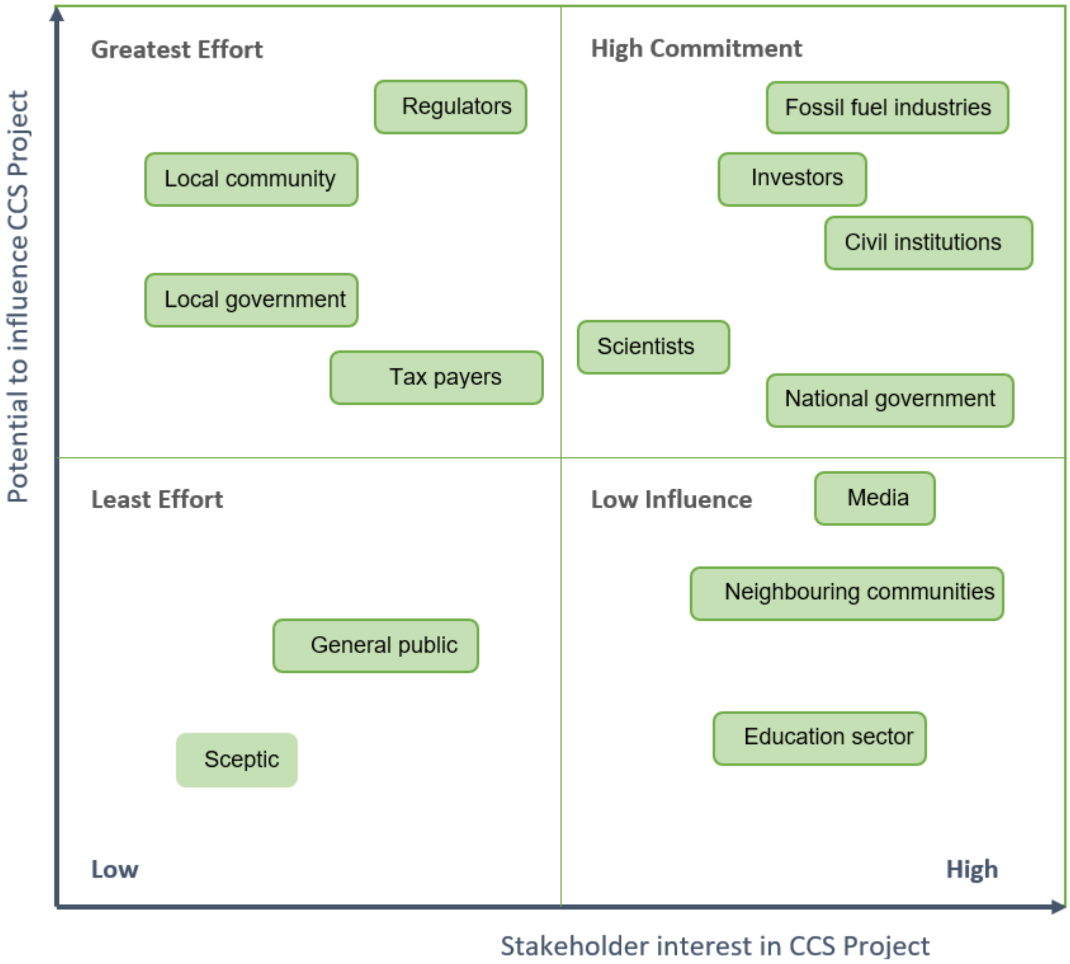

Figure 7.1 Stakeholder map

Analyses of CCS programs set up by governments, that of large scale and pilot and demonstration projects to find out what lessons were learned in the last few decades. Main outcomes show several points to have a successful project (Herzog, 2016):

1. There are strong links between the successful CCS demonstration projects and the oil and gas industry.
2. Access to markets has to move beyond EOR.
3. Regulatory drivers are critical to creating markets for CCS.
4. Business drivers play a major role.
5. Over reliance on government subsidies is a risky business.
6. Successful CCS power projects used multiple financing components
7. CCS projects that have shorter timelines have greater chances of success
8. Stronger political support is needed for CCS.
9. All major CCS demonstration projects require a public outreach program.

8. PROVISIONAL TIMELINE AND FUNDING OPPORTUNITIES

This chapter will include possible timeline for realization of proposed pilot project and a review of funding opportunities for timely implementation.

8.1. Provisional timeline of the project

Activities in CO_2 storage project are similar to hydrocarbons or geothermal exploration, as they include same or similar techniques and technologies and are all covered by the same law[4]. Such projects are developed in phases due to engagement of experts from different fields in a multidisciplinary research. The phases are mostly long-lasting so the development of the project can last for several years.

Five activity phases of the project can be distinct, where each of them includes activities imposed in CCS Directive[5] and EIA Directive[6], and are summarised in Table 8.1.

[4] Law on exploration and exploitation of hydrocarbons (OG 25/2018)
[5] Directive 2009/31/EC, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0031
[6] Directive 2011/92/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:02011L0092-20140515; Directive 2014/52/EU, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32014L0052

Table 8.1 Life cycle of a CCS project considering obligation settled in the CCS Directive and in the EIA Directive

<table>
<tr><th>CCS Project / activity phase</th><th>CCS Directive (2009/31/EC)</th><th>EIA Directive (2011/92/EU)</th></tr>
<tr><td rowspan="2">Phase 0
Screening criteria for site selection
Planning
Project feasibility evaluation
Local storage risks assessment
EIA Report</td><td colspan="2">Detailed project description
Complete geographic, geological and environmental characterisation of selected site and surrounding area including qualitative risks assessment
Storage complex characterization</td></tr>
<tr><td>Explorations permits request
Development of site-specific monitoring, control and corrective measures plan
Application for storage permit
Requires: EIA full report submitted and approval</td><td>Environment impact
Assessment procedure</td></tr>
<tr><td>Phase 1
Construction and substructures for site testing and operation</td><td rowspan="3">Site specific Monitoring, Control and Corrective
Measures Plan development
Possible environmental impacts as criteria in strategic decision making
Mitigation measures incorporated in the facility design: project review</td><td rowspan="3">Monitoring of significant effects on the environment and effectiveness of the control measures
Quantitative risks assessment: re-evaluation of EIA report</td></tr>
<tr><td>Phase 2
Testing: CO_2 Injection tests</td></tr>
<tr><td>Phase 3
Operation: CO_2 storage at commercial scale</td></tr>
<tr><td>Phase 4
Deactivation: site closure and decommissioning</td><td colspan="2">Maintenance of the specific Monitoring, Control and Corrective Measures Plan
Quantitative risks and impacts recording and evaluation</td></tr>
</table>

Source: Barros et al., 2012

Three different timelines were created, one for each of the analysed scenarios. According to Scenario 1, beginning of the injection is foreseen for 2021 and cost-effective analysis is conducted for period of 20 years (Figure 8.1). However, it is assumed that the CO_2 injection project may continue after 2040 as CO_2 storage project.

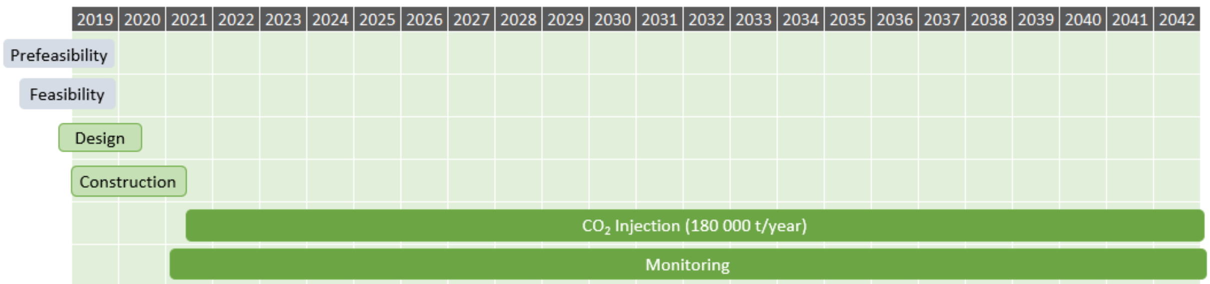

Figure 8.1 Provisional timeline of the project according to Scenario 1

According to Scenario 2a, beginning of the injection is foreseen for 2023 and cost-effective analysis is conducted for period of 20 years (Figure 8.2), with injection rate of 60 000 t/year.

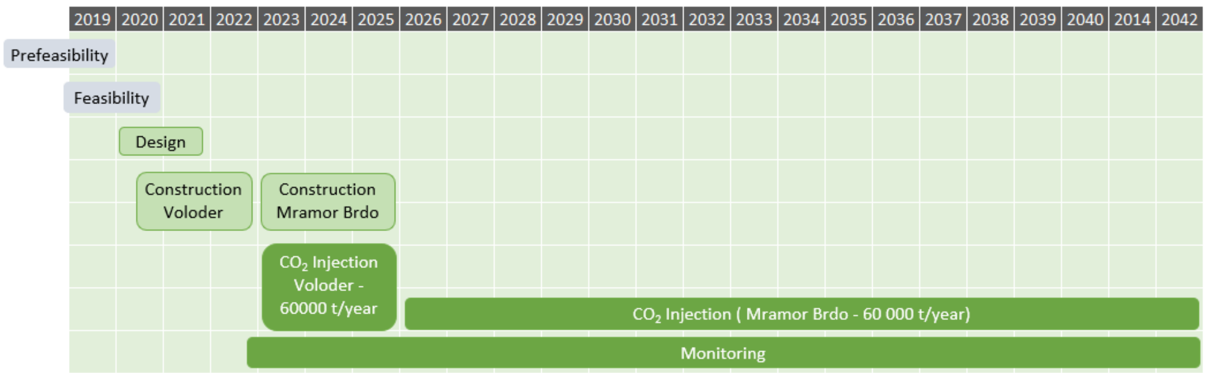

Figure 8.2 Provisional timeline of the project according to Scenario 2a

According to Scenario 2b, beginning of the injection is foreseen for 2026 and cost-effective analysis is conducted for period of 15 years (Figure 8.2), with injection rate of 80 000 t/year.

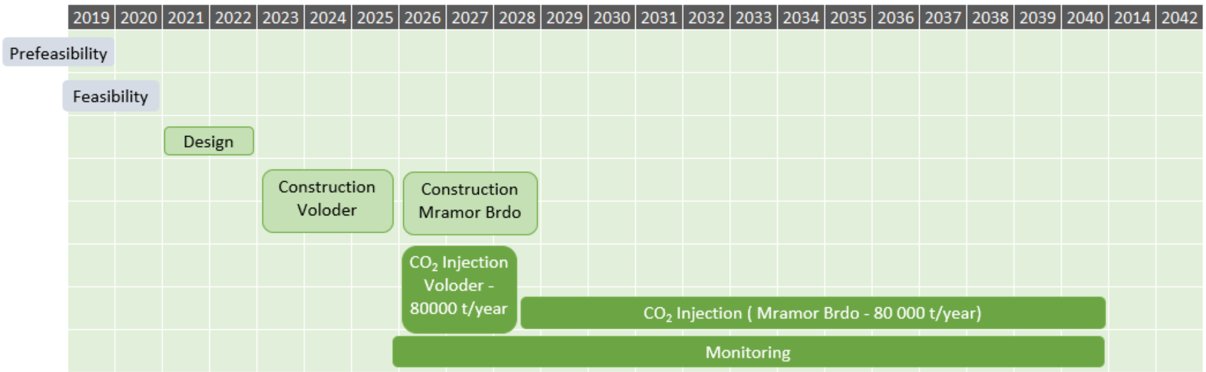

Figure 8.3 Provisional timeline of the project according to Scenario 2b

Table 8.2 Proposed phases of the project with relevant activities

Phase	Activities			
Phase 0	**Regional site studies**	**Examine potential sites**	**In-depth assessment of potential site**	**Prefeasibility study**
	Identify storage areas	Identify specific sites within the area	Social and technical characterization of potential sites	Analysis of potential geological storage projects
	-Review literature -Estimate capacities	-Specific desktop research in relation to locations -Examine approvals and feasibility studies that would be required	-Risk assessment -Examine pre-existing infrastructure -Baseline surveys -Identify critical issues, impacts and benefits to the community through collection of social data	-overview of the project concept, logistics and capital requirements with different scenarios -overview of potential risks and challenges
Phase 1	**Feasibility study**	**Geological storage permitting**	**Pipeline construction permitting**	**Environmental impact assessment**
	Evaluation of the project feasibility	Development of studies required for permitting procedure	Preparatory works for the pipeline construction	Evaluation of the environmental impact of the project
	-development of feasibility study for selected site -Risk assessment of the project -overview of the legal framework	-Collection of relevant data on the selected site -Development of studies required for permitting procedure	-Overview of the route -pipeline design development -preparation of the required studies for building permit	-development of Environmental impact assessment study for geological storage and for the pipeline

Table 8.2. Proposed phases of the project with relevant activities - continued

Phase	Activities			
Phase 2	**Exploration and testing**	**Pipeline construction**	**Compressor station construction**	**Monitoring plan development**
	Geological and petroleum engineering Characterization of the potential site	Pipeline construction activities	Compressor station construction activities	Development of site-specific monitoring, control and corrective measures plan
	-Seismic testing -testing of existing wells -well refurbishment if needed -installation of well equipment	-preparing the route for the pipeline -pipeline construction -cleaning up the construction site -testing	-landfield works -construction of building for compressor -installing the compressor -testing	-analysis of potential risks and impacts -creating measures for risk mitigation -developing controlling activities plan -installing monitoring devices
Phase 3	**Operation**	**Maintenance**	**Monitoring**	

8.2. Funding opportunities

CCUS projects are of vital importance in achieving Paris agreement's objectives. Vision for a clean planet by 2050 includes 7 building blocks. CCS is comprised within 7th building block aiming at rapid deployment of renewable energy and new options to decarbonize industry and reduce the need for CCS. Still, CCS has a crucial role to close the circle for a net-zero economy in energy intensive industries where other alternatives do not exist. On the other hand, if CCS is combined with sustainable biomass it could create negative emissions.

However, CCUS is facing barriers: lack of demonstration plant and proof of economic viability, regulatory barriers in some EU Member States, public opposition etc. and therefore EU has established **Innovation Fund** to spur large-scale demonstration, scale up private investments, provide the right signals to the markets and reassure public opinion. This is the first tool to implement long term strategy for driving low carbon technologies to the market. Regulatory framework was adopted at the end of February 2019. Volume of the Fund will be at least 10 billion EUR at current carbon prices and will be financed from the revenues of the EU Emissions Trading System. The Fund anticipates support of up to 60% of additional costs related to innovative technology and support of additional capital and operating costs (up to 10 years) (Figure 8.4). First call expected in 2020 and regular calls up to 2030. Comprehensive selection criteria and project development assistance will be provided.

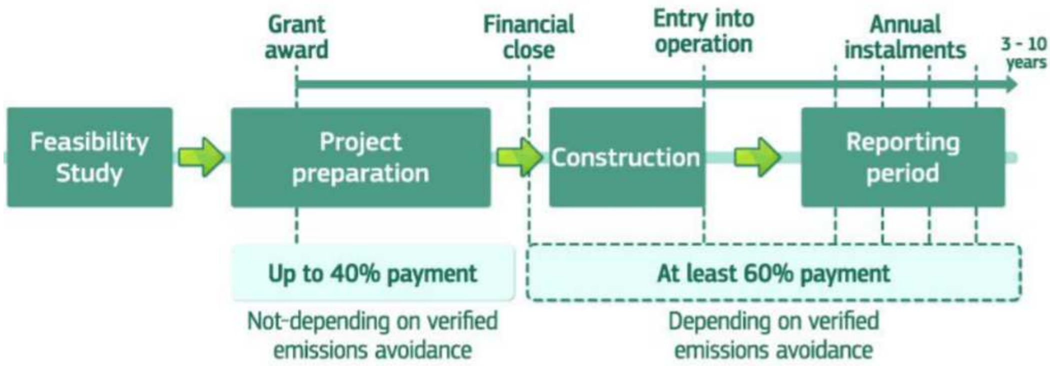

Figure 8.4 Innovation Fund financing

Another possibility of getting the project funded from the EU funds is the next research and innovation framework programme Horizon Europe, 100 billion EUR programme that will succeed Horizon 2020. Focus will be on research and innovation missions for cancer, climate, oceans and soul.

Within the Operational Program Competitiveness and Cohesion 2014-2020 the Republic of Croatia has available 6.8 billion EUR, out of which 4.3 billion EUR from the European Regional Development Fund (ERDF) and 2.5 billion EUR from the Cohesion Fund (CF). Within operation programme an announcement of Scheme for strengthening applied research for adaptation measures to climate change is expected with available 34.2 million HRK. Projects will be co-financed with up to 3 million HRK non-refundable funds.

National funding opportunities could include public procurements by the Environmental and energy efficiency fund through LIFE 2019 program subsidies to companies within subprogram Climate activities. for pilot and demonstration projects. Projects will be co-funded up to 55%, and available amount is 3.46 billion EUR. The projects will be financed with amounts up to 3 million HRK.

Beside non-refundable fund, there are European bank for research and development, European investment bank and other commercial banks.

9. PROJECT RISK ASSESMENT

This chapter will assess risks in early phases of the project (policy, permitting, health, safety and environment) as well as in development and construction.

Permitting

According to Law on exploration and exploitation of hydrocarbons (OG, 25/2018), the procedures for CO_2 sequestration are very similar to those for hydrocarbon or geothermal waters exploration and production. The permitting procedure duration is always an issue due to amount of relevant documentation needed, but skilled staff can prepare it in a reasonable time.

Policy

There is a clear correlation between the number of projects and incentives from the governments. Changes in policy can significantly influence the project development and completion, so the consistence of supportive policy is of the essence.

In Croatia, the Government generally supports CCS through policy documents, strategies, laws and regulation but the initiative to develop CCUS projects is coming from different companies and institutions. Still, the Ministry of environment and energy seems cooperative and there is a support to this project in all aspects.

Construction risk

Construction, in terms of this project refers to construction of pipelines, compressor stations and required secondary facilities.

The risks lie in possible delay of construction works or failure to achieve the required quality and functional requirements. Considering large construction works on pipelines in the last decades, building companies have proven to be experts in this area, and to be able to deal with all challenges ahead.

Health and safety

Carbon dioxide, CO_2, is at standard conditions a colourless, odourless gas, undetectable to human senses and with a density about 60% higher than that of dry air, so it accumulates in low-lying areas. Humans have a certain tolerance for carbon dioxide; it is indeed one of the products from our metabolism and normally present in our blood but will in higher concentration become harmful or even lethal.

At atmospheric pressure carbon dioxide may only exist as a gas or in solid form; the sublimation temperature is at -78.5°C. However, CO_2 intended for injection will for technical and economic reasons mostly be compressed into liquid or even supercritical form before transportation.

There are some potential environmental risks associated with CCS technology, most particularly in terms of potential leakage of CO_2 from storage sites. The environmental risks associated with CCS can be categorized as local risks — effects caused by high, localized concentrations of CO_2 resulting from leakage; and global risks — effects on the global climate due to low-level CO_2 leaked back into the atmosphere over the longer term.

Carbon capture, conditioning and compression facilities in an industrial plant, are generally located in confined areas. This is the case in *Petrokemija* factory, where the Ammonia and UREA facilities are located within the fertilizer factory. The release of excess CO_2 is regular part of technological process of ammonia production and does not represent any danger to the people nor animals.

However, one of the major and most serious environmental challenges posed at the local level is water contamination. The IPCC report (2005) on CCS outlines the risk of water supply contamination due to leakage either through a major structural failure of the carbon well, or over time due to an undetected geologic fault allowing the CO_2 to migrate into water zones. Such contamination of a water supply would have a secondary impact on aquatic plant life and any other life forms that use the groundwater, or aquifer, as a source of drinking water. In concentrated exposure, such CO_2 contamination can be lethal to plant and animal life. Remedial measures are available, but intercepting CO_2 leakage prior to aquifer contamination is essential. Once contamination occurs, techniques for contamination removal are very expensive (IPCC, 2005).

Experience in monitoring the activity of naturally occurring deposits of CO_2, in transporting hydrocarbons via pipeline for many years and in the injection and storage of CO_2 over the past 10-15 years, means that the risk of adverse and harmful outcomes from CCS is minimal[7].

Many of the risks typically associated with infrastructure projects are well understood and are routinely addressed through compliance with applicable standards and regulations, sound engineering and design, proper planning, use of proven technologies, and application of best practices.

[7] http___www.aphref.aph.gov.au_house_committee_scin_geosequestration_report_chapter5%20(1).pdf

Ensuring the protection of local aquifers, and the structural integrity of carbon injection sites, must be an integral component of CCS projects. This applies to the planning and operation phases of projects, as well to abandonment procedures, which must ensure that abandoned wells are not susceptible to failure after their usage period and that human health is not affected as a result.

The risks associated specifically with CO_2 can be mitigated in part by adopting technologies proven in other applications, by applying expertise and knowledge gained from these other areas as well as from carbon sequestration pilots and current research and development, and by selecting appropriate site(s) for project infrastructure. Successful completion of early projects will contribute to addressing some of the challenges to further full-scale carbon sequestration by providing information to governments to support regulatory and policy decision-making; by encouraging investment and take-up by industry as reliability and economics are proven; and by increasing public buy-in as the safety and effectiveness of the technology is demonstrated and communicated.

Table 9.1 Specific risks associated with capture of CO_2

Capture risk	Probability of occurrence	Direct and indirect consequences of the event occurrence	Risk level	Impact level
Malfunction of compressor station	Very low (controlled by mitigation measures)	Increase of concentration of CO_2 in the air	Moderate	Significant but mitigable

Table 9.2 Specific risks associated with transport of CO_2

Transport risk	Probability of occurrence	Direct and indirect consequences of the event occurrence	Risk level	Impact level
Malfunction of compressor station	Very low (controlled by mitigation measures;	CO_2 leakage, pipeline rupture	Moderate	Significant but mitigable
Pipeline rupture	Very low (controlled by mitigation measures; selection of suitable material and operating conditions)	Increase of CO_2 concentrations and impurities surrounding of a failed pipeline	Moderate	Significant but mitigable

Table 9.3 Specific risks associated to the CO_2 storage

On-shore storage risk	Probability of occurrence	Direct and indirect consequences of the event occurrence	Risk level	Impact level
Overpressure in the reservoir due to CO_2 injection and storage	Very low (controlled by mitigation measures; limitation of injectivity and CO_2 flow pressure)	- Rise of hydrostatic pressure in the reservoir: displacement of brine (saline aquifers) or other fluids (as CH4, from coal seams) - Activation of micro fractures and /or faults as a result from hydrostatic pressure elevation - Temporary or definite lack of capacity of the reservoir: Impossibility of further CO_2 injection in the site - Selection of other CCS unit or inactivity (Closure of the CCS unit)	Moderate	Irrelevant to Significant but mitigable
Migration of CO_2 into neighbour geologic formations	Very high (expected behaviour of CO_2 plume)	- Lateral and/or descendent diffusion of CO_2 from the storage complex into neighbour formations (the caprock - top sealing rock layer is, by definition, impermeable to CO_2) - -- CO_2 reactive processes with minerals of neighbour geologic formations (secondary trap mechanisms occurring at long-term storage)	Very Low	Irrelevant
Migration of CO_2 into neighbour aquifers	Very low (screening criteria for site selection excludes locations near aquifers)	- Dissolution of CO_2 into the water, possible pH decrease and water acidification -Reaction of CO_2 with other water dissolved substances - Potable water contamination with impurities (from the CO_2 stream such as H_2S)	Very High	Significant not mitigable
Leakage of CO_2 into the atmosphere from storage complex through: 1. Caprock 2. Injection wellbores 3. Abandoned well bores	1.Unlikely (containment criteria for site selection)	- Possibility of CO_2 entry into the caprock due to integrity failure (caused by unexpected geologic events such as an earthquake) - Possibility of CO_2 to find a way through the overburden to the subsurface, ground waters or even the atmosphere	Acute	Significant not mitigable
	2. Low and 3. Low (continuous monitoring of wells during operation and post-closure phases; mitigation and remediation plans)	- Flow of fluids along the well (CO_2 and possibly also brine) caused by: - failure of well integrity or improper sealing of an injection well - degradation of well cement, casing or plugging after long-term storage period - Eventual penetration of CO_2 leaking flow into the subsurface, ground waters or even atmosphere	Moderate to Very High (depends on CO_2 flow rate through well)	Significant but mitigable
Soil and ground water disruption after long-term storage	Not yet determined (requires further data from tests and field experience from existing CCS units)	- Possibility of ground movement and fracture through induced micro seismicity and stress - Possibility of groundwater circulation disturbance caused by fracturing activation or expansion -Possibility of uplift or subsidence of layers caused by overpressure of the reservoir	Acute	Unknown (but probably not mitigable)

Risks Level: Very Low → Low → Moderate → High → Very High → Acute
Impact level: **Irrelevant** → Significant but mitigable → Significant but not mitigable

Source: Modified after Barros et al., 2012

10. CONCLUSION

The key goal of CCS is to achieve an environmental benefit by removing a large quantity of CO_2 from the earth's atmosphere and, in doing so, help redress some of the problems associated with climate change.

Potential environmental risks are mostly associated with potential leakage of CO_2 from storage sites. However, experience in monitoring in the injection and storage of CO_2 over the past 10-15 years, means that the risk of adverse and harmful outcomes from CCS is minimal.

The proposed Pilot study of selected reservoirs (i.e. potential storage objects) of the Voloder and Mramor Brdo oil fields is interesting from several aspects. Detection and monitoring of CO_2 migration across the fault could be tested on the NE potential storage object of Voloder oil field and it would be especially convenient for testing migration of CO_2 through the fault between the Northern and Central potential storage objects on Mramor Brdo. The advantageous circumstance for both oil fields is existence of wells that could be used as monitoring wells. All studied reservoir sandstones are interlayered with marls, so it is interesting to test the possible effect of pressure response induced by injection. Interaction between the reservoir rock and fluids could be investigated by means of geochemical monitoring (through baseline analyses of reservoir fluids and comparison with results of continuous analyses of fluids from monitoring wells).

The reservoir engineering estimates that are given here a merely an example of variations in reservoir and fluid properties might affect the eventually achievable estimated CO_2 storage capacity. In the first case when these reservoirs are included in the CO_2 EOR operation and in the second case if they are used only for geological storage of CO_2.

The given geological setting and resulting models do not allow any significantly larger capacities to be estimated in the reservoirs that were studied here, but one should take note that bot fields contain also vertically stacked additional reservoirs with similar rocks pertaining to other Upper Miocene units. These were not analysed here because of the lack of publicly available data and any estimates simply cannot be given without thorough additional study by preparing the models starting from the raw data. It can only be reasonably assumed that on both fields additional potential storage objects exist which would result in up to 5 times higher total capacity estimates. This study might be prepared in the second phase, again including geological models and then also maybe dynamic reservoir engineering models.

According to the results of the analysed scenarios, Scenario 1 that foresees the use of CO_2 within the existing EOR project shows better financial results than Scenarios 2a and 2b that assume CO_2 storaging in depleted oil/gas fields. The basic factor that has a beneficial effect on the feasibility of the project is the capacity of the reservoir or the annual injection capacity of CO_2. Regardless of the unfavourable results of cost-effectiveness analysis of Scenarios 2a and 2b, it is necessary to make more detailed analyses of these scenarios and to explore the possibilities that would enable the realization of this type of projects.

Table 10.1 Comparison of the results for the analysed scenarios

Scenario	IRR	Payback period	NPV
	%	years	Mill EUR
Scenario 1	23	5	17.3
Scenario 2a	2	18	-7.4
Scenario 2b	7	11	-2.2

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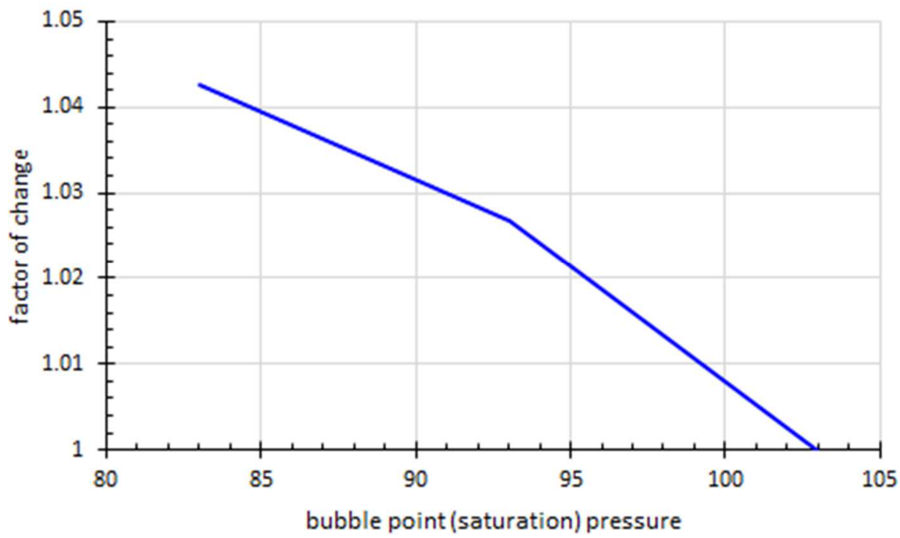
12. LIST OF TABLES

13. LIST OF FIGURES

APPENDIX 1

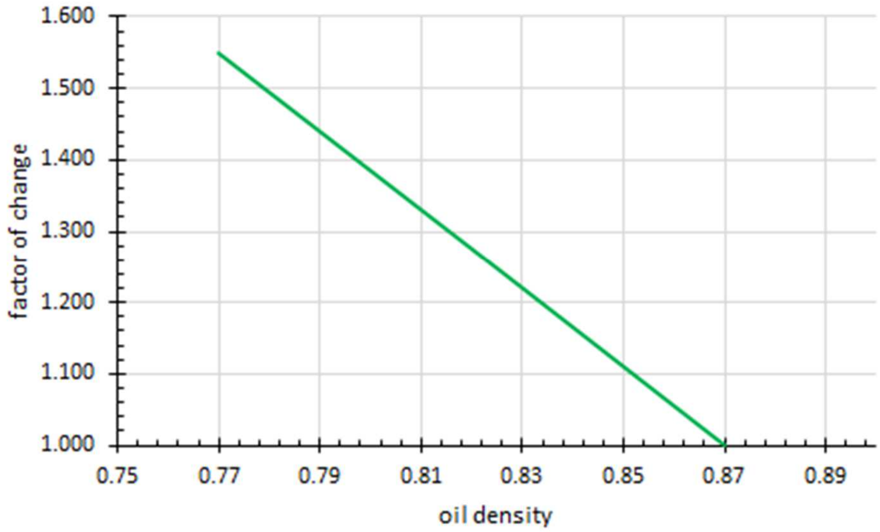
A1.1. Sensitivity to saturation pressure (bubble point pressure)

Sensitivity to saturation pressure is non-linear. For respective reservoir (Mramor Brdo Northern, S_{oi}=0.5), from initial estimate (p_b=103 bar), storage capacity might be 4.3 % higher (factor of change = 1.043 @ p_b = 83 bar) if p_b = 83 bar.



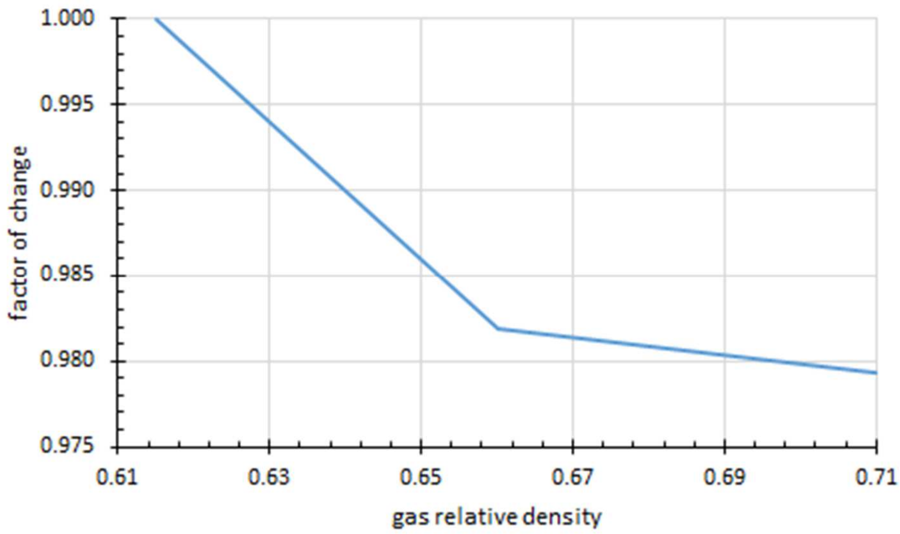
A1.2. Sensitivity to oil density

By overestimating density of oil, storage capacity is underestimated. Relationship between oil density and storage capacity is linear.



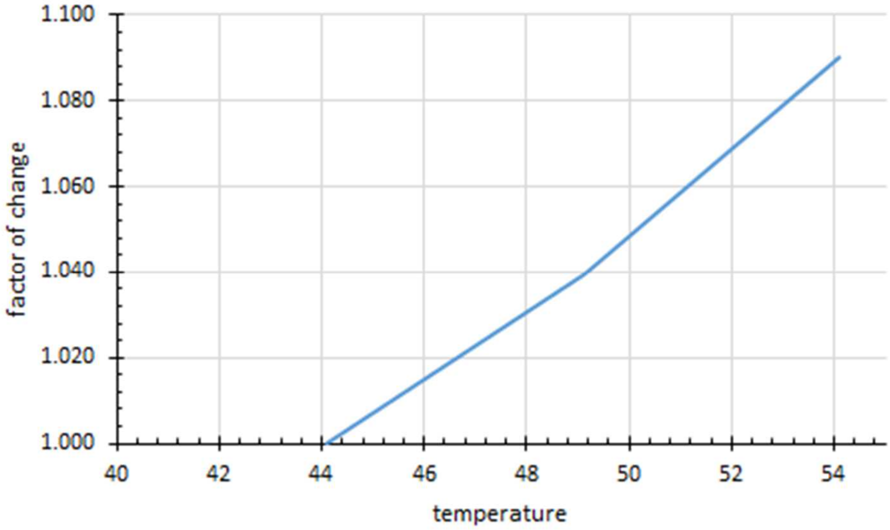
A1.3. Sensitivity to gas relative density

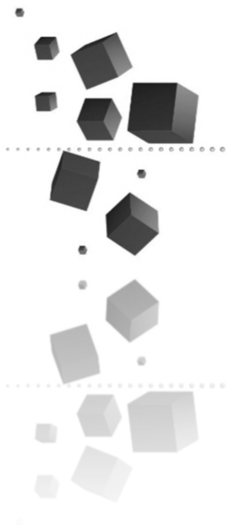
By overestimating density of gas, storage capacity is underestimated. Relationship between gas density and storage capacity is non-linear.



A1.4. Sensitivity to reservoir temperature

By overestimating reservoir temperature, storage capacity is overestimated. Relationship between oil density and storage capacity is almost linear.





ENOS
Enabling Onshore CO_2 Storage

A CO_2GeoNet Initiative

ENOS Future Pilots
New pilot and demonstration project opportunities in Europe
Havnsø, Kalundborg, Denmark
Author: Niels E. Poulsen, GEUS, nep@geus.dk

Project name Project website Project number	ENOS http://www.enos-project.eu Grant Agreement No 653718

Introduction

In order to successfully deploy commercial CCS with onshore storage across Europe, a series of pilot projects needs to be developed and realized, preferably in a variety of geographical and geological settings across the continent, followed by largescale demonstration projects. Additionally, the experience gained from existing pilots needs to be maximised through knowledge sharing and identifying analogous sites where the lessons learned can be most effectively applied to catalyse the next generation of successful onshore storage projects.

• Establishing partnerships and sharing experience and knowledge with groups and entities executing CO_2 storage pilots, demonstration projects and leakage simulation tests worldwide;

• Liaising and exchanging knowledge with other pilot and demonstration projects in Europe across the full pilot/ demonstration lifecycle (planned-operational-closed);

• Identifying success criteria that can be applied to create a catalogue of potential situations where new storage sites might be successful;

• Paving the way for pilot sites in the ENOS project portfolio to further develop beyond the end of the project through planning of follow-up stages of their development and/or upscaling to a larger amount of stored CO_2

• Preparing a Roadmap for upscaling identified synergies of CO_2 storage with CO_2 utilisation

Context

Existing pilot and demonstration sites enhance confidence in the ability of geological formations to safely store CO_2 on a regional basis and local demonstration of CCS technology will encourage further project development. So far, onshore storage has been tested and demonstrated only at a few pilot sites in Europe (i.e. Ketzin, Lacq-Rousse, and recently Hontomín), which is deemed insufficient. A ZEP/CGS Europe study identified several promising opportunities for possible onshore storage pilots across Europe, based on proposals by partners with 19 potential onshore locations for pilot projects. There was a limited assessment of the probability of these pilot sites moving forward and as the CCS landscape changes rapidly. This could now be updated and the assessment of the likelihood of these storage pilots moving forward enhanced by considering a wider range of factors including regional circumstances and potential impact, variability of geological settings, comparison with successful projects etc.

Activity

A study focusing on onshore pilot/demonstration project opportunities across Europe (D6.8) will be prepared, delivering on a diverse portfolio of geological settings (covered / not covered so far) and regions with little CCS activity to date.

The study will identify factors that have helped lead to a successful pilot or demonstration site and look for other sites where there is a good chance that success could be replicated. The aim is to seek out areas where the geological setting and other technical factors (e.g. CO_2 sources, infrastructures etc.) are similar to existing successful pilot projects in order to identify regions likely to be favourable for future pilot projects or regions with potential to scale up to demonstration scale. This task will use data from existing pilot sites, key recommendations from other research projects (inter alia EU GeoCapacity, SiteChar, RISCS, CO2CARE, etc.) and build on the CGS Europe 'State of Play of CCS' report and the CGS Europe/ZEP report on potential pilot projects in Europe. A catalogue of the most prospective candidates for second generation pilots will be developed for a few regions that offer the greatest potential. These regions will be selected to provide representative and concise case studies to illustrate the possibilities. Direct links will be established with the ECCSEL Research Infrastructure (https://www.eccsel.org/), to whom ENOS will provide a written recommendation on future opportunities for second generation pilots.

Content

1 LOCATION DATA

The city of Kalundborg situated in Denmark at the north-western coast of Zealand. With a deep-water harbour, the city hosts a refinery and a large coal/oil emulsion fired power plant which is under conversion from coal to wood chips. The potential CO_2 storage site described in this case study is a 4-way domal closure situated at the small city of Havnsø approximately 15 km northeast of Kalundborg (Figure 1; Figure 2). The closure covers an area of approximately 166 km^2 with top reservoir situated approximately 1500 m below sea level (Figure 7). The structure was formed by salt movements in the underlying Zechstein Group and appears unfaulted. The main reservoir consists of siliciclastic sandstones of the Upper Triassic – Lower Jurassic Gassum Formation with a net-sand thickness of 100 m. The reservoir is sealed by around two hundred metres thick succession of marine mudstones of the Fjerritslev Formation (Figure 5; Figure 7). The sandstones are laterally extensive and have been followed throughout most of the Danish Basin although the net sand thickness decreases towards the northwest.

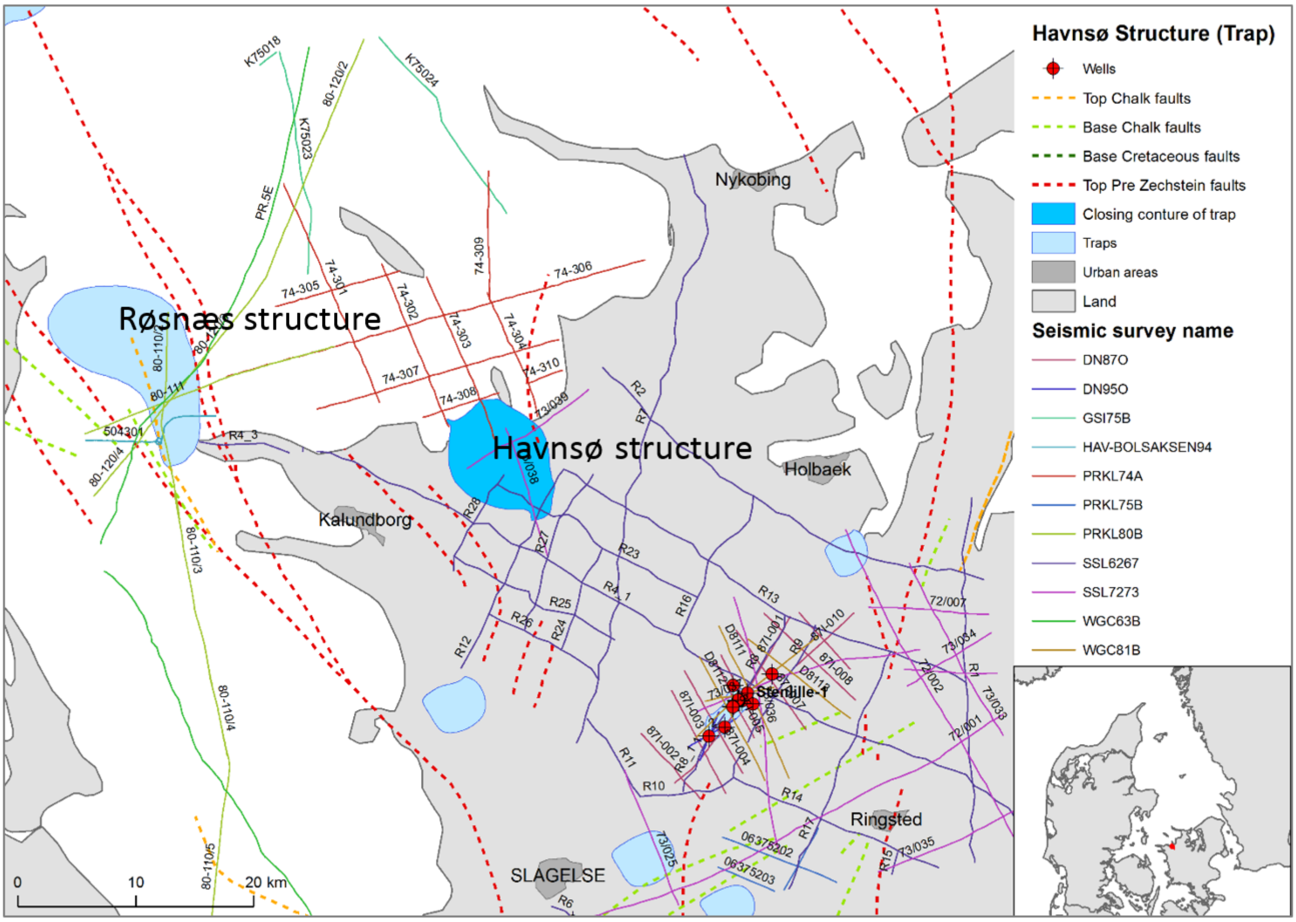


Figure 1: Map of the Havnsø structure showing position of structural trap defining the potential storage site at Havnsø. The structure is interpreted from unpublished seismic maps. A second possible Mesozoic sandstone reservoirs of good quality is the Røsnæs structures; however poorly constrained by the presently available data.

The name Havnsø structure is used for a domal closure at Gassum Formation level situated at the small harbour Havnsø approximately 15 km northeast of Kalundborg (Figure 1). Approximately 1/3 of the structure is situated offshore, with the top point situated onshore. The structure was evaluated as possible natural gas storage in the nineteen-eighties but was excluded for the nearby Stenlille structure (Figure 3).

The structure is situated in the Danish Basin (Figure 3). The sandstones of the Gassum Formation were sourced from the elevated areas towards the northeast, east and southeast. The reservoir quality of the sandstones might be less favourable than in the Stenlille structure (see 4.2 and 4.3) where the formation is well-known. The Gassum Formation has been described in detail by Nielsen et al. (1989), Hamberg & Nielsen (2000) and Nielsen (2003).

This pilot proposal is partially based on the Danish case study during the CO2STORE project (Larsen et al. 2007). The Havnsø pilot will be located near two potential point sources located close to the city of Kalundborg; the coal/biofuel fired power plant Asnæs Power Plant and the Equinor refinery. The Havnsø structure is expected to have sufficient capacity to be up-scaled to a demo-project and even to a full-scale project. The harbour Port of Kalundborg (Figure 2) is one of Denmark's big ports and will allow CO_2 transport by ships to a CO_2 storage site here. The port can accommodate distribution facilities for intermediate storage and conditioning before piping or shipping CO_2 to the storage site.

Figure 2: Port of Kalundborg (https://portofkalundborg.dk/en/first-cruise-ship-at-kalundborg-new-west-port/)

The initial mapping of the storage structure during the EU funded research project GESTCO identified a large underground structure forming a potential, future storage site at Havnsø 15 km to the northeast of Kalundborg. A preliminary calculation suggests a storage capacity of nearly 900 million tonnes of CO_2 equal to more than 150 years of CO_2 emissions from the two point sources. In the case study a fictive capture and storage scenario has been formulated and modelled based on experiences learned through the SACS and GESTCO projects. Detailed geological modelling, reservoir simulation, reservoir and caprock characterisation and risk assessment are important issues in the case study (Larsen et al. 2007). The proposed storage pilot aims at injecting less than 100 kilotonnes by the end of its operation. This quantity is less than the amount of natural gas injected at Stenlille in half a summer month.

2 CONTRIBUTOR

2.1 The Geological Survey of Denmark and Greenland – GEUS

The Geological Survey of Denmark and Greenland (GEUS) is an independent research and advisory institution within the Danish Ministry of Climate, Energy and Utilities.

GEUS carries out activities to exploit and protect geological resources in Denmark and Greenland. Primary activities are mapping, compilation and storage of data, research, monitoring and consultancy within water, energy, minerals and climate and environment. This includes research and technology development in relation to administration of legislation.

GEUS also undertakes assignments related to energy, minerals, water, climate and the environment on a contractual basis for other public authorities, research agencies, private companies and clients outside Denmark.

2.2 GEUS' mission

- GEUS is responsible for scientific exploration of the geology of Denmark and Greenland with the associated continental shelf areas.
- GEUS is to carry out research at the highest international level into matters of significance for exploitation and protection of geological natural resources, and carry out mapping, monitoring, data collection, data management and communication about these.
- GEUS is to provide consultancy services to authorities and the private sector and is to carry out authority tasks within its core areas.
- GEUS is a national geological data centre.

3 CONTACT PERSON

3.1 GEUS

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G E U S

4 GEOLOGICAL DESCRIPTION

4.1 Geological setting of the study area

The Danish Basin (i.e. eastern part of the Norwegian-Danish Basin) was formed by rifting in Late Carboniferous to Early Permian. The basin is bounded to the north-east by the Fennoscandian Border Zone and to the south by the Ringkøbing-Fyn High. The Fennoscandian Border Zone marks the transition to the stable Precambrian Baltic Shield and includes the Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform. Both the Skagerrak-Kattegat Platform and the Ringkøbing-Fyn High is characterised by a relatively thin succession of sedimentary cover (Figure 3; Figure 4).

The Danish Basin is characterised by an up to 9 km thick succession of sedimentary rocks of Late Palaeozoic to Cenozoic age (Figure 3). The sedimentary succession is affected by mainly northwest–southeast striking normal faults. Locally, over salt structures for instance, the succession is deeply truncated. Faults often accompany the salt structures (Figure 4).

The Early Permian rifting phase involved deposition of coarse-grained sediments. Subsequently the Zechstein Sea covered most of the basin and thick deposits of salt were formed. Post depositional flow of Permian salt formed large domal structures, which strongly influenced later deposition (Michelsen et al. 2003; Nielsen 2003).

A several kilometre-thick Triassic succession of sandstones, mudstones, limestones and salt deposits succeeded the Zechstein salt. During the Early Jurassic period deposition of marine sandstones took place at the northern and eastern rim of the Danish Basin and in the central part of the basin marine mudstones were deposited (Michelsen et al. 2003; Nielsen 2003).

The basin including the Ringkøbing-Fyn High and the Skagerrak-Kattegat Platform was uplifted and eroded during the Middle Jurassic period while deposition of sandstones still proceeded in the Sorgenfrei-Tornquist Zone at a slow rate. The basin expanded during the Late Jurassic and the Early Cretaceous, and deposition of sandstones and mudstones resumed. In Late Cretaceous and Danian a reduced topography and rising sea level lead to the deposition of up to 2 kilometres of limestone. The limestone succession was succeeded by deltaic mudstones and sandstones in the Palaeogene period. A regional uplift in the late Neogene caused extensive erosion of the northern and eastern parts of the basin at the same time as accelerating subsidence took place in the central North Sea (Michelsen et al. 2003; Nielsen 2003).

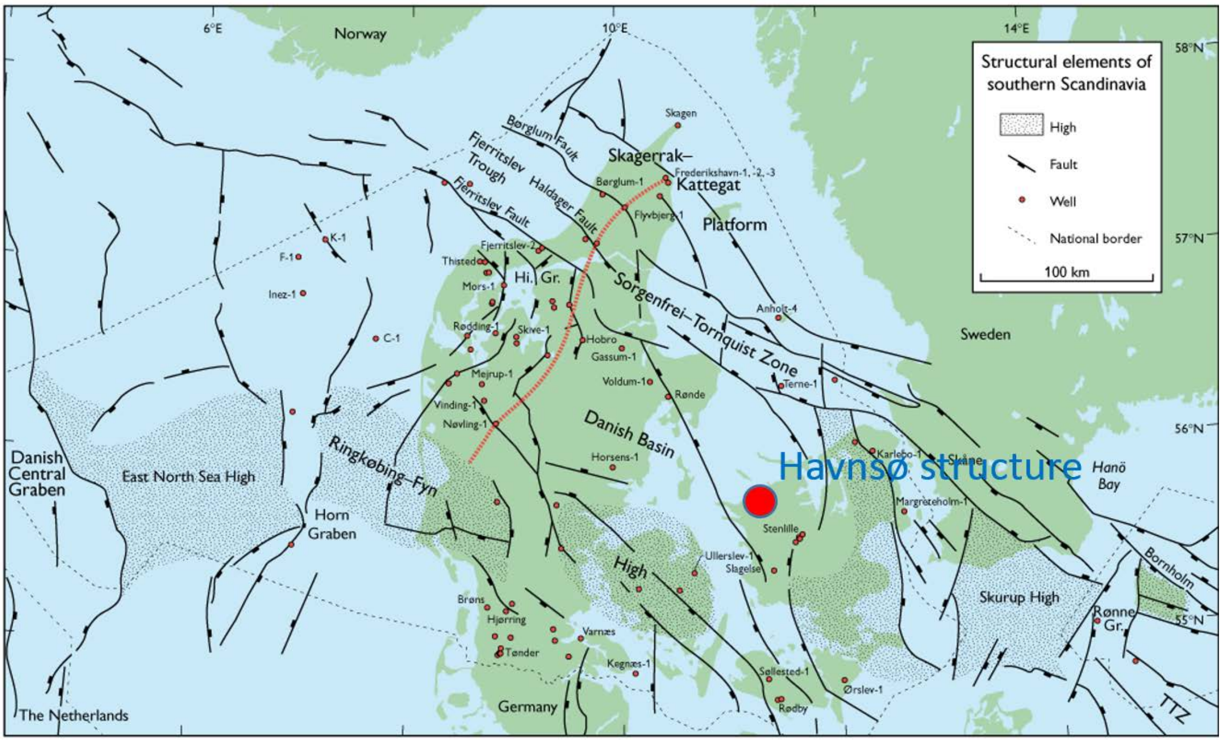

Figure 3: The principal structural elements of southern Scandinavian including the Danish Basin (i.e. eastern part of the Norwegian-Danish Basin), the Sorgenfrei-Tornquist Zone, Skagerrak-Kattegat Platform and the Ringkøbing-Fyn High (Michelsen et al. 2003; Nielsen 2003). Position of geological cross-section shown in Figure 4 is indicated by a red line. The Havnsø Structure is marked by the big red dot.

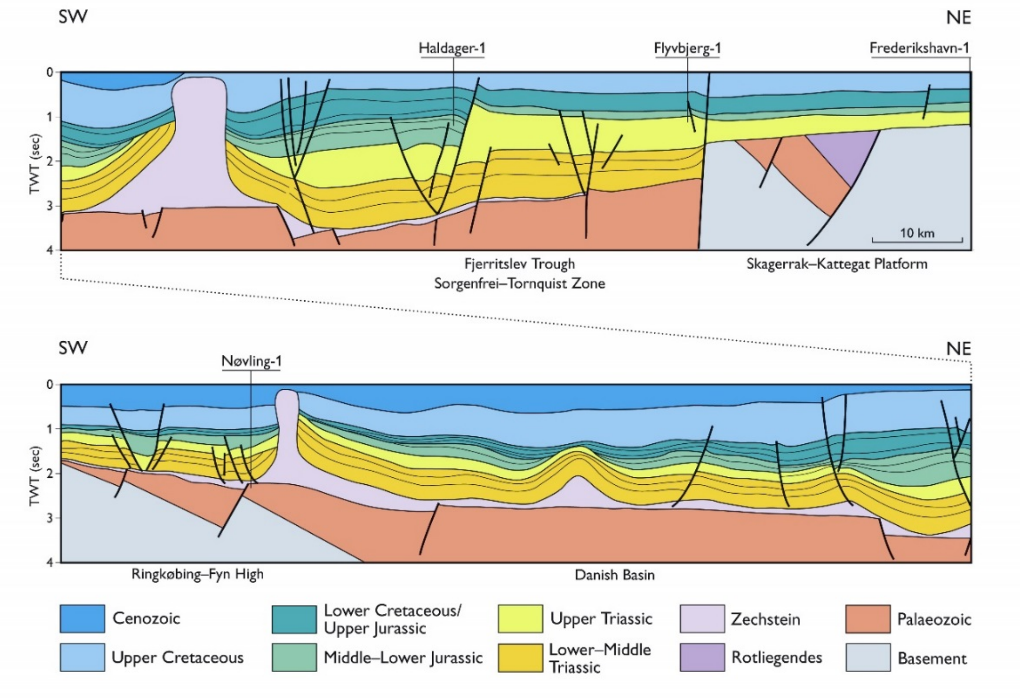

Figure 4: Geological cross-section trending SW–NE across the Danish area from the Ringkøbing-Fyn High (SW) to the Skagerrak-Kattegat Platform (NE). The section illustrates the variation of the salt structures ranging from gentle four-dip domal closures with a fully preserved overlying sedimentary column to salt diapers penetrating most of the Mesozoic succession. The Danish area has several large domal structures with preserved reservoirs and cap rocks (Michelsen et al. 2003; Nielsen 2003).

4.2 Stenlille structure

The Stenlille structure is situated about 40 km south-east of Kalundborg in the Danish Basin (Figure 3) where the storage formation and seal are well-known. The structure is situated in the Danish Basin (Figure 3). The sandstones of the Gassum Formation were sourced from the elevated areas towards the northeast, east and southeast. The reservoir quality of the sandstones might be less favourable than in the Stenlille structure (see 4.2 and 4.3) where the formation is well-known. The Gassum Formation has been described in detail by (Nielsen et al. 1989; Hamberg & Nielsen 2000; Nielsen 2003).

Following the decision in 1979 by the Danish parliament to use natural gas from the North Sea, a transmission network was established in 1981–1984. The primary network, including transmission plant and gas storage facilities, is operated by the state-owned Danish Oil and Gas Company that is also in charge of buying natural gas from the producers. Transmission of natural gas began in 1984 and the throughput of gas has increased steadily since then and is now c. 7.5 billion Nm^3 (volume under 'normal' conditions) per year. In order to buffer the supply of gas to consumers, two natural gas underground storage facilities were established; one in salt caverns at Ll. Torup and the other in a deep aquifer near the town of Stenlille (Figure 3). Storage of natural gas at the two sites started in 1987 and 1989 respectively (Laier and Øbro 2009).

Storage of natural gas in an aquifer therefore appeared to be the most suitable option for the densely populated Copenhagen area. A potential storage site near the town of Stenlille, c. 70 km SW of Copenhagen, was identified using older seismic mapping. Investigations began in 1979 with the drilling of the first deep well into the Stenlille structure. Coring and test-pumping of fluids from the Gassum Sandstone Formation confirmed it's potential for natural gas storage. Six additional wells were drilled for further development of the underground storage that permitted more tests of the future reservoir sandstone as well the caprock above. The storage at Stenlille finally came into operation in

1989 with the large-scale injection of natural gas into the sandstone reservoir, 1500 m below surface (Laier and Øbro 2009).

4.3 Geological setting of the Stenlille structure

The good reservoir quality of the Gassum Formation is known from a number of onshore wells in Denmark. Mapping the extent of this sandstone sequence had been carried out as part of a geothermal energy feasibility study (Bertelsen 1978). The large amount of geological information obtained from drilling and coring the Stenlille structure allowed for a detailed description of the depositional environment responsible for the formation of the Gassum Sandstone Formation (Hamberg & Nielsen 2000). The Gassum Sandstone Formation was formed in Rhaetian times when the Danish Basin was narrow and semi-enclosed. The Danish Basin itself is an intracratonic feature located in the eastern part of the North Sea rift system. It formed as a result of Late Palaeozoic rifting followed by Mesozoic thermal subsidence. The Gassum Formation consists of recurrent interbedded sharp-based shoreface sandstones and offshore marine mudstones interrupted locally by fluvio-estuarine and lagoonal deposits (Hamberg & Nielsen 2000; Nielsen 2003). The Gassum Formation represents part of the general long-term second-order transgression of the Danish Basin, starting from continental to shallow marine deposits of the underlying Upper Triassic sediments, and ending in the overlying fully-marine claystones of the Lower Jurassic Fjerritslev Formation (Bertelsen 1978).

The Fjerritslev Formation, 250–300 m thick, forms the caprock of the sandstone reservoir that holds the natural gas in the Stenlille structure. A number of interbedded thin sand layers exist over the gas reservoir allowing for the efficiency of the caprock to be checked against vertical leakage of gas. The Gassum Formation at Stenlille forms an anticlinal structure with a vertical closure of c. 35 m covering an area of 14 km^2. The structure formed as a result of movements of Zechstein salt forming a pillow approximately 2800 m below surface (Laier and Øbro 2009) similar to the Havnsø structure.

5 STORAGE FORMATION LITHOLOGY/POROSITY/THICKNESS

5.1 Potential reservoirs

The formations with the most promising potential for CO_2 storage in Denmark are the Bunter Sandstone Formation (the Ljunghusen Formation in Sweden is regarded as equivalent to the Bunter Sandstone Fm by GEUS), the Skagerrak Formation, the Gassum Formation, the Haldager Sand Formation and the Frederikshavn Formation (Figure 5).

The Upper Triassic–Lower Jurassic Gassum Formation is present in the Danish Basin, the North German Basin and on parts of the Ringkøbing-Fyn High in the Lolland Falster area (Figure 6). It shows a remarkable continuity with thickness between 100 and 150 m throughout most of Denmark and reaches a maximum thickness of more than 300 m in the Sorgenfrei-Tornquist Zone. The Gassum Formation is truncated by the base Cretaceous unconformity on the Ringkøbing–Fyn High and it provides the best storage possibility in the Havnsø area (Michelsen et al. 2003).

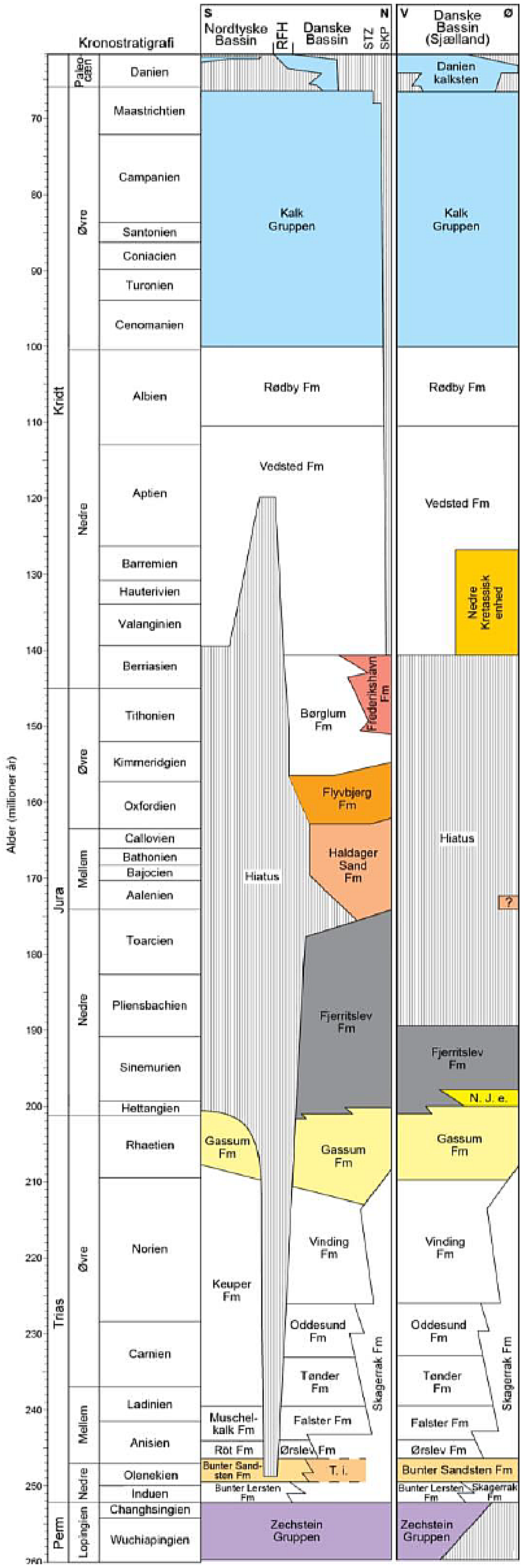

Figure 5: Schematic lithostratigraphic classification of the relevant part of Danish subsurface. The **left column covers** the Danish part of the North German Basin, across the Ringkøbing – Fyn High Ridge (RFH) to the Danish Basin and furthest to the north the Sorgenfrei – Tornquist Zone (STZ) and the Skagerrak – Kattegat Platform (SKP). The **right column** is the division of the Zealand subsoil from west to east within the same time interval. To the left of the chart is the geological time periods to which the lithostratigraphic units belong as well as their approximate ages for millions of years (thus, the thicknesses of the units are not reflected in the chart). The temporal extent of the Lower Jurassic unit and the Fjerritslev Formation in eastern Zealand is under review. Abbreviations used not shown above: N.J.e: Lower Jurassic unit; TI: Time equivalent interval to the Bunter Sandstone Formation in the Skagerrak Formation. Source: Geotermi WebGIS-portalen (http://DybGeotermi.geus.dk)

5.2 Gassum Formation

The Gassum Formation is well known as an excellent reservoir and the sandstones serve as geothermal reservoir in the existing geothermal power plant in Denmark situated in northern Jylland. Southeast of Havnsø the Gassum Formation forms the main reservoir in the natural gas storage facility at Stenlille (Figure 3). There is no hydrocarbon or potable water interests related to the Gassum Formation in the Havnsø area.

Lithology of the aquifer is expected to be relatively similar to the lithology described for the Gassum Formation at the Stenlille gas storage facility. In Stenlille, the basal part records a thick, relatively coarse-grained sandstone unit. This unit is followed upwards by four sequences containing fine-grained sandstones and mudstones (Nielsen et al. 1989). The porosity varies between the different reservoir units but an average of 22% has been applied for the storage calculations. The permeability of the Havnsø structure is unknown but is estimated to be comparable to the values seen in Stenlille where the Gassum Formation occurs at similar depth, having average permeability around 500 mD. The high permeability is crucial for obtaining high injection rates of CO_2. The depth to the top point of the reservoir is 1500 m and the closure is estimated to cover an area of 166 km^2. The spill point is situated in the south-eastern part of the structure at approximately 1850 m depth. Based on the reservoir information from the Stenlille natural gas storage and the probable facies changes of the Gassum Formation, the gross thickness is estimated to be 150 m with a net/gross of 0.67 leading to approximately 100 m of net sand. No information exists on the actual reservoir pressure and temperature and hydrostatic pressure and regional temperature gradients have been applied in the storage calculations. A more detailed model for the reservoir is presented by Bech & Larsen (2003; 2005).

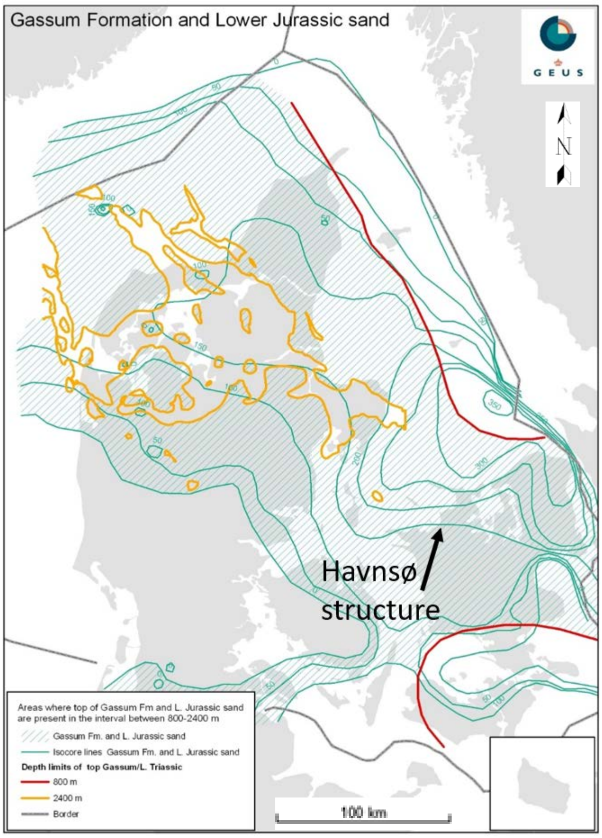

Figure 6: Distribution of the Gassum Formation including Lower Jurassic sandstone stringers in the Fjerritslev Formation. The green contour lines illustrate the combined thickness of the two units. Refer to Figure 4 and 5 for stratigraphic position.

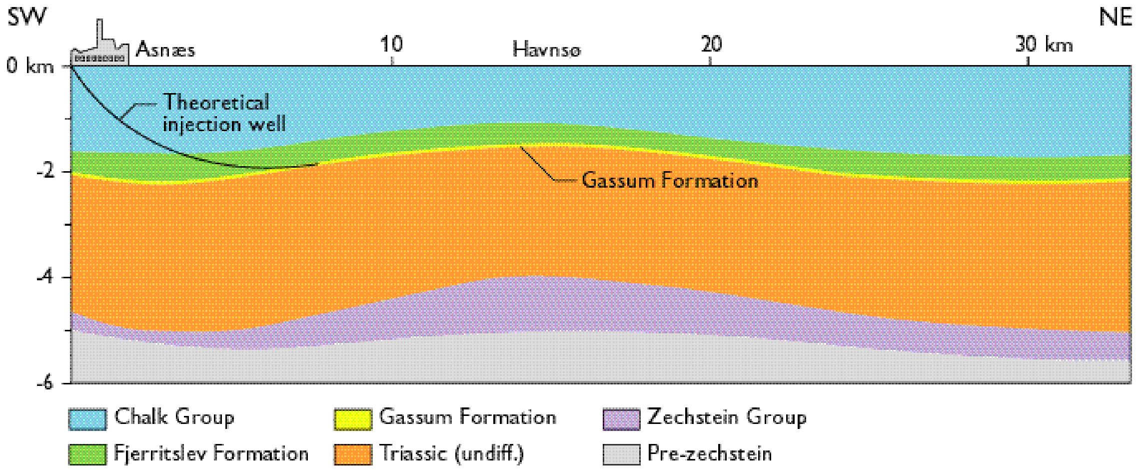

Figure 7: Geological cross-section of the Havnsø structure. Note the theoretical injection well drilled from the industrial site into the flank of the structure. (Larsen et al. 2003)

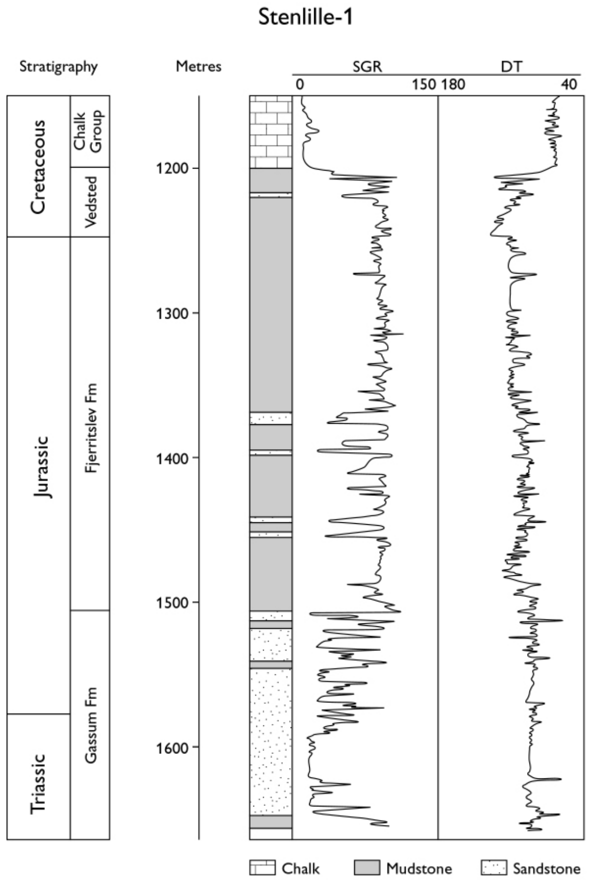

Figure 8: The Havnsø structure is yet undrilled but geological information from Stenlille exploration wells and a nearby natural gas storage are used to calibrate the storage model. (Larsen et al. 2003)

The reservoir in the Havnsø structure is divided into five reservoir compartments separated by clay or mudstones (Figure 8). The largest of the five units contains however 77% of the total storage volume of 926 Mt, corresponding to 651 Mt of CO_2 A preliminary simulation model running for a period of 100 years has been made for the Havnsø structure with the CO_2 injected into this main reservoir through a single well. The calculations show that the rock properties in the reservoir will allow injection of 200 kg CO_2/sec equal to approximately 6 Mt/year (the total estimated emissions from the power plant and the refinery being approximately 4 Mt/year) in more than 150 years (Larsen et al.

2007). The structure is expected to have sufficient capacity to be up-scaled to a demo-project and even to a full-scale project.

6 SEALING FORMATION LITHOLOGY/THICKNESS/DEPTH INTERVAL

6.1 Potential seals

Geological formations in Denmark with sealing properties are lacustrine and marine mudrocks, evaporites and carbonates. The most important sealing rock type in the Danish area is marine mudstones, which are present at several stratigraphic levels (Figure 5).

Marine mudstones of the Lower Jurassic Fjerritslev Formation form the primary sealing unit for the Gassum Formation (Figure 7; Figure 9). The formation overlies and locally interfingers with the sandstones of the Gassum Formation. The formation is present over most of the Danish Basin with a thickness of up to 1000 m although this varies significantly due to mid-Jurassic erosion. It is present over the Gassum Formation at the Havnsø Structure with thickness of about 500 meters. Laboratory experiments and full-scale test at the Stenlille natural gas storage facility suggests that the claystones form a tight seal. The integrity of the claystones towards CO_2 has not been tested (Anthonsen et al. 2014).

6.2 Secondary seal

In most of the Danish area a 0.5 to 2 km thick succession of mainly low-permeable carbonate rocks of Late Cretaceous – Danian age forms a possible secondary seal in the onshore and Kattegat areas (Figure 5).

6.3 Havnsø Structure, Fjerritslev formation

The structure is sealed by a thick package of marine mudstones of the Fjerritslev Formation (Figure 9). Laboratory experiments and full-scale test at the Stenlille natural gas storage facility proves that the claystones form a tight seal. The integrity of the claystones towards CO_2 has not been tested.

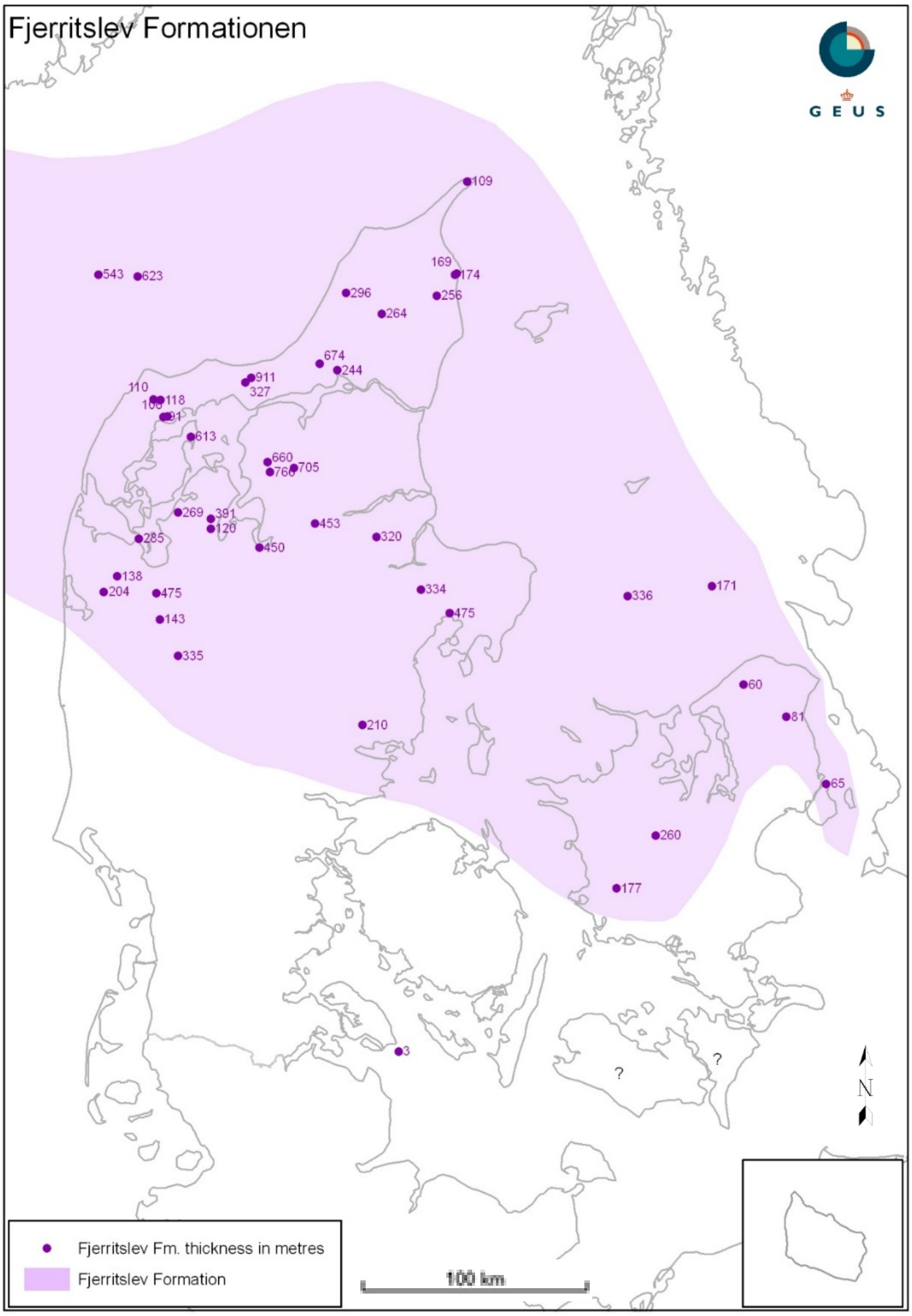

Figure 9: The distribution and thickness of the Fjerritslev Formation based on well data. The Fjerritslev Formation is the sealing formation overlying the principal reservoir in the Danish area, the Gassum Formation. Refer to Figure 5 for stratigraphic position

7 STORAGE

7.1 Storage quality

Lithology of the basal part aquifer, the Gassum Formation, records a thick, relatively coarse-grained sandstone. This unit is followed upwards by four sequences containing fine-grained sandstones and mudstones unit (see above 5.2).

7.2 Porosity and permeability

The porosity and permeability of the Havnsø structure is unknown but is estimated to be comparable to the values with average permeability around 500 mD seen in the Stenlille structure where the Gassum Formation occurs at similar depth. Work by Kristensen et al. 2017 has demonstrated a fairly robust relation between reservoir properties and depth in the Danish Basin (Figure 10). Generally, the reservoir properties are excellent with porosity 18–27% (maximum 36%) and permeabilities up to 2,000 mD. An average porosity of 22% and a permeability measurement from the Horsens-1 well at 500 mD (gas permeability) have been applied for the storage calculations in Table 1. The porosity was calculated from the deep-reading resistivity log (64”) and calibrated to core porosity data (Stenlille-1). The Gassum Formation is only partly cored and accordingly, the porosity evaluation outside the cored intervals is associated with considerable uncertainty.

The Gassum Formation forms the reservoir in the Stenlille natural gas storage and has been studied in great detail (Nielsen et al. 1989; Hamberg & Nielsen 2000; Nielsen 2003). The studies illustrate the facies complexity and the lateral variability present within the reservoir units. In the Stenlille area the formation is thus shown to consist of stacked shoreface units with excellent reservoir properties separated with thin claystone or heterolithic units. Each of these units may act as discrete reservoir units and is characterised by a set of porosity and permeability parameters. Based on palaeogeographic reconstructions it is anticipated that the net/gross sand contents will decrease towards the northwest. In order to properly evaluate the storage potential within the formation, it may thus be necessary to address the individual sandstone units.

Table 1 Summary sheet for the Gassum structure (Anthonsen et al. 2014).

Havnsø Structure (trap)	
Storage Capacity (Mt)	926
Reservoir properties	
Primary reservoir fm.	Gassum
Depth, top (msl.)	1500
Porosity (%)	22
Permeability (mD)	500
Heterogeneity (N/G)	0.67
Facies	Shore/delta
Pore pressure	hydrostatic
Net sand thickness (m)	100
Seal properties	
Primary seal fm.	Fjerritslev
Thickness (m)	260
Lithology	mudstone
Fault intensity	low
Lateral extend	continuous
Multiple seals	yes
Safety/risks	
Seismicity	low
Groundwater contamination	no
Data coverage	
Wells	0
Seismic survey	2D
Ranking score (max. 45)	**43**

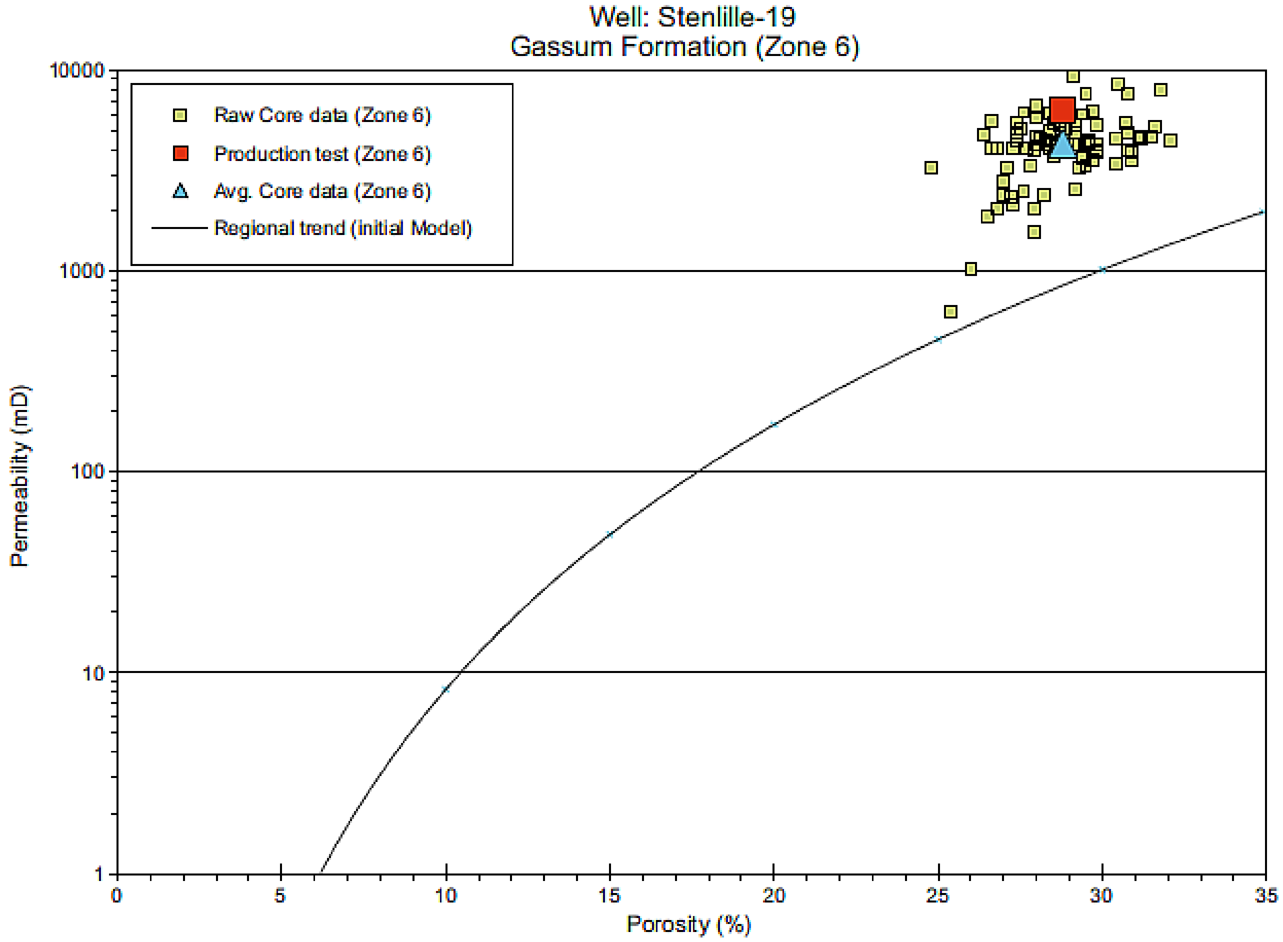

Figure 10: Porosity–permeability plot, including a comparison between permeabilities derived from cores and well test data. Both unprocessed and averaged core permeability measurements are shown along with a reservoir permeability value linked to a production test conducted in the Stenlille-19 well (for location, see Figure 3). The average core permeability (gas permeability) is about 4300 mD, whereas the well test permeability (liquid permeability) is about 6300 mD (Kristensen et al. 2016).

7.3 Reservoir modelling

A preliminary reservoir simulation model using Eclipse 100 has been made for the Havnsø structure. The calculations are reported in Bech & Larsen (2003; 2005) and show that the rock properties in the reservoir would allow injection of 200 kg CO_2/sec equal to the average daily emission rates of Asnæs Power Plant in Kalundborg.

The reservoir in the Havnsø structure is divided into five reservoir units separated by clay or mudstones. The largest of the five units contains however 77% of the total storage volume of 926 Mt, corresponding to 651 Mt of CO_2. A preliminary simulation model running for a period of 100 years has been made for the Havnsø structure with the CO_2 injected into this main reservoir through a single 8 km long horizontal well completed over a length of 200 m. The calculations show that the rock properties in the reservoir will allow injection of 200 kg CO_2/sec equal to approximately 6 Mt/year (the total estimated emissions from the power plant and the refinery being approximately 4 Mt/year before a conversion from coal to wood chips) in more than 150 years. The injected CO_2 will migrate to the top of the reservoir sequence while partly dissolving in the water. Eventually some CO_2 will escape by molecular diffusion, but numerical analysis suggests it will take more than one million years before such CO_2 reaches the surface (Larsen et al. 2007).

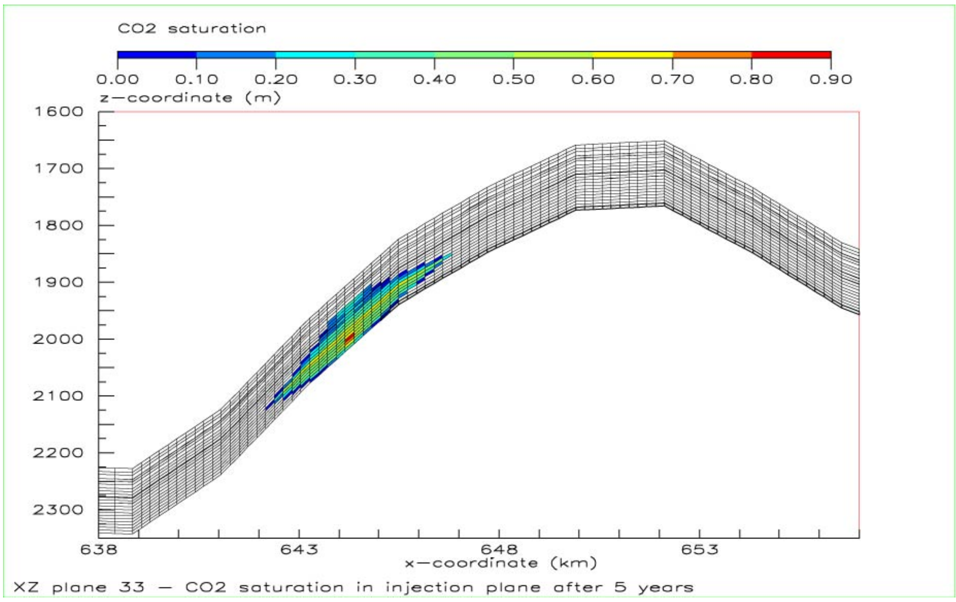

Figure 11: Vertical distribution in injection plane of CO2 saturation in the Havnsø structure after 5 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years (Larsen et al. 2007)

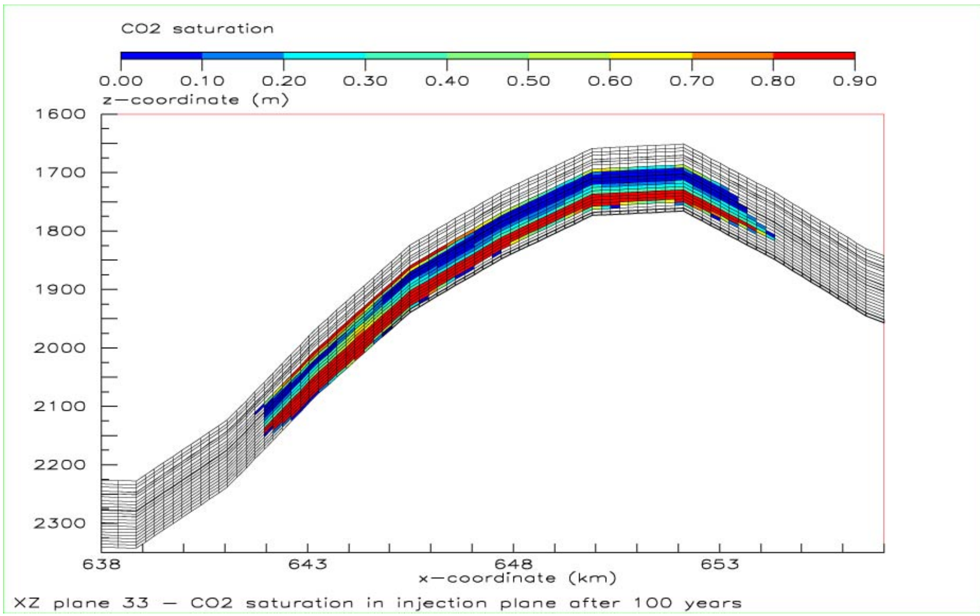

Figure 12: Vertical distribution in injection plane of CO_2 saturation in the Havnsø structure after 100 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years (Larsen et al. 2007)

7.4 Economic modelling

As part of the GESTCO project the economics in the Kalundborg case was modelled using the GESTCO DSS module and it was calculated that the total cost would be 32€/t CO_2 avoided with the capture costs contributing with 2/3 of the amount. In the present case study, a new economic evaluation using a modified version of the GESTCO DSS has been made. The conclusion from this sensitivity study was that a very high capture cost of e.g. 40€/t could make the scenario uneconomic which shall be seen in the light that most studies report present costs of 40-50 €/t CO_2 captured foreseeing reduction of capture costs to about 20 €/t (Larsen et al. 2007).

An overview of the CO_2QUEST project that addresses fundamentally important issues regarding the impact of typical impurities in the gas or dense phase CO_2 stream captured from fossil fuel power plants on its safe and economic transportation and storage. Previous studies have mainly investigated the impact of CO_2 stream impurities on each part of the carbon capture and storage (CCS) chain in isolation. This is a significant drawback given the different sensitivities of pipeline, wellbore materials and storage sites to the various impurities. The project brings together leading researchers and stakeholders, to address the impact of the typical impurities upon safe and economic CO_2 transportation and storage. State-of-the-art mathematical models, backed by laboratory and industrial-scale experimentation, are implemented to perform a comprehensive techno-economic assessment of the impact of impurities upon the thermo-physical phenomena governing pipeline and storage-site integrities (Brown et al. 2014).
The Carbon Capture & Storage Association (CCSA) estimated that the earlier CCS projects in the power sector would cost between €60–€90 per tonne of carbon dioxide abated, the equivalent of around $69-$103 per tonne. The association (CCSA 2018[1]) also predicted that these costs will decline to €35–€50 ($40-$57) in the early 2020s, thanks to technological advancements.

7.5 Injection wells and monitoring

According to the reservoir model of Larsen et al. (2007), the Havnsø structure may be filled by one injection well, but this depends on the amount of CO2 to be injected. More wells will be needed in order to obtain the best injection control. One of these wells is assumed to be reuse of a data acquisition well, planned as part of a fictitious data acquisition programme in the case study (Larsen et al. 2007).

7.6 Stenlille monitoring

To be able to detect any trace of natural gas that may have leaked from the underground storage, it is imperative to know the characteristics of the hydrocarbon gases that may have been present in that environment prior to the injection of natural gas into the underground storage. A baseline study on naturally occurring hydrocarbon gases in the subsurface of the Stenlille area was therefore performed. The study comprised analysis of hydrocarbon gases, including stable isotopes, in cuttings from a number of deep wells and analysis of dissolved gas in shallow groundwater. Stable isotope ratios of different constituents, e.g. methane and ethane, may give useful information about the origin of the hydrocarbon gas. Since isotope ratios change insignificantly during migration, they are potentially useful for detecting leakage of gas from an underground gas storage (Laier and Øbro 2009).
For the baseline study of naturally-occurring hydrocarbon gases in the subsurface, samples from the drilling of three observation wells were analysed (Laier 1989b). Analysis of shallow groundwater was also performed, as part of the baseline study and for monitoring after injection of natural gas had begun. Finally, the chemical and isotopic composition of the natural gas was analysed every second year (Laier and Øbro 2009).
In August 1995, a minor gas leakage occurred in a new well during gas injection. Later investigation revealed that the leak was due to gas seeping from the tubing into the water filled annulus between tubing and casing. Due to unfortunate circumstances, water in the annulus was displaced by gas which then escaped through a small leak in the casing out into the cement and confining rocks, c. 780 m below surface. Having escaped, gas then migrated towards the surface where it was recorded as tiny bubbles in the pit around the wellhead of the new well. Chemical and isotopic composition of gas collected at the surface was similar to that of natural gas, so there was little doubt that it had leaked from the well. The injection tubing was then plugged and filled with water, after which gas bubbling ceased within two weeks. The casing was repaired and the tubing replaced by a new one. The well was put back in service and no leakage of gas has been observed since (as per 2009) (Laier and Øbro 2009).

[1] https://www.power-technology.com/features/carbon-capture-cost/

8 STORAGE CAPACITY

8.1 Storage capacity

Based on results from natural gas storage facilities in Europe, Larsen et al. (2007) applied an effective storage capacity of 40% resulting in a total capacity of approximately 1 Giga ton CO_2 for the Havnsø structure. With the present day CO_2 sources the storage system could be operated for more than 150 years (Larsen et al. 2007). Two industrial facilities are situated at the Kalundborg harbour approximately 15 km from the top of the structure and less than 10 km from the down-dip closure.

Based on the reservoir information from the Stenlille natural gas storage and the north-westwards facies changes of the Gassum Formation, the gross thickness is estimated to be 150 m with a net/gross of 0.67 leading to approximately 100 m of net sand. No direct information exists on the actual reservoir pressure and temperature; thus hydrostatic pressure and regional temperature gradients have been applied in the storage calculations. The structure is calculated to be able to hold a maximum of 923 Mt CO_2. A more detailed model for the reservoir is presented by Bech & Larsen (2003; 2005) following the methodologies in the previous GESTCO project and other projects (e.g. EU GeoCapacity).

Table 2 As summed up in NORDICCS report D 6.2.1201, several CO_2 screening and exploration programs have evaluated the Danish CO_2 storage potential, since 1993. The table summarises the storage capacity calculated in the respective exploration programmes through the years (Lothe et al. 2014)

Storage site	Project	Capacity	Remarks
Havnsø Structure	GESTCO	923 Mt	Storage efficiency factor 40%
	CO2STORE	Min. 1028 Mt	Reservoir information from Stenlille natural gas storage.

9 UPSCALING POTENTIAL

9.1 Major CO_2 emission points

The Havnsø structure is situated within a distance of 15 km from three major industrial point sources at Kalundborg Harbour (see Chapter 11). The size of the structure furthermore makes it attractive for storage of CO_2 from the point sources in the Copenhagen area. The distance to Copenhagen is approximately 85 km.

9.2 Site selection for the Kalundborg case

Two structures, both domal closures at Gassum Formation level have been considered for the Kalundborg case study (Larsen et al. 2007). These are the Røsnæs structure and the Havnsø structure and based on the initial screening and comparison of the two structures, the Havnsø structure was chosen for further work in the CO2STORE case study (Larsen et al. 2007) (Figure 11) (see 5.2).

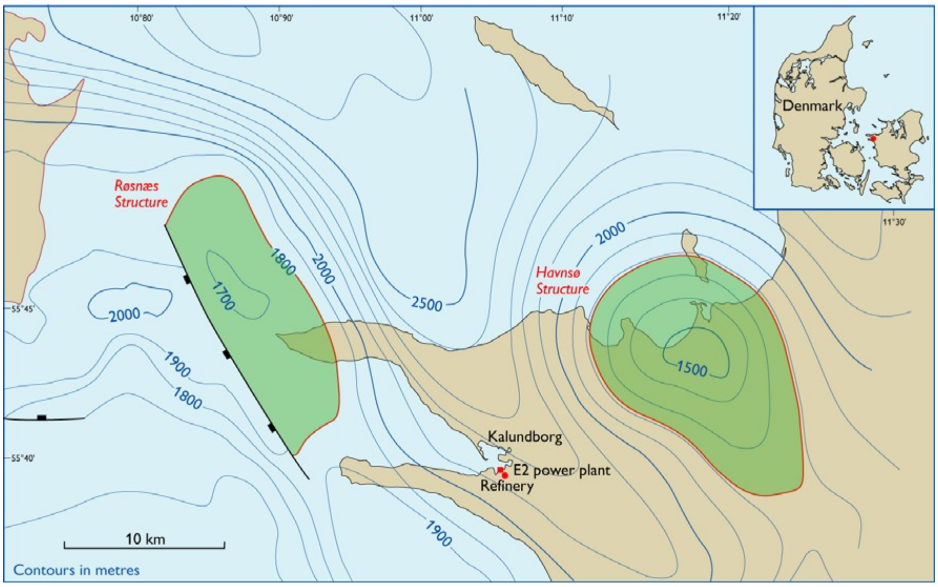

Figure 13: Depth structure map of the Havnsø and Røsnæs closures. Both structures are defined in the Upper Triassic-Lower Jurassic Gassum Formation.

Table 3: Comparison of the Havnsø and Røsnæs structures (Larsen et al. 2007)

Storage	**Havnsø**	**Røsnæs**
Onshore/offshore	2/3 onshore, 1/3 offshore	Offshore
Reservoir	Gassum Formation	Gassum Formation
Stratigraphy	Late Triassic	Late Triassic
Lithology	Siliciclastic sandstone	Siliciclastic sandstone
Top depth msl	1500 m	1700 m
Gross thickness	150 m	100 m
Net/gross	0.67	0.5
Net sand	100 m	50 m
Porosity	22	20
Permeability	500 mD	200 mD
Pore volume	3 670 km^3	900 km^3
Pressure	150 bar	170 bar
Temperature	~ 50 °C	~ 55 °C
Reservoir density of CO_2	629 kg/m^3	631 kg/m^3
Seal	Fjerritslev Formation	Fjerritslev Formation
Stratigraphy	Early Jurassic	Early Jurassic
Lithology	Marine mudstone	Marine mudstone
Gross thickness	500 m	500 m
Trap	4-D domal closure	Fault closure (Neogene movement)
Area of closure	166 km^2	90 km^2
Distance to source	15 km	18 km
Effective storage factor	40%	40%
Storage capacity	923 Mt	227 Mt

Economic/Risk evaluation	**Havnsø**	**Røsnæs**
3-D seismic	High costs	Low costs
Drilling	Low costs	Medium costs
Transport	Onshore pipeline	Offshore pipeline
Monitoring	Wells	Seismic
Permission requirements	National and local authorities	OSPAR/ National and local authorities
Risk project	High seismic costs	Fault sealing capacity
Risk humans	Low	None
Risk environment	Low	Low

The Røsnæs structure is smaller than the Havnsø structure and is poorly defined by few old (low-quality) 2-D seismic lines. The fault bounded structure may, however present an interesting storage complex being mainly offshore and located near the Havnsø structure and serving as an additional storage option (Figure 13). The Røsnæs structure is expected to have less porosity at 20 %, a permeability at 200 mD and a storage capacity of 227 Mt CO_2 (See Table 3).

10 DATA AVAILABILITY ISSUES

Initial screenings projects (GESTCO, EU GeoCapacity, CO2StoP and NORDICCS) have indicated a number of structures in the Danish subsurface with a potential for safe storage of large amounts of CO_2. The screening has identified the partly onshore partly offshore Havnsø structure and the mainly offshore Røsnæs structure as promising closed structures with sandstones in the Upper Triassic-Lower Jurassic Gassum Formation serving as reservoir with the overlying mudstones of the Lower Jurassic Fjerritslev Formation acting as the primary seal and Upper Cretaceous chalks being a secondary seal.

10.1 Information from wells and seismic coverage

The Havnsø structure has not yet been drilled and the aquifer data are extrapolated from the Stenlille-1, Stenlille-19 and Horsens-1 wells. The structure is identified on seismic SSL Survey line 73/038, 73/039, 74-302, 74-303, 74-304, 74-307 and 74-308, (Figure 1). At present no structural map has been published and the interpretation is based unpublished work.

The Røsnæs structure has not yet been drilled and the aquifer data are extrapolated from the Stenlille-1, Stenlille-19 and Horsens-1 wells. The structure is identified on seismic SSL Survey lines 1-140, 80-110/2, 80-110/3, 80-120/4 and 80-111 (Figure 1). At present no structural map has been published and the interpretation is based unpublished work.

The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).

Palaeogeographic models suggest that the reservoir quality of the sandstones will decrease in an offshore direction towards the northwest relative to the Stenlille structure where the formation is well-known. The Gassum Formation has been described in detail by Nielsen et al. (1989); Hamberg & Nielsen (2000) and Nielsen (2003).

The nearby Stenlille structure has been used and monitored for gas storage for decades without leakage. It is a close geological analogue and all relevant geological, geophysical, geochemical and production information will be drawn upon including 3D seismic data, well-logs and numerous core data, drilling campaigns (boreholes Stenlille 1-19 to base of the Gassum Fm, approx. 1300-1400 m). These data will be integrated with regional 2D seismic lines and GEUS´ sequence stratigraphical model for the Gassum (reservoir) and Fjerritslev Formations (primary caprock) and the secondary caprock formed by about 1 km Chalk.

11 OTHER IMPORTANT ASPECTS

11.1 Major CO_2 emission points

The Havnsø structure is situated within a distance of 15 km from two (three) major industrial point sources at Kalundborg Harbour. The size of the structure furthermore makes it attractive for storage of CO_2 from the point sources in the Copenhagen rural area. The distance to Copenhagen is approximately 85 km.

The Asnæs Power Plant is one of the largest single source of CO_2 emission in Denmark. The future CO_2 emissions are estimated to more than 1.6 Mt/year. The Equinor (Statoil) refinery is situated as neighbour to the power plant and produces close to 0.5 M tonnes CO_2/year. A new refinery, AVISTA OIL Danmark Refining ApS is expected to be ready soon for use. The point sources are located side by side close to the city of Kalundborg on the Northwest coast of Zealand in the Eastern part of Denmark.

11.2 Asnæs Power Plant

The Asnæs Power Plant near Kalundborg is Ørsted's largest power plant with three active blocks, which together can supply 1,057 MW of electricity and up to 741 MJ / s of heat. The first production facility, Asnæs 1, was commissioned in 1959, and in 1981, Asnæs 5, Denmark's largest 640 MW power plant block, was commissioned. The power plant uses coal as its main fuel, but the big block 5 can also run on Oil emulsion. Oil is reserve fuel on all three active blocks.

In 2015, the Danish Energy Agency promised a grant of DKK 422 million DKK for the conversion from coal to wood chips at Asnæs Power Plant. The aid was subject to the approval of the European Commission. At the end of 2016, the Kalundborg Municipal Council approved Local Plan No. 564, which permits a biomass-fired power plant block at the Asnæs plant. The final investment decision on a biomass fired block was taken by Ørsted in June 2017. The steam turbine for the new plant was installed in November 2018, and Ørsted's expected in 2018 is the plant to be ready for use by 2020.

Asnæs Power Plant is part of an environmental collaboration - industrial symbiosis - in Kalundborg and in addition to electricity, Asnæs Power Plant produces district heating for the Municipality of Kalundborg and process steam for the neighbouring companies Equinor, Novo Nordisk and Novozymes. The conversion from coal to wood chips at the Asnæs Power Plant will results in an annual CO_2 reduction of up to approx. 800,000 tons.

If the CO_2 from the power production is stored, the process is called BECCS, i.e. bioenergy with carbon capture and storage and offers large-scale negative emissions (carbon removal) where CO_2 emissions are removed from the atmosphere through the application of CCS to the transformation of trees and crops into energy fuels. (Global CCS Institute, 2018).

11.3 Equinor Refining Denmark

The Equinor refinery is also the largest refinery in Denmark with a production capacity of 5.5 million tonnes of hydrocarbon products/year. It refines crude oil and condensate into petrol, diesel, propane, heating oil and fuel oil. The oldest part of the refinery was built in 1961. After expansion in 1995, it can accept a larger proportion of condensate, allowing it to produce petrol with a lower content of benzene. Deliveries of petrol with 1% benzene to the Danish market started in 1997. The refinery also supplies petrol and diesel with under 50 parts per million (0.005%) of sulphur. The production capacity at Kalundborg is up to 5.5 million tonnes of oil products per year, depending on the type of raw material. The emissions have been almost constant around 0.5 Mt/year in the project period, but not all of the CO_2 will be available for the capture process.

11.4 Avista Oil Danmark Refining ApS

AVISTA OIL Danmark A/S has entered into a collaboration with British Greenbottle Ltd. Together, the two parties, via the newly established joint venture, AVISTA OIL Danmark Refining ApS, are responsible for the re-construction of the waste oil refinery. Significantly larger quantities will in future be shipped in and with the capacity of the new refinery almost doubling from the previous 55,000 tonnes to 100,000 tonnes annually. The CO_2 emission is unknown.

11.5 Gas Storage Denmark A/S

Gas Storage Denmark A/S owns and operates Denmark's two underground gas storage facilities:

- the aquifer storage facility at Stenlille in the central part of Zealand
- the salt cavern facility at Lille Torup in northern Jutland

Gas Storage Denmark A/S (https://gasstorage.dk/) operates the two storage facilities based on synergy and complementarity of the technical equipment and capability that an aquifer and a salt cavern offer, when operated together. Gas Storage Denmark A/S is a fully-owned subsidiary of Energinet (https://energinet.dk/) and is an independent operator. Energinet's owner is the Danish state, and its business purpose is to own and operate the vital gas and power infrastructure in Denmark. Gas Storage Denmark A/S business is based on customer requirements, market value and commercial innovation. By pooling a decade of technical and commercial market experience, we develop innovative storage products in a dialogue with our customers and the market and Gas Storage Denmark A/S looks to other sectors and foreign countries for inspiration.

12 PROJECT BUDGET

Costs estimates on CO_2 storage involve a high degree of uncertainty, given the significant variations in technical characteristics, scale and applications between projects. There is also uncertainty over how costs will develop with time. Site selection and the economics of storage will drive the commerciality of large-scale integrated CCS projects. According to the EU GeoCapacity project several specific geological criteria are required for a site to be suitable for CO_2 storage:

- Appropriate depth of reservoir to guarantee that CO_2 reaches its supercritical dense phase but not so deep that permeability (injectivity) and porosity are low;
- Integrity of seal to prevent migration of CO_2 from the storage site;
- Enough CO_2 storage capacity to receive the CO_2 projected to be released from the source; and

These criteria hinge on the values of a number of geological and physical parameters and it is critical in the search for appropriate sites for CO_2 storage to assess whether the criteria listed above, and their related geological and physical parameters are satisfied (Bachu et al. 2007; Bradshaw et al. 2007; Chadwick et al. 2008; Poulsen et al. 2009; Vangkilde-Pedersen et al. 2009)

If a number of similarly appropriate CO_2 sites are identified in the screening procedure, other non-geological criteria such as economic, logistical and conflict of interest considerations can be used to select which of those sites shall be investigated in further detail.

Cost of captured CO_2 for different process plants, capture technologies and storage solutions.

	Cost ($2015/tCO$_2$) Min	Max
Process plant		
Coal-fired power	41	62
Gas-fired power	52	100
Iron and steel	57	69
Refineries and natural gas processing	20	79
Cement production	35	110
Natural gas combined cycle	75	95
Oxyfuel combustion	45	50
Capture technology		
Post-combustion (amine)	50	110
Chemical looping	35	52
Oxy-combustion	45	66
Storage		
CCS	20	110
EOR/EGR	52	62

Cost of CO_2 transport for onshore and offshore pipelines with different capacities (modified from Ref. [109]).

Methods	Capacity ($MtCO_2$/yr)	Transport cost ($2015/tCO$_2$/250 km) Min	Max
Onshore pipelines	3	4.4	11.1
	10	2.2	3.8
	30	1.3	2.2
Offshore pipelines	3	7.3	15.1
	10	3.5	4.9
	30	1.9	2.4

Cost of CO_2 storage for various storage sites (modified from Ref. [109]).

Properties	Storage cost ($2015/tCO$_2$) Min	Max
Depleted oil and gas field – reusing wells onshore	1.6	11
Depleted oil and gas field – no reusing wells onshore	1.6	15.7
Saline formations onshore	3.1	18.8
Depleted oil and gas field – reusing wells offshore	3.1	14.1
Depleted oil and gas field – no reusing wells offshore	4.7	22
Saline formations offshore	9.4	31.4

Figure 14: Costs of CO2 storage (after Budinisa et al., 2018).

According to the Global CCS Institute report, Global Status of CCS (GCCSI 2011), in the initial demonstration phase of CCS development there is a strong economic driver to find storage locations close to emissions sources. In regions deprived of adequate storage potential, long-distance transport of CO_2 by pipeline or ship might be feasible in the long-term once wide-scale deployment of CCS underpins the scale efficiencies that are necessary to moderate the price of CO_2 transport over great distances.

Budinisa et al. (2018) reviewed potential barriers to the worldwide adoption of CCS and considered whether this technology has the potential to enable access to more fossil fuel reserves in the future, where these reserves would otherwise be ‘unburnable’. The authors analysed the status and costs of CCS, studied its impact on fossil fuel consumption across a selection of global climate change mitigation models used in the IPCC 5th assessment report, and examined the extent of global CO_2 geological storage capacity. However, accurate cost analysis of its implementation in Denmark is needed.

12.1 Pilot preparation, site development, budget

The Havnsø pilot preparation, drilling, injection and closure will cover about 15 years. The cost estimation (Table 4) gives an estimate of person months (PM) to be invested as a minimum during a 15 years lifetime for the Havnsø pilot project. It given as a minimum, however, more research projects will most likely appear in the Havnsø pilot lifetime period.

The costs estimation does not cover CO_2 nor insurances. In the Hontomin pilot there have been requested a 750 M€ guarantee fund. There is no knowledge or experience on any Danish expectations to a similar insurance or guarantee fund.

Assuming the Havnsø pilot will inject near 60–100 kilo tonnes with a cost price of 30–60 € per tonnes, the CO_2 costs for the Havnsø pilot will be 2–6 mill. €. For comparison the GFZ German Research Centre for Geosciences terminated the injection of CO_2 near the town Ketzin/Havel after about five years of operation. Injection work at the Ketzin site has been safe and reliable from June 2008 till August 2013. During that period 67,271 t of CO_2 were stored in the reservoir. In total 67,271 tons CO_2 were injected at the pilot site. (http://www.co2ketzin.de/en/pilot-site-ketzin/storage-operation/)

Table 4: Havnsø pilot Gantt chart and cost estimation

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	PM	Costs k€
Applying/award of exploration permit																2	39
Communication plan																2	39
Stakeholder and public engagement																30	583
Risk management plan																2	39
Baseline																6	117
Monitoring																45	875
Seismic 2D investigation																6	117
Site selection																2	39
Assessment of storage potential																6	117
Applying/award of drilling permit and storage permit																3	58
Applying for storage permit																1	19
Establishment of drilling site(s)																3	58
Drilling																3	58
Injection start																3	58
CO_2 acquiring																6	
Monitoring of injection																12	233
Injection closure																3	58
Post closure investigations																6	117
Transfer to authorities																3	58
Post transfer																3	58
Other costs																	
Communication material																	3
Baseline study equipment																	14
Monitoring equipment																	20
Seismic 2D investigation																	55
Establishment of drilling site(s)																	405
Drilling, 1 injection well, 2 monitoring wells																	12,000
CO_2 acquiring																	2,000
Monitoring equipment of injection																	13
Total																	**15,596**

13 POTENTIAL COMBINATION WITH CAPTURE PROJECTS

The potential for CO_2 capture from Asnæs Power Plant as well as requirements and technical aspects regarding capture has been described by ENERGI E2 (ENERGI E2[2] was a Danish production and energy trading company. In 2006, the company merged with DONG Energy, now Ørsted) as a constructed scenario and does not reflect present plans. As the capture plant probably is to be used for both existing units as well as for a new power unit a conventional post combustion capture plant is anticipated. A flue gas rate of approximately 550 Nm3/s (dry, 6% O_2) equal to round 1,800,000 Nm3/h (wet, act. O_2) is estimated and a quite large capture plant is therefore needed. Dimensions of the absorber and stripper towers are expected to be 30–40 meters in height and 20–23 meters in diameter or alternatively divided into two towers each and a possible site for a future power unit and the capture plant has been located. An average CO_2 capture rate of 90% is expected and according to the EU project ENCAP a CO_2 delivery pressure of 110 bar and CO_2 delivery temperature of max. 30°C should be expected. There are no standards for CO_2 purity for different applications, but in the EU projects ENCAP and CASTOR CO_2 purity requirement is an area of investigation and provisional results prescribe purity for aquifer storage less restrictive than for e.g. Enhanced Oil Recovery or for ship transportation.

13.1 Surface transport

The requirements and costs for a 15 km surface pipeline from the power plant to the south-eastern flank of the Havnsø structure for transportation of maximum 6 Mt CO_2 per year has been evaluated by Statoil ASA (Equinor) as a "best guess" estimate. The lowest allowable pressure in the pipeline in order to prevent the CO_2 to change to gas phase is 60 bar and onshore gas pipelines are often operated at 80 bar. This will require an inside diameter of 0.330 m (13"), and the construction costs are estimated to be 625–750 € per metre or in total 9.4–11.3 Mill. € for 15 km pipeline. Calculations does however show that a change in pressure from 80 bar to e.g. 120 bar will not cause a dramatic change in diameter and the costs will thus not change significantly if a higher operating pressure is chosen.

A tentative pipeline route has been chosen to avoid densely populated areas and where possible to follow existing pipeline routes and high voltage cables. The pipeline would be dug into the ground and covered, and it is anticipated that the soil types will not present major problems to the pipeline construction, but no geotechnical analyses have been made concerning the practicality of pipeline route and ground stability. Expropriation costs to landowners, cost for EIA (Environmental Impact Assessment) and other costs covering the period from draft project to start of detailed project are not included in the estimate of the construction cost. Furthermore, the cost estimate assumes that the pipeline and a normal ±25 m wide security zone with strict restrictions concerning buildings and general use can be constructed without conflicts with existing buildings (Larsen et al. 2007).

14 OTHER CO_2 EMISSION REDUCTION ACTIVITIES IN THE AREA

Asnæs Power Plant is part of an environmental collaboration - industrial symbiosis - in Kalundborg and in addition to electricity, Asnæs Power Plant produces district heating for the Municipality of Kalundborg and process steam for the neighbouring companies Equinor, Novo Nordisk and Novozymes. The conversion from coal to wood chips at the Asnæs Power Plant will results in an annual CO_2 reduction of up to approx. 800,000 tons.

[2] https://da.wikipedia.org/wiki/Energi_E2

14.1 Bioenergy with carbon capture & storage (BECCS)

Bioenergy can be used in various parts of the energy sector, including for electricity, liquid fuel, biogas, and hydrogen production. It is this flexibility that makes bioenergy and bioenergy technologies valuable for the decarbonization of energy use (Klein et al. 2014; Krey et al. 2014a; Rose et al. 2014; Bauer et al. 2018). Most bioenergy used is combined with CCS (BECCS) if available (Rose et al. 2014). If CCS is unavailable, bioenergy use remains largely unchanged or even increases due to the high value of bioenergy for the energy transformation (Bauer et al. 2018). As land impacts are tied to bioenergy use, the exclusion of BECCS from the mitigation portfolio will not automatically remove the trade-offs with food, water and other sustainability objectives due to the continued and potentially increased use of bioenergy. Trees can grow on agricultural land (Zomer et al. 2016), and harvested wood can be used with BECCS and pyrolysis systems (Werner et al. 2018; IPCC SR15 Chapter 2, 2018)

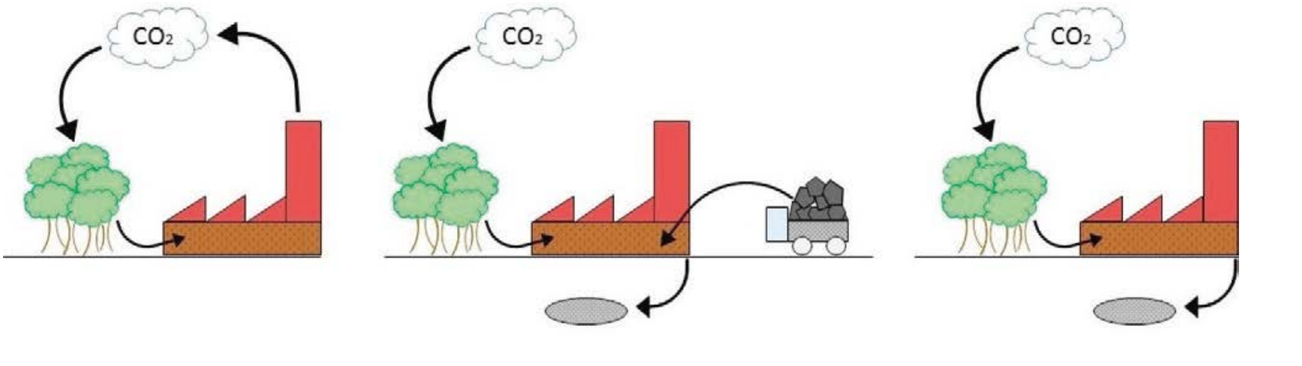

Figure 15: Integration of biomass in heat and power generation sector: (a) 100% biomass firing in a power plant for power and heat generation with close to neutral net emissions; (b) Co-firing biomass and coal for power generation coupled with CCS; negative emissions are achieved depending on the biomass content; (c) 100% biomass firing combined with CCS (EASAC, 2018)

The BECCS concept is fairly straightforward (Figure 15). Biomass captures CO_2 during growth and stores it in the form of organic material, such as trunks, stalks, roots, etc. The biomass is subsequently burned in a power plant (or converted in another energy conversion plant), producing electricity (or another energy carrier). The CO_2 that is produced during biomass combustion is captured and stored underground, thereby effectively removing it from the atmosphere. As indicated, the use of biomass for BECCS is not limited to the power sector, but can also be integrated in other sectors, such as hydrogen, biofuel, or biogas production. The technology is currently being demonstrated (albeit on a small scale) at several locations around the world (EASAC 2018).

14.2 CCUS Opportunity

CCUS provides the opportunity not just to decarbonise energy or products, but also to create negative CO2 emissions through Bioenergy with CCS - BECCS (CAG 2019). CCUS technologies provide the foundation for carbon removal or "negative emissions technology" when the CO_2 comes from bio-based processes or directly from the atmosphere. The BECCS represents one of the few technologies that can deliver negative emissions at scale, by removing carbon from the biosphere for permanent sequestration. For example, it is expected to play an important role in meeting the UK's 2050 emissions targets (Danish plans is still under development). The CCC's Further Ambition scenario (which identifies measures that "will definitely be needed for a net-zero emissions target") states that up to 51 million tonnes of BECCS will need to be stored per year by 2050. This is based on an assumed overall biomass available to the UK for BECCs of around 173TWh. The UK ambition scenario estimates that bioenergy could account for up to 10% of primary energy in 2050. Of this, 6% of UK electricity in 2050 could be generated by BECCS, with the remaining bioenergy resources used to achieve decarbonisation in other sectors (CAG 2019). In addition to BECCS and hydrogen production, bioenergy could also be deployed for biofuels. A combination of all these approaches will play a role in achieving a 'net zero' economy by 2050 (CAG 2019).

15 LEGAL AND POLICY ISSUES

The legislation on CCS in Denmark follows EU legislation and the EU CCS directive (Shogenova et al. 2014) was included in the Danish subsurface law in 2011. However, the Danish Parliament decided in 2011 to pause large-scale CCS in Denmark in order to wait for experiences from other European countries. Subsequently, no practical experiences with implementation of CCS in Denmark have been achieved. With the anticipation that the Danish Parliament will put CCS high in the agenda in the near future, the Havnsø pilot project will identify the challenges that have halted implementation of CCS and identify issues and ways forward with the economic drivers, regulatory framework, public acceptance and political incentives while linking them to the BECCS and CCS mitigation options. A presentation, discussion and decision of the deployment of CCS in Denmark is currently under preparation. The project work will include a gap, risk and barrier analysis on Danish terms for large-scale implementation of CCS. International cooperation can be involved when necessary. Identification of possible economic and legislative incentives will be done in close cooperation with the Energinet, Ministry and Danish Energy agency.

The Helsinki Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention) was adopted in 1992 and entered into force in 1996[3 & 4]. The Helsinki Convention prohibits dumping waste in the Baltic Sea area including the Kattegat, which also includes CO_2. This means that the Convention must be amended to enable CO_2 storage in the seabed in the Baltic Sea and the Kattegat in accordance with the EU CCS Directive. It is questionable whether the legislation context in the Baltic Sea area currently is at all consistent with the CCS operations. Dumping is defined as any deliberate disposal at sea or into the seabed of waste or other matters, injection of any matter. The fact that prohibition of geological storage in the London Protocol has been removed, a very similar provision in the Helsinki Convention has not been addressed.

16 PUBLIC ACCEPTANCE ISSUES

It is of uttermost importance that the local population are confident about the implementation of a CO_2 storage project. This will not only require the projects to be compliant with technical best practices but also to ensure that the implementation process is recognized by the population as following safe state-of-the-art practices. In other words, it is not enough that the site follows regulations, it is also necessary that it is perceived as such. The Havnsø pilot project will undertake activities that can fill the gap between the technical and the societal level of perception of the Havnsø pilot. To achieve this, the Havnsø pilot project will create conditions for the establishment of a long-term relationship with a group of public's representatives, within which research and technological issues will be discussed with two main objectives:

- gain input from the population to make sure that the best practices developed by the ENOS project don't neglect reasonable societal concerns and integrate the point of view of the population;
- to produce a public information tool specific for CO_2 storage sites that enables people to understand and follow site development and operation.

The two objectives are closely related, the outcomes will be directed to satisfy the authorities and the operators, through the contribution to best practice documents and to engage the general public and other societal stakeholders, through the production of a dedicated public information tool.

[3] Helsinki Convention can be found here: http://www.unece.org/env/water/
[4] Helsinki Convention guide: http://www.unece.org/index.php?id=33657

Interaction with the population on technical issues is not new in other sectors. For instance, the application of methodologies that seek to include social and societal aspects into what is commonly referred to as 'technical' challenges has largely taken place in formerly technical issues such as water and soil management. This approach is only just starting in the field of CCS within the ENOS project.

This will be an important step towards good communication between scientists, operators, local authorities and the local population. A successful societal exchange on storage themes and on the advantages of an organized and long-term joint effort could be replicated by future storage operators.

16.1 Public communication and policy

Implementation of CO_2 storage projects including pilot projects needs to build confidence to the local population especially within the technology safety aspects. This will not only require the projects to be compliant with technical best practices but also to ensure implementation process is recognized by the population and is following safe state-of-the-art practices. In other words, it is not enough that the site follows regulations, it is also necessary to undertake activities with the goal of developing knowledge that can fill the gap between the technical and the societal level of perception on CCS.

To achieve this, the Havnsø pilot project will create conditions for the establishment of a long-term relationship with a group of public's representatives, within which research and technological issues will be discussed. It is expected to establish a public relation group that can receive input from the population to make sure that the best practices developed by the ENOS project, WP5 (Vercelli et al. 2017) will establish societal communication and integrate the point of view of the population.

The group shall produce public information specific for CO_2 storage sites that enables people to understand and follow site development and operation. Discussion at societal level on technical topics requires support of the technical community and suitable supporting material. There are existing examples of researchers working together to integrate their knowledge from different disciplines related to storage and making the effort of expressing it in lay terms, which have produced a variety of materials for communication with the public.

The most notable one is CO_2GeoNet brochure "What does the geological storage of CO_2 really mean?", now available in 27 languages, which some of the ENOS partners have contributed to. However, these are one way communication materials, produced for general engagement purposes, without direct input or verification by the population.

The group shall work for local participation and discussion with civil society on technical topics and integration of public concerns in research and implementation projects a common language, terminology and understanding of concepts is required.

Monitoring is essential in the risk management of a CO_2 storage site, both in order to ensure progress during operation according to planned targets as well as to verify that leakage to other geological strata or the atmosphere is not taking place. Thus, the monitoring program from baseline and onwards will be followed by the citizen group.

Management systems are essential for the implementation and public credibility of geological storage processes. Successful management systems are flexible so that operators can make changes during the project and are robust enough to ensure that they meet site-specific project and regulatory needs. Management systems for a storage project interconnect through all project activities and phases and provide an auditable trail of the decision-making processes.

Management systems also help to ensure that quality assurance and quality control, regulatory compliance, process improvements, and efficiency improvements are integrated into regular management processes and decision-making, as well as ensuring project transparency so that project stakeholders, regulatory authorities, and the public develop confidence in the management and implementation of storage projects.

16.2 Learnings from the Ketzin site

At Ketzin, in Germany, a close collaboration with the county officials (e.g. reporting of GFZ to the city council, town hall meetings) and their approach to energy related questions were very helpful. The CO_2 storage project was embedded in the community's strategy for a sustainable energy production which also included renewable energy sources. Hence, acceptance for the Havnsø pilot project can be reached with a similar plan for transparent communication including open houses and weekly possibilities to visit the site for all interested citizens maintained throughout all phases of the life cycle of the site. The outreach has also a regional component with visits at schools and talks on different occasions. It cannot be excluded that the acceptance for the pilot project in Ketzin was good because GFZ is a research institute and the project scale of 100,000 tonnes was never questioned. However, a targeted communication and dissemination programme was able to establish a wide public acceptance for the research activities like the Ketzin project (Streibel et al. 2014)

16.3 Learnings from the Hontomin site

An integral communication plan and public outreach strategy has been designed and implemented in two areas, the site of the Technology Centre for CO_2 Capture and Transport located in Cubillos del Sil (NW Spain) and the CO_2 Storage Technology Development Plant in Hontomin (Burgos, N Spain). Both sites are different in terms of population, size, educational level and employment ratio. The actions are in place in parallel with the technology development activities, with significant success. Main findings extracted and lessons learned are the following: Strong Outreach Team, with trained speakers and diverse backgrounds Integral Communication Plan, developed in early stage. Fundamental components are: Intense interaction with stakeholders, especially with mass media materials tailored to audiences Key messages: CCS part of the climate change solutions; CIUDEN as R&D organisation which promotes public-private cooperation; the economy of knowledge generates jobs and opportunities in the areas networking with other projects (synergies). Educational Programmes: critical issue for near future Site-specific Communication Plans Application of socio economical characterisation in order to identify stakeholders and accommodate the Integral Communication Plan (Vercelli et al. 2017).

For the Havnsø pilot at Kalundborg it is the ambition to establish the same good practice as for Ketzin and Hontomin within the ENOS project.

16.4 Local interests

Kalundborg is a promising location for a CCS pilot because several industry companies are present in the area and because cooperation and network between these companies through Kalundborg Symbiosis already exists, because transport of CO_2 by ship (e.g. from Copenhagen) seems immediately possible due to the deep water port and because there are geological structures in the area that are expected to be suitable for CO_2 storage. The Port of Kalundborg can accommodate distribution facilities for intermediate storage and conditioning before piping or shipping CO_2 to the storage site.

The Røsnæs structure as a possible alternative is located mainly offshore. This is partly due to the fact that this structure will be a good example of a geological structure that is located off-shore but still near-shore, so infrastructure costs will be reasonably comparable costs associated with on-shore storage. The pilot site, if in future upscaled to a demo project or even a full-scale injection site, can be compared with industrial projects in the UK, which are expected to create hundreds of long-term jobs, directly and indirectly associated with the operation (including maintenance) (Global CCS Institute 2017).

16.5 Positive/ neutral/ public protests causing cancellation of planned CCS projects

It is important is accepted by the citizens of Kalundborg; therefore it is considered how the Municipality of Kalundborg can be involved in the project. The Havnsø pilot will create new opportunities for jobs in the area which for several years has been challenged by high rates of unemployment. Accordingly, labour market and skills policy should seek to maximise the benefits for workers.

17 FUNDING

The Danish government has recently earmarked one billion DKK to research in climate mitigation solutions and sustainable energy production technologies - in addition to what is used in previous years. The additional billion DKK will be used to develop new knowledge and solutions to our massive climate and environmental challenges, stated by the Minister of Education and Research, September 14, 2019.

"We do not know all the solutions to the environmental and climate challenges. But one thing is clear: We will only reach our goals if we get help from the research. For it, it is in research that we must find new, green solutions that benefit the environment, the climate and our common future. The new green billion comes above the 2019 level for earmarked funds for green research and on top of the growth in green funding for energy technology development and demonstration programs provided for in the 2020 energy agreement."

The funds will provide support for research that can help solve the climate challenges and Denmark to reach the 70 per cent objective. The funds will be further focused and prioritized within strategic thematic initiatives that contribute to the government's climate policy objectives (For example, more sustainable construction and transport, how we can better store CO_2 and get more sustainable production of food). https://ufm.dk/aktuelt/pressemeddelelser/2019/1-milliard-kroner-mere-til-gron-forskning

The Government has by November 2019 provided GEUS with the first year funding (2020) of 2 mill. Euro for a CCUS-Centre. The centre shall over de coming years perform research activities that can facilitates the deployment of CCUS in Denmark as a mean for reducing significantly the Danish CO_2 emission in order for Denmark to reach its 70% reduction goal. In parallel with this goal, the centre shall secure that the geological-technical aspects are well analysed and prepare for an application for the coming EU Innovation Fund to be announced in mid-2020.

18 EXPECTED DATE OF OPERATION AND DURATION

The Havnsø pilot project is expected to be initiated as soon as all financial and collaboration agreements are cleared and the needed licences approved by the authorities.

Prior to licences and related measures, a storage plan (work plan), including organization and plants and any pipelines thereof (extraction measures, etc.) must be approved by the Danish Energy Agency.

The plan must be submitted for approval by the Danish Energy Agency no later than 6 months prior to the implementation, unless otherwise agreed with the Danish Energy Agency. Wells that are expected to be used for recovery are also considered recovery measures.

The recovery plan must contain all such data, studies, interpretations, map models, etc. that are necessary for the Danish Energy Agency's assessment of the project. The material shall include:

(a) description of seismic data, drilling data and other data underlying the geothermal occurrence assessment;

(b) a description of the geothermal resource(s) planned to be recovered, with detailed analyses and assessments of geological, reservoir and extraction technologies;

(c) a description of the assumptions on which the recovery plan is based with regard to the heat planning for the sales area and the size of the expected sales;

(d) description of the installations, including the number, type and location of boreholes as well as recovery and reinjection equipment. An outline of the geothermal system and its interconnection with the rest of the district heating network must be enclosed, including the expectation of temperatures, production / injection rates, power, etc.,

(e) indication of the anticipated time of commencement of production and the expected size of annual production for each year the occurrence is scheduled to be in production;

(f) description of project economics, including costs for drilling, construction, pipelines, operating expenses, etc., as well as the heating price for geothermal heat, which shows the expenses / income included in the heating price and a comparison with the heating price for current district heating plants;

(g) the licensee's plan for how the recovery project is intended to be implemented, including the timetable and plan for the organization with which the licensee will implement the project; and

(h) an account of any uncertainties in the project with regard to reserves, drilling, schedule and finances, etc., as well as all other data, studies, interpretations, map models, etc. necessary for the assessment of the project.

Havnsø pilot GANTT chart															
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Applying/award of exploration permit	■														
Communication plan	■														
Stakeholder and public engagement	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Risk management plan	■														
Baseline	■														
Monitoring (pre- to post-operational)		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Seismic 2D investigation	■	■													
Site selection		■	■												
Assesment of storage potential		■	■												
Applying/award of drilling permit and storage permit			■												
Applying for storage permit			■												
Establishment of drilling site(s)				■											
Drilling					■										
Injection start						■									
CO2 acquiring					■	■			■			■			
Monotoring of injection						■	■	■	■	■	■	■	■	■	
Injection closure												■			
Post closure investigations													■	■	■
Transfer to autorities														■	
Post transfer															■

Figure 16: Gantt chart for a pilot project near Kalundborg (pre to post operational monitoring)

19 SCIENTIFIC AND OTHER BENEFITS

19.1 Objectives

The proposal is pilot project and it aims for a feasibility study facilitating large-scale deployment of CCS in Denmark. Without implementation of CCS, Denmark may not meet its obligations defined in the Paris Agreement. CCS is one of the few options that can deliver negative CO_2 emissions when applied to biomass-based power generation, waste incineration or biogas production. There is a great global challenge as stated by recent reports from the IPCC, IEA and EU emphasizing that the international goal of keeping the temperature rise below 1.5-2.0 °C may only be met if CCS projects are implemented in the near future. The primary aim of the project is to establish the necessary technical, economical and societal knowledge to enable large-scale CCS in Denmark.

Subsurface storage of CO_2 requires a suitable reservoir, preferably with a large capacity and overlain by a tight layer to prevent upward migration of the stored CO_2. Several promising candidates for establishing storage sites exist in Denmark, but available information on their subsurface characteristics is not yet sufficiently detailed to ensure the storage potential of each site. In the Havnsø pilot project, we will determine the suitability of potential storage sites close to the city of Kalundborg and design the accompanying monitoring program, thereby providing best practices for evaluation of other promising storage sites. The objective of pilot project is to verify that the Havnsø and/or the Røsnæs structures fulfil the requirements of the EU CCS directive and through pilot storage and experiments to determine CO_2 storage efficiency.

To demonstrate safe and environmentally sound storage is essential for later development of CCS. The main research and information interests for the Havnsø pilot will be to establish a good relation to the local population, to stakeholders, to establish a good baseline study and monitoring programme, a risk management programme and to ensure storage and drilling techniques and verify storage potential in the Gassum Formation and it possibility for storage upscaling.

Increase understanding on CO_2 injection and operational procedures will be acquired in the Havnsø Structure, which will give an opportunity to demonstrate operational procedures, monitoring techniques and integrated risk management approaches.

The project will investigate the ongoing processes during underground CO_2 storage; thorough observation of the injected CO_2 using geophysical and geochemical techniques; developing and applying numerical models and simulations for CO_2 migration; expanding the geological model for the research site. Activities:

- To assess storage potential
- To ensure seal integrity
- To define storage sites and exploration requirements, followed by site characteristics, risk assessment, and modelling
- To submit exploration permit applications (Compliance with all requirements of the Danish Subsoil Law and the EU CCS Directive, considering opinions of Commission)
- Establishing an oversight of any baseline monitoring & reporting, select relevant
- To develop an integrated risk management workflow leading to reliable and safe CO_2 storage operation, fulfilling the requirements of the European Directive for CO_2 Storage, in order to meet the needs of regulators, local population and operators; encompassing monitoring activities, update of risk assessment and potential risk mitigation and corrective measures.
- Start of monitoring and prepare corrective measures plans, eventual monitoring/corrective measures' plan updates
- To develop the smart integration of the different monitoring data acquired during operation.
- Site operation during the operation and decommissioning
- Well flow test, coreflow test, seal capacity analyses

- Monitoring the migration behaviour of the injected CO_2
- Determining the sensitivity of individual monitoring methods and
- Developing geophysical monitoring concepts for CO_2 storage pilot
- Characterizing and quantifying the CO_2-induced interactions between fluids, rock and the microbial community in the storage system
- Validating the tools for statistic modelling and dynamic simulation during the Havnsø pilot storage process
- To validate methodologies using microseismic monitoring network data to manage induced seismicity risk.
- CO_2 stream composition (clean, O_2 or other content)
- Seismic measurements for monitoring of underground CO2 migration
- Monitoring updates to site characteristics, risk assessment, and modelling
- To demonstrate innovative injection strategies and approaches for increased confidence of operators in managing sites safely
- Monitoring to detect leakages
- To validate tools and methodologies for monitoring the CO_2 plume in the reservoir and for acquiring data on reservoir properties for improved understanding on reservoir behaviour.
- To perform an integrated approach for the definition of technical guidelines for CO_2 storage operation, through cooperation with of research institutions, industry and service providers.
- Transferring knowledge to the public and to interest groups, policy-makers and approval agencies
- Data management, modelling & simulation

Issues arising from operational phase will be tackled in this pilot project, using real-life experience from other pilot sites e.g. the Hontomin and Ketzin pilot sites.

Reservoir mapping and seal integrity – For final site selection reservoir simulation models will be constructed using Petrel and Eclipse to simulate the injection depth, process, distribution of the CO_2 plume, pressure and storage efficiency. CO_2 core flooding experiments using core samples of reservoir and seal will be performed in the laboratory at relevant reservoir conditions to investigate flooding performance, and geochemical reactions between rock and gas-impure CO_2 saturated brines.

19.2 Benefits

Using the Havnsø Structure as an injection test site is an opportunity that will allow researchers from Denmark and Europe to meet the objective of performing CO_2 injection tests in the Gassum Formation and also here ensure demonstrating safe and environmentally sound CO_2 storage.

In addition, on a broader perspective, the Havnsø pilot CO_2 injection site also represents an opportunity for the development of CCS in Europe, as it could help:

- advance learnings from this real field test in terms of knowledge, methods and tools useful for CO_2 storage in saline aquifers in Europe,
- unlock the CO_2 storage potential in the Gassum Formation and initiate a business case for CCS and pave the road for large-scale storage implementation,
- demonstrate to stakeholders in Denmark and Europe that CO_2 storage is possible and makes sense from an environmental and economic point of view,

Integration into research programmes - This site will extend the ENOS project portfolio for the task of demonstrating CO_2 injection in an aquifer reservoir environment; i.e. CO_2 injection at depths relevant to large-scale CO_2 storage in Europe. The controlled injection tests will be used to examine the real-life impacts of different injection schemes in terms of safety and efficiency, including discontinuous CO_2 injection. Work can be planned to demonstrate safe and efficient CO_2 storage operations and testing different injection schemes, performing history matching, monitoring and testing a risk management protocol.

The proposed integration of the experience from the Hontomin and Ketzin sites into this pilot work programme will demonstrate safe and efficient CO_2 injection in Europe, which is key for public perception and convincing investors on the business case for CCS in the long term.

The nearby Stenlille structure has been used for gas storage for decades without leakage. It is a close geological analogue to the Havnsø and Røsnæs structures in terms of structural generation, reservoir and cap rock, and all relevant geological, geophysical, geochemical and production information from the gas storage are archived at GEUS and will be drawn upon including 3D seismic data, well-logs and core data. These data will be integrated with new regional 2D seismic lines and GEUS´ sequence stratigraphic model for the Gassum (reservoir) and Fjerritslev Formations (primary cap rock) to characterize the Havnsø structure.

Injection testing - The Havnsø pilot can perform controlled injection tests that will enable the team to complete the objectives initially planned:

- Study the impact of (vertical and/or horizontal) heterogeneities of the reservoir rock that trap the CO_2
- Test strategies to optimise CO_2 injection into a heterogeneous reservoir
- Verify the history matching modelling technique
- Well flow test, core flow test, seal capacity analyses

This will be performed by investigating different injection strategies such as water alternating with CO_2, different injection pressure, different injection temperatures (similar to the plans in Hontomin). The data and experience gained will be relevant to storage in both aquifers and oilfields in Denmark and neighbouring countries since the CO_2 will be injected at similar depth and the monitoring technologies deployed will be applicable to other sites and scenarios. The majority of lessons learned from history matching of the pressure impacts on the reservoir based on the real data will also be relevant to storage in aquifers and abandoned oilfields (though the oilfield models will be more complex because there are more types of fluids in the subsurface to consider). Expected injection activities:

- Injection tests and data interpretation to ensure safe and efficient operations
- Verification of storage (also useful for safety)
    - Well-based logging, potentially electrical, electromagnetic, VSP and reflection seismic, pre and post injection measurements to image the reservoir
    - Groundwater monitoring
- Demonstration of operational risk management for safe operations
    - Potentially induced seismicity monitoring: deployment of microseismicity monitoring station and interpretation of data. Comparison to the Stenlille study of the SECURe project
    - Risk assessment (in particular wells risk assessment, extent of study will depend on data availability)
    - Potentially test of risk management procedure (depending enough data set)

Seal integrity studies - The sealing Fjerritslev Formation in the Stenlille gas storage site has proven its integrity while holding a gas. The objective of the studies in Havnsø is to describe the characteristics of the seal, qualify the relevant properties for its integrity and assess its geomechanical integrity through modelling.

A study of the Fjerritslev Formation and overburden of geomechanical input the dynamic elastic moduli can be directly computed from the seismic inverted volumes, whereas static elastic moduli can be computed using statistical relations.

Core studies of the Fjerritslev Formation seal (depending on coring programme of the injection well) can describe pores in high specific surface clay-rich caprocks give rise to high capillary entry pressures and high viscous drag that hinder the migration of buoyant carbon dioxide CO_2. We can measure breakthrough pressure and ensuing CO_2 permeability through sediment core plugs studies.

Monitoring techniques - The objective of pilot project is also to develop a cost-effective and social accepted CO_2 monitoring program. Monitoring is essential in the risk management of a CO_2 storage site, both in order to ensure progress during operation according to planned targets as well as to verify that leakage to other geological strata or the atmosphere is not taking place. Thus, key performance indicators (KPIs) for a monitoring program can be defined. Based on the KPIs, legislative requirements and expected public acceptance criteria, a monitoring program can be designed for the Havnsø pilot. In order to identify the best possible technical solutions and associated costs, experience from similar other pilot and storage sites can be taken into consideration.

Demonstration of safe and environmentally sound storage - the CO_2 injection activities and deployed modelling and monitoring techniques can further demonstrate the concept of environmentally sound storage, understanding leakage risks and thereby mitigating them. If unforeseen leakage occurs, then monitoring methods will ensure it is more likely to be detected early and that possible emissions to the atmosphere can be quantified with greater precision. The injection of up to 100 kilotonnes of CO_2 together with the monitoring data gathered can confirm that the injection can be performed safely and efficiently.

Optimising safe operations and fine tuning of regulatory issues - Integrated workflows with a clear link to Risk Management will allow regulators to have a better overview of site behaviour, thus offering a collaborative link between site operators and regulatory authorities. The development of a protocol for daily management of injection and an alert system can allow integration of monitoring data and thereby optimisation of injection and storage while ensuring safety. Through consultation with representatives of regulatory authorities, the Havnsø pilot project can develop best practices targeting this pilot site.

The testing of different injection strategies will allow researchers to analyse and evaluate each of them and identify the optimal settings for injection. The injection experiment will provide scientific evidence to support decision making for upscaling CO_2 storage in Denmark.

Increased confidence of the local population - The demonstration of safe and environmentally sound storage is key to building confidence in the local population. This includes demonstration of the ability to manage and mitigate leakage risks and to ensure the protection of groundwater resources. This will be achieved by communication programme about the validation of monitoring tools for leakage detection and their integration into a comprehensive and effective monitoring programme. Most importantly, an innovative and cooperative process will be developed to involve the local population and to integrate their concern into the research agenda as far as practicable with the aim of increasing the confidence of the local population and the general public in the long term. An on-line communication tool, providing real-time information on site operations can be created, based on the needs expressed by the local community.

Increased confidence of operators, emitters and investors - Site operators, emitters and investors need greater visibility on the implications of CCS project developments and their economic potential to advance CCS as a favourable option. In addition to providing key technologies, sensors and protocols adapted to their needs, the Havnsø pilot will improve the reliability of capacity estimates, participate in de-risking early site characterisation and outline methods for clearly communicating storage capacity and uncertainties to these end users. In order to improve the business case for CCS, additional studies can investigate opportunities to integrate CO_2 storage in the economic development of the Kalundborg region.

The work performed on the Havnsø pilot site will be useful to demonstrate if the structure can be upscaled to a CO_2 storage site, which in the future could become an option for reducing emissions. In addition, the research will demonstrate the value for operators to maximise CO_2 storage (as soon as the value of CO_2 on the market allows for establishing a business case for CCS in Europe).

Public awareness - The Havnsø Pilot will publish documents for civil society, to explain the CO_2 storage technology. Online dissemination materials will be made globally and openly accessible through the project and partner websites. Work with the media will be undertaken, in particular in relation to the experimental and pilot sites, in collaboration with site operators.

Enhanced and effective cooperation between key stakeholders - The Havnsø Pilot project will be building on the pan-European coverage and expertise of CO_2GeoNet. The portfolio gathers sites in several Member States and the Havnsø Pilot can ensure cooperation between these sites. Testing technologies in real-life conditions requires field work that is costly, both in terms of capital costs and operational costs. The added value of the Havnsø Pilot project will be to enable additional testing of innovative technologies at these sites, longer test periods, and a site specific portfolio approach necessary to demonstrate technologies across the storage cycle in a socio-economic context:

- Enhancing knowledge transfer from existing sites worldwide to catalyse new projects;
- Bringing key technologies, developed in the Havnsø Pilot and necessary for CCS deployment onshore, to operators and engineers;
- Building a roadmap for upscaling;
- Training and educating scientists and engineers to face the challenges of CCS.

Local societal readiness - the societal readiness is expected to be raised having a continuous dialog with the local stakeholders and local group of public's representatives. This is achieved by a strong partnership between public and private stakeholders and local group of public's representatives that can fertilize the ground for future EU-funding of Danish CO_2 projects. The project focuses on a Danish case and ties together the principal components necessary to realize negative CO_2 emissions in order to reduce future climate changes.

20 SPECIFIC BENEFITS FOR LOCAL COMMUNITIES

Green jobs are very heterogeneous in terms of job skill requirements, pay levels and working conditions. The transition towards green growth is thus unlikely to either significantly exacerbate or ameliorate concerns about job quality or inequality, which are best addressed by other policy instruments (OECD 2012).

Kalundborg municipality has both large and small companies in many different industries, from high-tech industry to agriculture to retail and more. The labour market in Kalundborg Municipality is experiencing a positive development with a growing workforce, increased employment rate, more employed and fewer unemployed. The labour force has grown since 2013, and thus the supply of manpower has increased. The labour market in Kalundborg Municipality is experiencing a positive development with a growing workforce, increased employment rate, more employed and fewer unemployed. The challenges are in matching the offered and sought-after competencies. Until the end of 2019, a positive development in the labour market in Kalundborg Municipality is expected. Kalundborg Municipality has a focus on companies getting the manpower they need - both now and in the future. The Havnsø pilot will create new opportunities for jobs in the area which for several years has been challenged by unemployment. Accordingly, labour market and skills policy should seek to maximise the benefits for workers in job generation within marketed goods and services and construction of the pilot site. Once construction is complete, job generation tends to decline, but staff responsible for operation and maintenance, including the associated supply chain, will be employed permanently. There is a large amount of data and case studies available on potential job creation from CCS (TUC Clean Coal Task Group 2011)

21 POTENTIAL CONSORTIUM

A potential consortium may be found within a few of the possible stakeholders to the Havnsø pilot, see 22.2.

22 STAKEHOLDER ENGAGEMENT AND EXPECTED IMPACT, INDUSTRIAL AND PUBLIC OUTREACH

The stakeholder engagement is expected to be through having a continuous dialog with the local stakeholders and local group of public's representatives as well as within the list of potential stakeholders or partners (see below).

Currently, climate changes and the need for reduction in CO_2 emissions have been well articulated in Denmark. However, the magnitude of the problem and the relative importance of different capture means leading to negative emissions are poorly understood among the public.

22.1 Stakeholder identification and engagement

The project operator shall identify project stakeholders early in the storage project life cycle and engage them during all phases of the project (ISO/TC265 2018).

The project operator should organize, allocate human resources, and direct the activities of a storage project in accordance with the storage project periods specified in this pilot.

22.2 Possible stakeholders to the Havnsø pilot

Stakeholders can include decision makers, employees, shareholders, academia, insurance companies, banks, community residents, suppliers, customers, non-governmental organizations, governments, regulators, labour unions, and other individuals or groups. The stakeholders identified so far are:

- Amager Ressource Center – ARC[5]
- Avista Oil Danmark A/S, Kalundborg[6]
- Dansk SymbioseCenter, Kalundborg[7]
- DTU Kemiteknik, Institut for Kemiteknik[8]
- Energinet.dk[9]
- Equinor Refining Denmark A/S[10]
- Gas Storage Denmark (GSD)[11]
- Kalundborg Bioenergi, Bigadan Kalundborg[12]
- Kalundborg Forsyning A/S[13]
- Kalundborg Kommune; Biotekbyen[14]
- Københavns Kommune, Teknik- og Miljøforvaltningen[15]
- Pentair[16]

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- Rambøll[17]
- University of Copenhagen, Department of Geosciences and Natural Resource Management[18]
- University of Aarhus, Institute for Geoscience[19]
- Ørsted Bioenergy & Thermal Power A/S[20]

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This publication was completed with the support of the European Commission and European Union funding under Horizon 2020 research and innovation programme. The contents of this publication do not necessarily reflect the Commission's own position. The document reflects only the author's views and the European Union and its institutions are not liable for any use that may be made of the information contained here.

MINING AND GEOLOGICAL SURVEY OF HUNGARY

ENOS project

CO_2 storage pilot at Kenderes

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1. Aims of the pilot project at Kenderes site

The main goal of the ENOS project is to enhance the development of CO_2 storage onshore, close to CO_2 emission points. In the frame of the project several field pilots in various geological settings are studied in detail and best practices that stakeholders can rely on will be produced. The main outcome of the ENOS project will be to demonstrate that CO_2 storage onshore in Europe is safe and environmentally sound. In this way it will increase the confidence of stakeholders and the public in CCS as a viable CO_2 emissions mitigation option.

The motivation behind selecting Kenderes for pilot investigations is based on over a decade of screening of the potential geological CO_2 storage reservoirs in Hungary. This screening activity started as a basic assessment of potential storage formations. The initiation and funding came from to EC FP6 and FP7 research projects (i.e., EU GeoCapacity, CO2Stop, etc…). From 2012 (the implementation of the Geological Storage Directive (2009/31/EC) in the Hungarian regulation system) the process continued in the frame of the national regulation and under State funding. Detailed screening of potential storage sites has led to a narrow down of sites to be studied in detail.

Hungary lies within the Pannonian Basin, a Cenozoic basin system with thick Miocene-Pliocene sedimentary fill comprising of potential storage lithologies separated by thick, impermeable clay and mudstones. The geology of basin filling sediments, due to the analogue sedimentary process, is quite similar throughout the whole basin system. A successful pilot injection project realized in this geological environment could be a good practice for the other countries (Austria, Slovenia, Croatia, Romania and Slovakia) sharing the Pannonian Basin.

The Kenderes site is a mature, practically depleted gas field. The field comprises of several reservoirs with a broad range of volumes. Comprehensive exploration, including seismic, gravity, as well as borehole geophysics, water and gas analysis have been carried out in several exploration phases, already from the 1950s. There is also a long record of the production history in the field that provides valuable information for any potential feasibility study and detailed planning. Furthermore, some of these reservoirs contained gas with high CO_2 content. Hence, the risk that injection of carbon dioxide would result in violent water-rock interaction, compromising the safety of storage is minimal.

The selection of Kenderes area as a pilot injection site also offers a favorable potential to upscale the pilot project, when proven successful. The upscaling potential is twofold. Firstly the field in the Kenderes area consists of multiple reservoirs with similar geological structure and comparable reservoir geological parameters. When successful, more reservoirs of the field could be involved in the storage of carbon dioxide. Secondly Kenderes area lies in the eastern-northeastern part of Hungary, close to several industrial facilities within relative vicinity (<100 km), namely power plants, facilities related to chemical industry. The overall annual emission in the region related to large point sources is over 6 million tons.

2. Review of geography and geology

2.1. Geography in the pilot area

The pilot area lies in the Jász-Nagykun-Szolnok County. Geographically the area lies in the Great Hungarian Plain within the Middle Tisia area, in the Szolnok–Túr Plain, on the plain of an alluvial fan covered by loess. The relative relief is 2 m/km^2. In some parts of the area 1-5 m high sand dunes covered by loess and sand, dry riverbeds and ox-bow lakes are found.

Climate is dry and warm. Average temperature is 10.2–10.4 °C with a maximum of 34–34.5°C, whereas, the minimums fall between -16.5 – -17°C. Annual precipitation is >520 mm. The snow coverage in the area is lasting for 32–34 days annually, reaching approximately 150–160 mm thickness. Dominant wind directions are N, S and W. Wind velocities are generally higher than >2.5 m/s. From agricultural point of view the soils are high quality black earth lands with favorable productivity potential.

The Kenderes pilot area lies in the Great Hungarian Plain, east to Nagykörű and Fegyvernek hydrocarbon fields in the vicinity of Karcag, Dévaványa and Jászberény concession areas. (Figure 1).

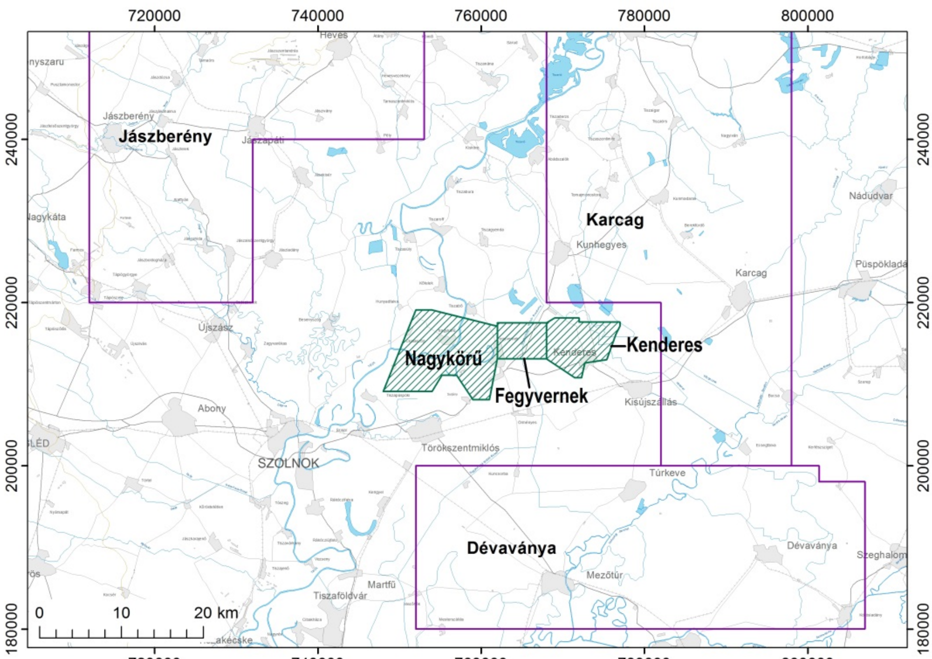

Figure 1. Geographic sketch map of Kenderes pilot CO_2 storage site

2.2. Main tectonic setting of the area

The tectonic setup of the area is described based on Haas et al. (2010). The pilot CO_2 storage area lies south of the Mid-Hungarian Lineament and is part of the Tisia structural megaunit. Within the megaunit the area belongs to the Mecsek unit. In Hungary the Tisia megaunit is composed of three structural units, namely the Mecsek unit, the Villány-Bihor unit and the Békés-Chodru unit (Figure 2). The Mid-Hungarian Lineament, which is dominantly a transform shear zone (Csontos and Vörös, 2004; Palotai and Csontos, 2010) runs north of the pilot. This structural lineament represents the boundary between the Tisia and ALCAPA megaunits.

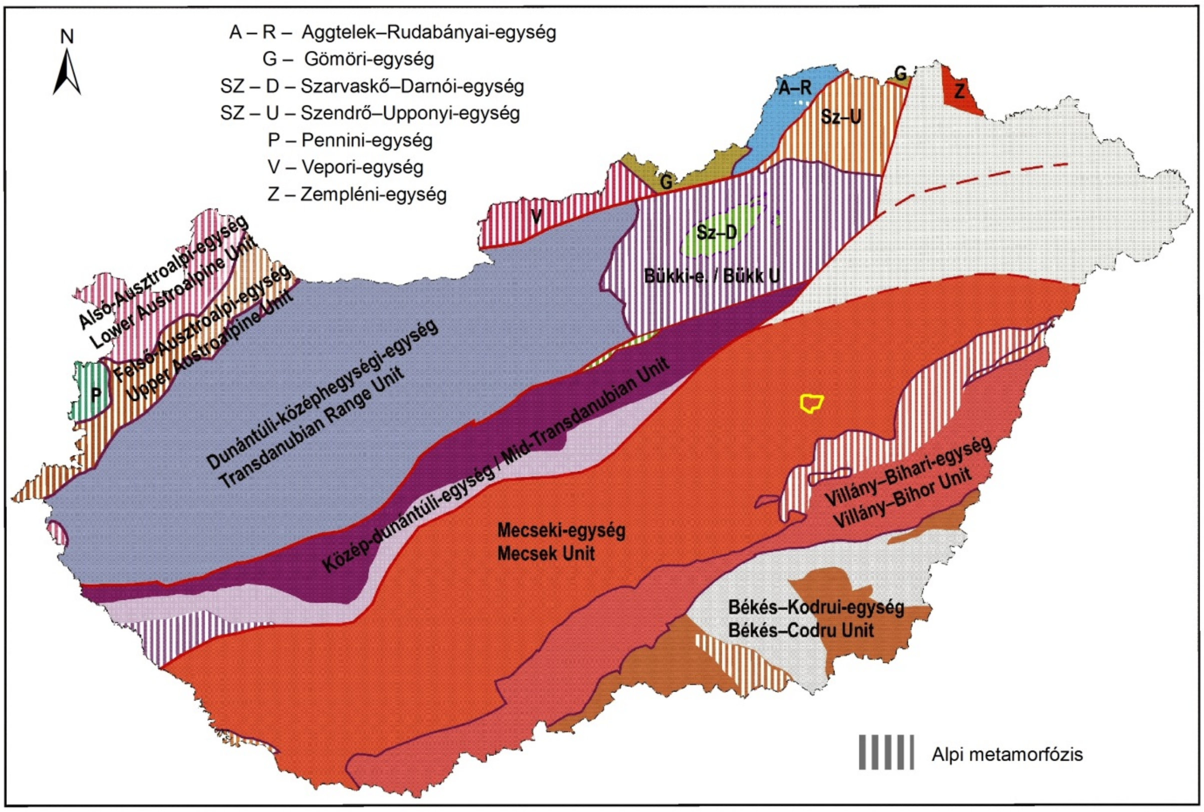

Figure 2. Structure of the basement (based on Haas et al. 2010), The CO_2 storage pilot is indicated by the yellow polygon

The units composing the Tisia megaunit have amalgamated in the Carboniferous (Szederkényi 1998, Császár 2005). The NE-SW tending belt like structure of the megaunit is related to Alpine nappe formation. The current structure has been developed during orogenesis in the neoalpine orogenic phase. The northern boundary of the Villány-Bihor unit is formed by the nappe front separating it from the Mecsek unit. Along this first order Mesozoic nappe boundary, the Variscan metamorphic complex of the Villány-Bihor unit, at its central part was overthrusted on the Mecsek unit from the south (recent geographic direction), in the Middle- Late Cretaceous. Cretaceous flakes of the Mecsek unit are overlain by the Szolnok

Flysch, which is a thick series of Upper Cretaceous- Paleogene sandstone. This Flysch stratum is strongly tectonized, folded and has a flake structure (Figure 3)

The main tectonic lineaments of the basement have NE-SW strike and represent either reverse faults, flake or nappe boundaries. Besides the Mid Hungarian Lineament and the Cretaceous nappe boundary, originally acting as a reverse fault then switching to transform character, significant reverse faults are present within the Szolnok Flysch (Figure 4)

The geometry of the units and megaunits in the area is well expressed on the PGT-1 deep seismic cross section. An interpreted version of this seismic section is shown on Figure 3 by Tari et al. (1999). The Kis-1 borehole on Figure 3 lies on the eastern boundary of the pilot area

On the cross section heading from the NW we find the Jászság depression, which is a sinistral transform zone filled by a thick Neogene volcanic series. Heading towards the SE, we find the Mecsek unit, consisting of Variscan metamorphic units overlain by Permo-Mesozoic sedimentary cover that is followed towards the SE by the nappe units. According to the geological interpretation of the cross section the Cretaceous reverse fault is lying below the flysch zone where the metamorphic basement and its sedimentary cover are thrusted as a single unit towards the NW. Further towards the SE, south of the pilot area, we find the nappes of the Villány unit that was metamorphosed during Variscan and Alpine orogeny.

The cross section (Figure 3) does not provide geometric explanation to the occurrence of the Cretaceous-Paleogene flysch sequence that covers the boundary between sheets within the Mecsek unit. Nevertheless, the transposition of sedimentation in the Miocene, in the syn-rift phase of the Pannonian Basin to the Mid-Hungarian zone is clearly observed. The development of several km thick Neogene basin filling sediments in the whole region was enabled by post-rift subsidence.

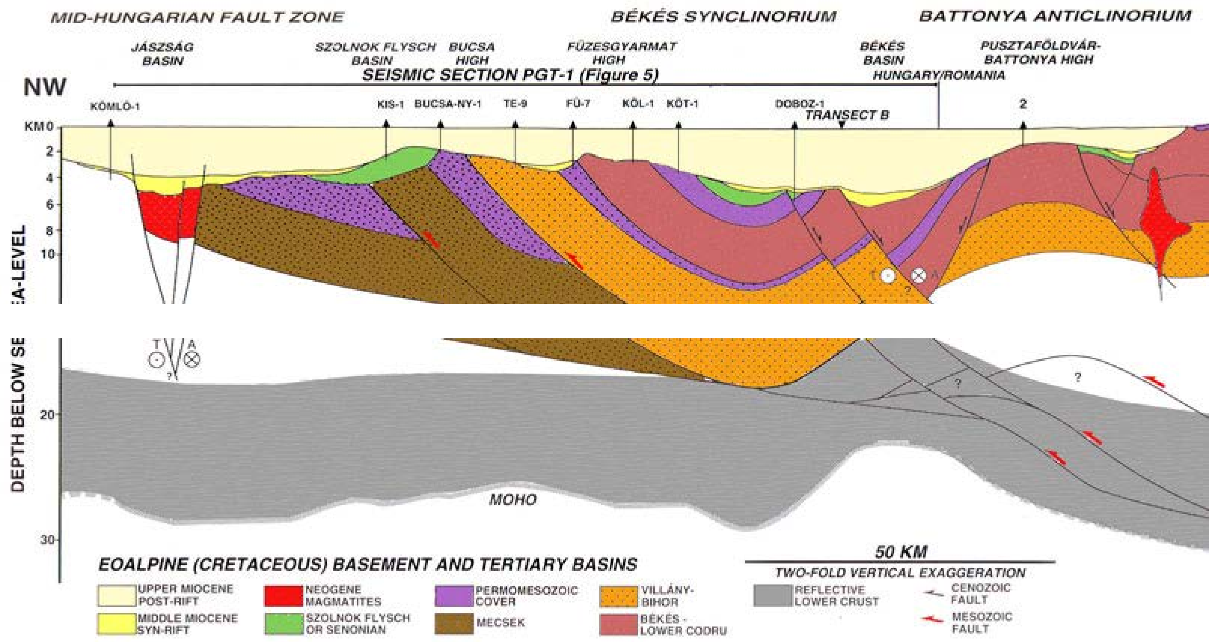

Figure 3. Nappe structure of the basement shown on the PGT-1 seismic section (Tari et al. 1999)

The main structure of the Tisia megaunit is determined by two E-NE – W-SW striking anticlines and two synclines in between. These structures are of Variscan age. They were deformed during alpine tectonics, however their domal structure and synclinal geometry has been preserved. From the south, this structure is bounded by an Upper Cretaceous nappe boundary. The synclinal ranges contain granite and migmatite bands (Szederkényi 1998).

2.3. Lithology of the area

Composition of the basement

Formations of the basement are discussed following the Pre Cenozoic geological map of Haas (2010) and are based on reinterpreted deep boreholes. Some boreholes falling outside the pilot area are also used for the discussion.

It is very likely that the Paleozoic formations of the Mecsek unit can be found beneath the Upper Cretaceous-Paleogene Szolnok Flysch belt. However their presence has not been proved, because none of the boreholes had reached these formations. The basement of the whole pilot area is composed of a single assemblage, namely the lithostratigraphic units of the Cenon – Paleogene pelagic marl, the flysch (Figure 4, unit 1.)

The Izsák Marl Formation is an Upper Cretaceous formation in the pilot area, which is a calcareous marl - marl with deep basin facies. Its maximum thickness is approximately 330 m (Szentgyörgyi and Császár, 1996). This formation was not reached by boreholes in the pilot area. Towards the East the formation is heteropically interfingering with the Debrecen Formation (Császár, 2005).

Szolnok flysch belt (Upper Cretaceous-Paleogene):

The deep marine facies flysch is the oldest known formation in most of the pilot area. The flysch is an Upper Cretaceous-Paleogene post-tectonic deposit over the Mesozoic nappes of the Mecsek-Középalföld zone (Figure 3, green unit). The Szolnok Flysch is found on the northern margin in the vicinity of the Mid Hungarian Lineament. The flysch formation is separated from the lineament only by a poorly revealed thin crystalline range.

As discussed above, the Szolnok Flysch is deposited on a Mesozoic nappe system. Despite their different tectonic evolution, together they form the basement of the Pannonian depression that was developed from the Middle Miocene. The strike of the zone is NE-SW and can be followed approximately for 150 km from the city of Szolnok. The width of the zone only rarely exceeds 20-30 km.

The thickness of the Neogene cover ranges between 2-3 km. One of the most striking differences between the basement-forming flysch and the Neogene cover is the sub-horizontal layering in the Neogene, contrasting the tectonized, brecciated nature of the flysch with steep layering. Unfortunately, in several cases there is no clear separation between the Neogene sediments and the flysch, resulting in poorly defined boundary between them, especially with Badenian strata. The bottom boundary of flysch is also poorly defined, because there have been no boreholes in the area crossing the flysch units. Based on seismic data, the thickness of the Szolnok Flysch may reach 1000-1500 m.

The internal structure of the Szolnok Flysch zone is poorly constrained. Cretaceous formations occur sporadically but frequently, primarily in the northern part of the flysch zone. Cretaceous formations are known in the vicinity of the following villages Törtel, Szandaszőlős, Kunmadaras, Kisújszállás, Nádudvar, Püspökladány. No Cretaceous formations have been penetrated in the pilot area, therefore, their presence is uncertain. Paleocene-Eocene transitional formations are only known from the northern margin of the flysch zone, close to Alcsi, Fegyvernek, Kisújszállás, Józsa, Hajdúhadház (Nagymarosy, 1998).

Lithostratigraphic units of the Szolnok Flysch:

The Debrecen Formation is an Upper Cretaceous assemblage. The formation is built up by alternating layers of sandstone, aleurolite with subordinate silt, clay marl and conglomerate interlayering. The assemblage was formed as turbidite in bathyal environment. Its thickness has not been constrained (Szentgyörgyi, 1996). The formation has not been penetrated in the pilot area. A large unconformity is observed between the Cretaceous and the Upper Paleocene-Lower Eocene units.

The Nádudvar Complex consists of Paleocene-Oligocene formations. It is characterized by stiff, fractured sandstone, conglomerate, aleurolite, clay marl, and clay layers showing a rhythmic alternation ("Carpathian sandstone"). It represents a deep marine facies with thickness in the range of 100-1000 m (Bernhardt, 1996).

The Nádudvar Complex has been explored by several boreholes in the pilot area (Figure 4). In borehole Nkö-1-the complex is found in the 2269-2300 m depth range, whereas in the Su-1 borehole, it was identified between 2062-2300 m. In the Kis-ÉK-2 the assemblages of the complex are present in 270 m thickness. In SW direction the Fv.D-1 borehole (Figure 4) penetrates the complex in the depth range between 2247-2300 m. The Kis-1 between 1741-1745 m, the Kis-4 between 1734-1776 m, the Kis-6 between 1630-1700 m. These data clearly show that the formation is becoming more-and-more shallow towards the E-SE (Figure 3).

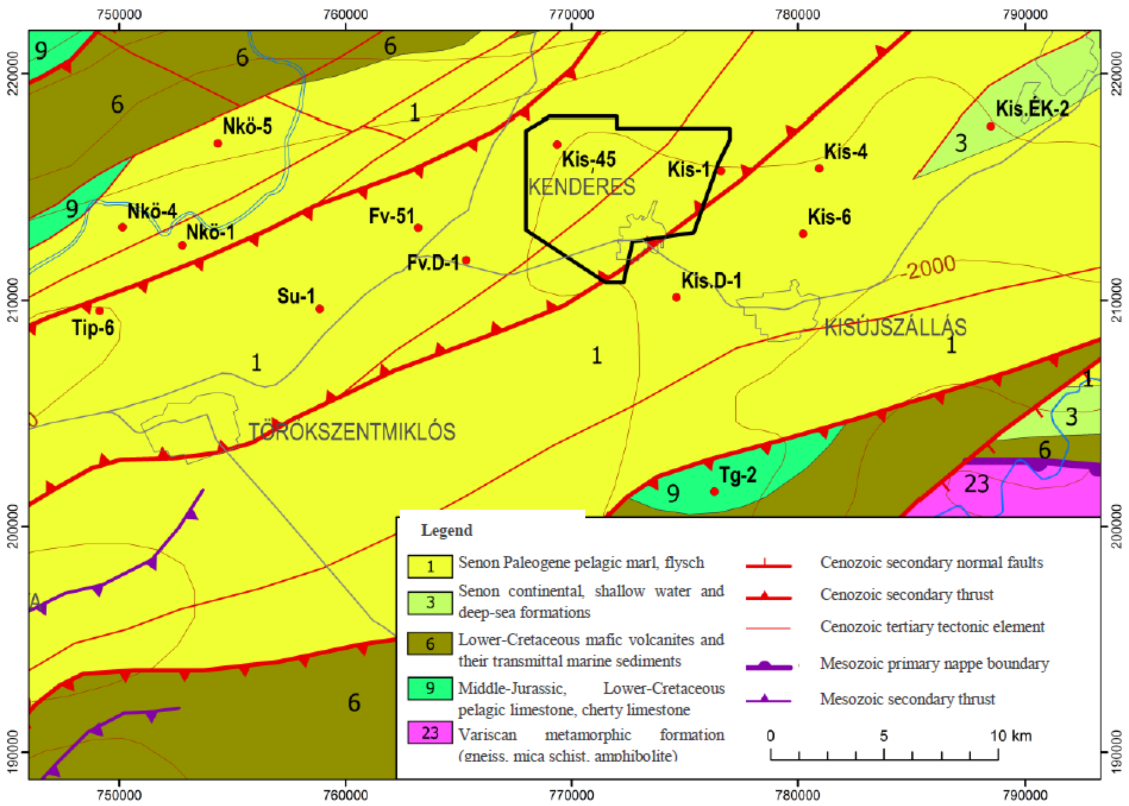

Figure 4. Pre-Cenozoic geological map of the pilot area, indicating reinterpreted deep boreholes (Haas et al 2010.), pilot area is indicated by black polygon

Tectonic character of the Szolnok Flysch

The flysch zone is strongly tectonized. Strata with 70-90°dip, deformed, shiny clay marls, brecciated rocks are dominant. The Neogene sequence covering flysch is less tectonized, therefore, this tectonized nature is one of the main characters to differentiate between flysch and overlying younger sediments.

Several large scale reverse faults have been described by Pap (1990) from the eastern portion of the Great Hungarian Plain. One of these reverse structures from the Bucsa-Ny l. borehole (Figure 3), SW from the pilot area), crosscuts the Szolnok Flysch. This structure overthrusts Upper Eocene strata by the Upper Cretaceous sedimentary sequence. Besides the Late Cretaceous nappe formation, after the formation of the Szolnok Flysch but predating the Neogene basin subsidence, the whole unit suffered strong compression followed by emersion and erosion in the Lower Miocene (Nagymarosy, 1998).

Paleocene-Oligocene events

During the Paleogene, most of the area emerged above sea level. Only the flysch basin remained below sea level where sedimentation continued *(Nádudvar Complex)*. The whole area emerged above sea level during the Oligocene, which enabled significant erosion, that was going on until the Lower Miocene (Lemberkovics 2009). The flysch is overlain by Miocene sediments and volcanoclastic rocks with large disconformity.

Miocene events

The Middle Miocene was characterized by repeated NW-SE directed tectonic forces, which deformed the NE-SW striking Pre-Cenozoic structural units. This effect developed a stress field within the Carpathian arc, which formed NE-SW striking asymmetric troughs along with small scale strike-slip movements. As a consequence direct sea connection formed with the Mediterranean basin through the collapsed Dinaric system. In the Carpathians, repeating transgression through these collapsed zones and basin forming, opening and widening of the trough system took place starting already from the Lower Badenian. In the Lower Badenian transgression occurred in a paleogeographic framework similar to that in the Carpathians, which resulted in similar facies distribution. The Pannonian Basin was formed in the Upper Miocene as a chain of mainly uniform sub basins (Hámor, 1984).

Strike-slip movements have renewed between 6.8 – 9.1 Ma resulting in considerable subsidence. This subsidence resulted in thick sedimentary sequence of delta front sediments deposited in the Pannonian Lake. According to the integrated stratigraphic analysis of Juhász et al. (2006) basin inversion took place following the development of the Pa–4 sequence boundary at 6.8 Ma. The fluvial sedimentary sequence with significant thickness represents continuous sedimentation from the Late Miocene to the beginning of the Quaternary. Considering the considerable thickness of the young Quaternary sediments, most of the area continued to subside (Juhász et al. 2006).

Miocene units of the pilot area

Miocene basin filling sediments of the pilot area are described based on the detailed analysis of drill cores and cuttings derived from the area. Other boreholes from the Nagykörű area and from a 5 km range of the pilot area are also used.

Very thick (1-5 km) sediment sequence has developed in 10 million years in the Pannonian Basin. Because of the strong subsidence the available space was large. The synchronously rising mountain belts, that surrounded the basin, namely the Carpathians and the Eastern Alps, provided voluminous easily eroding material. The erosion was most likely the strongest in the flysch and molasses type rocks, which yielded huge amount of siliciclastic sediments in the basin. The sub basins of the Pannonian Lake, with various subsidence rates were mostly interconnected. The supply from the margins was continuous, therefore, the sub basins were filled subsequently. The main directions of sediment transport are well identified on seismic sections: NW in the Great Hungarian Plain with subordinate NE-E transport routes (Juhász, 1998). The pilot area falls in the zone, where the different transport routes overlap. This feature has an influence on the geology and hydrocarbon geology of the subsurface.

The filling of the Pannonian Lake was terminated in the Late Miocene (Magyar, 2010).

The sediments of the Pannonian Lake deposited on older Miocene units or pre Cenozoic basement. The base of the Pannonian strata in the pilot area is approximately at 2000-2400 m depth. Only Middle and Upper Miocene formations are found in the pilot area.

Middle Miocene, Badenian units

Based on the reinterpreted well logs the thickness of the Middle Miocene units in the pilot area is 40-120 m. The base of the Miocene units is mainly built up by conglomerates and sandstone. This continental unit is overlain by thin red clay covered by marine Miocene layers with tuff horizons. A Lithothamnic biogenic limestone with variable thickness is the marker layer in the marine Miocene. The base of this layer is either tuff or sandstone, and is covered by clayey tuff layers. Heading from South to North, the ratio of volcanic material is increasing with respect to the siliciclastic material. Paleontological analysis concluded that these units are Badenien. The Kis-ÉK-2 borehole penetrated Badenian units in 145 m thickness (Figure 6). The Pannonian units overlying the Badenian formations are deposited with discordance.

Late Miocene – Pliocene units Peremarton Formation Group and Transdanubian Formation Group

The Peremarton Formation Group traditionally consists of Endrőd Marl, Szolnok Sandstone and the Algyő Formation the so called “Lower Pannonian” formations.

Far from the provenance areas in the innermost part of the basin, condensed sedimentation took place. This sedimentation process generated hemi pelagic lacustrine, landlocked marine clayey, carbonaceous layers that represent calcareous marl, marl, clay marl sequences. These lithologies comprise the Endrőd Formation that is the lowermost unit of the Pannonian strata. The thickness of this formation in the pilot area reaches 160 m. The formation was penetrated by the Kis-ÉK-1,-2,-3 boreholes (Figure 6). The filling of the basement took place from the NE. The sediments are dominantly distal marls. The unit thickens and deepens toward the West, Southwest. On the base of this unit, in not more than 100 m thickness, the Tótkomlós Calcareous Marl member can be distinguished.

The top of the formation is a sharp sequence boundary, where the direction of sediment inflow switches from NE to NW. Furthermore, pelites are replaced by psammites.

This group of sandstones is the Pl1-6. Its thickness is between 50-100 m and is wedged out towards the East. This unit is bounded by sequence boundaries both from its base and top. This assemblage represents the most important hydrocarbon migration pathway in the pilot area.

From paleogeographic point these sediments were deposited in delta slope, delta front environment. They were deposited with discordance on their bottom layer. Discordance can be observed towards the cover because of the transgression related nature of the covering lithologies. Typical delta sediments are found north of the pilot area. The nearing of the provenance area is indicated by the replacement of distal marls by delta foreland sandstone units. This series of alternating fine grained sandstone, aleurolite clay marl-marl is the *Szolnok Sandstone Formation.* Its thickness is strongly variable. In the deep basins it may exceed 1000 m, whereas it wedges out on basin margins. Its average thickness in the pilot area is 430 m.

These turbidites (namely the Szolnok Sandstone Formation) are covered by slope (delta slope and basin slope) sediments that deposited as a result of gravitational flow derived from fine grain sands, comprising the Algyő Formation. The thickness of the clayey, aleuritic strata with channel filling sediments, sand bars and gravitational aleurite and sandstone bodies is strongly varying. The overall thickness reaches 100-900 m with 550 m in the pilot area.

Sedimentation took place dominantly at the basin margins. The sediments are dominated by delta sediments, because these represent the dominant type and volume of sediments in the whole sequence. The basin filling process was mainly controlled by high flowrate rivers carrying large amount of sediments and depositing those in their estuaries. The Great Hungarian Plain is characterized by two delta systems, one approaching from the W-NW and the other from the NE.

Further away from the river throats, characteristic near shore sedimentation took place. The Újfalu Sandstone Formation deposited in the estuaries, delta front, delta plain and coastal plain. The so called traditional “Upper Pannonian” sequence comprises of the Újfalu Sandstone Formation, the Zagyva Formation and the Nagyalföld Variegated Clay Formation, the a Dunántúl Formation Group. The Újfalu Formation comprises of varying sandstone, aleurite and clay marl layers. The thickness of the sandstone layers may reach several tens of meters. Chars with plant origin are often found, sometimes forming layers in the rock. In the pilot area the delta plain sediments are characterized by thick-bedded facies with only 1-2 sand beds clearly identified in the seismic sections and well logs. The top of the delta plain forms an E-W directed mild syncline. The deepest point of this syncline is found in the Fegyvernek area. The thickness of the formation is between 20-1000 m, in the pilot area it reaches 150 m.

In the regions where the basin depression was already filled up fluvial-flood plain, lacustrine and marshland sedimentation occurred. These sediments comprise the uppermost part of the Pannonian sedimentation, namely the Zagyva and the Nagyalföld Variegated Clay Formations. This sequence can reach considerable thickness in the central part of the basin (Juhász, 2006). The Nagyalföld Variegated Clay Formation overlying the Zagyva Formation is poorly distinguished from its underlying formation. The amount of sand is strongly reduced in the sequence, which is very characteristic for delta background sedimentation. The development of sand beds transitions to thin layering of varying sandstone and clay. The dominantly lacustrine sedimentation in the delta background is identified as the Zagyva Formation. There is a slight regional thickening of this formation in the direction of

Kisújszállás (towards the East). The formation may reach over 1000 m thickness (Juhász et al., 1996). In the pilot area the thickness of the formation is approximately 300 m.

The Nagyalföld Variegated Clay Formation is composed of alternating sand and clay layers with varying thickness. Lignite and sandy gravel layers are also frequently developed. In the deepest part of the depressions, its development may have continued until the Lower Pleistocene. Its thickness is generally several hundred meters (Gajdos and Pap, 1996). In the pilot area the thickness of the Nagyalföld Variegated Clay Formation reaches 300 m. The Kis-45 borehole penetrated the formation between 355-615 m (Figure 6). In all boreholes that have reached the Pannonian strata the above listed and described formations are clearly identified.

The thickness of the Miocene formations shows a thickening tendency from W to E: in the Nkö-1 borehole 110 m, whereas in the Kis-13 and Kis-17 305 m and 372 m thick Miocene is penetrated, respectively. However, Miocene is entirely missing from the Kis-6 borehole drilled on the SE wing.

There has been a significant reinterpretation of Neogene chrono and lithostratigraphy starting from the 1980s. Therefore, we represent the currently accepted interpretation and its relation to earlier systems (see Table 1 and Figure 5).

Table 1. Major changes in chronostratigraphy

<table>
<tr><td colspan="4">Traditional classification</td><td colspan="2">Hungarian new classification

(from the 1980s)</td><td colspan="2">International accepted classification</td><td>Formation groups</td></tr>
<tr><td>Quaternary</td><td colspan="3">Q</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Pliocene</td><td rowspan="4">Pl</td><td>Uppermost Pliocene (Levantian)</td><td>Pl3</td><td rowspan="4">Pannonian (s. l.)</td><td rowspan="3">Upper Pannonian- (Pa2)</td><td rowspan="2">Pl</td><td rowspan="2">Pliocene</td><td rowspan="4">Dunántúl Fg.
Peremartoni Fg.</td></tr>
<tr><td rowspan="2">Upper Pliocene (Upper Pannonian)</td><td rowspan="2">Pl2</td></tr>
<tr><td rowspan="2">M3</td><td rowspan="2">Upper Miocene</td></tr>
<tr><td>Lower Pliocene-Pliocene (Lower Pannonian)</td><td>Pl1</td><td>Lower-Pannonian (Pa1)</td></tr>
<tr><td rowspan="6">Miocene</td><td rowspan="6">M</td><td>Sarmatian</td><td>M3</td><td rowspan="2">Middle Miocene</td><td>Sarmatian (Ms)</td><td rowspan="2">M2</td><td rowspan="2">Middle Miocene</td><td rowspan="6"></td></tr>
<tr><td>Tortonian</td><td rowspan="3">M2</td><td>Badenian (Mb)</td></tr>
<tr><td rowspan="2">Helvetian</td><td rowspan="4">Lower Miocene</td><td>Karpatian (Mk)</td><td rowspan="4">M1</td><td rowspan="4">Lower-Miocene</td></tr>
<tr><td>Ottnangian (Mo)</td></tr>
<tr><td>Burdigalian</td><td rowspan="2">M1</td><td>Eggenburgian (Me)</td></tr>
<tr><td>Aquitanian</td><td>Egerian (Mer)</td></tr>
</table>

*Fg.: Formation group

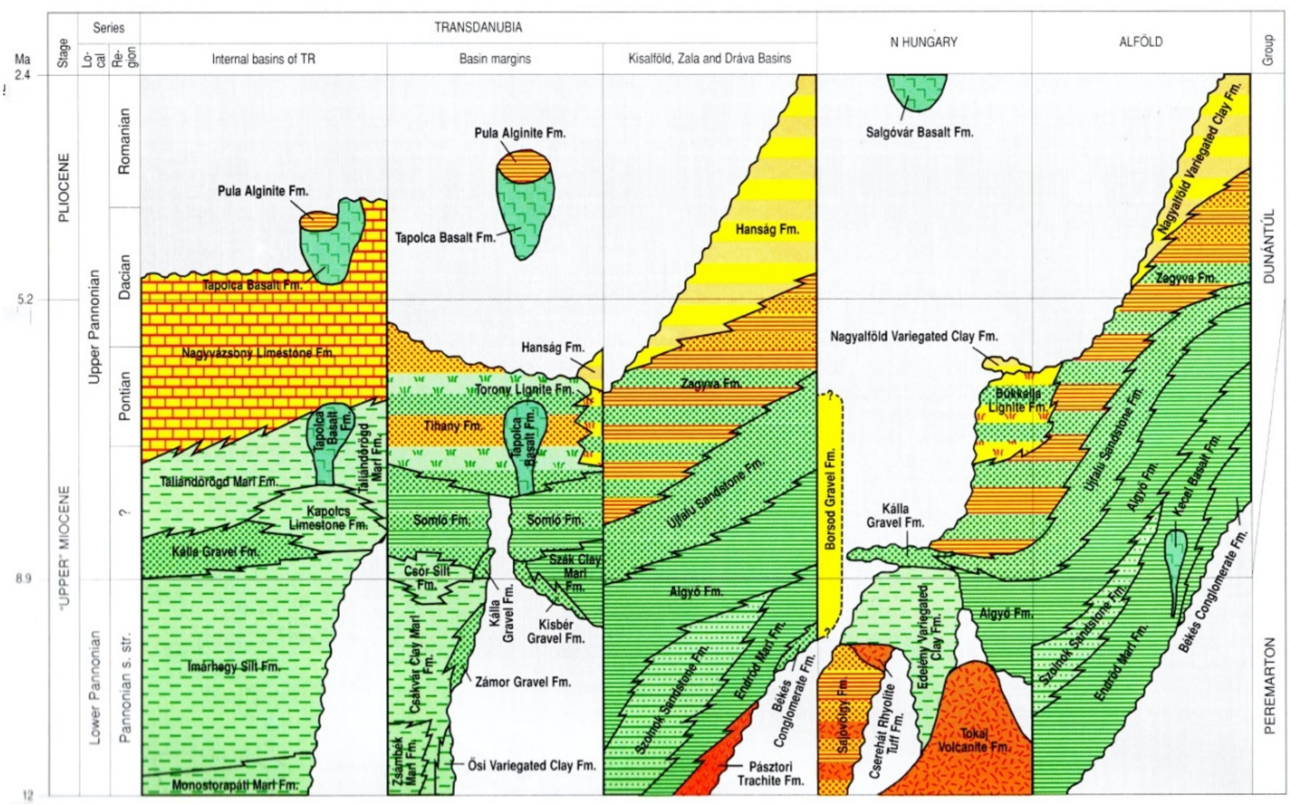

Figure 5. The chronology of Pannonian formations and their spatial distribution (Korpás-Hódi and Juhász, 1996**)**

Quaternary formations

In the central part of the basin depression the sedimentation is continuous during the Pliocene and Pleistocene. The thickness of the Quaternary units may reach several hundred meters (Rónai, 1985; Rónai and Franyó, 1989; Borsy 1990). The Quaternary sediments are overwhelmingly Pliocene and Pleistocene in age. The thickness of the Holocene sediments is generally only a few tens of centimeters. The thickness of the post-Pannonian sediments increases towards the South, the central part of the basin, similarly to the Pannonian ones.

The area was filled by sediments (sand, gravel, aleurite, clay) transported by rivers from mountain ranges. In the central part of the basin the following sediments are found: sand, sandy gravels, variegated clay, red clay, huminitic clay, loess, eolian sand, peat, dolo-mud, carbonaceous mud, travertine, diatomite and different soil layers (Jámbor, 1998).

In the pilot area the thickness of Quaternary units reaches 300-400 m. The underlying formation is the Nagyalföld Variegated Clay, which in part deposited until the Pleistocene in this region.

2.4. *Hydrocarbon geology*

Paleogeographic position of the Pannonian sandstones

Hydrocarbon reservoirs, dominantly natural gas, are found in the delta slope, delta foreland environment in hydrostatic sandstones between 1240 – 1980 m depth. Heading from the East towards the West the units containing the reservoirs are found in increasingly deeper stratigraphic units. The Lower Pannonian sandstones display heterogenetic lithology, resulting in several small scale sporadic reservoirs.

Over 80 exploration wells were drilled in the area, and despite this large number, the exploration could not be completed because of the following reasons:

- The gas reservoirs within the Pannonian sandstone unit fall dominantly in the delta slope facies, with only some in the delta foreland formations. As a consequence, the contour of reservoirs above each other are strongly shifted. Therefore, it is practically impossible to drill wells that could be used to understand more reservoirs.

- The main reason for the lithological heterogeneity is the slope facies itself.

- Stratigraphic correlation studies indicate that the accumulation of hydrocarbons in different areas is related to the same horizon; however stratigraphic correlation is uncertain between distant boreholes. Moreover, the lithological variance in the delta slope environment is significant.

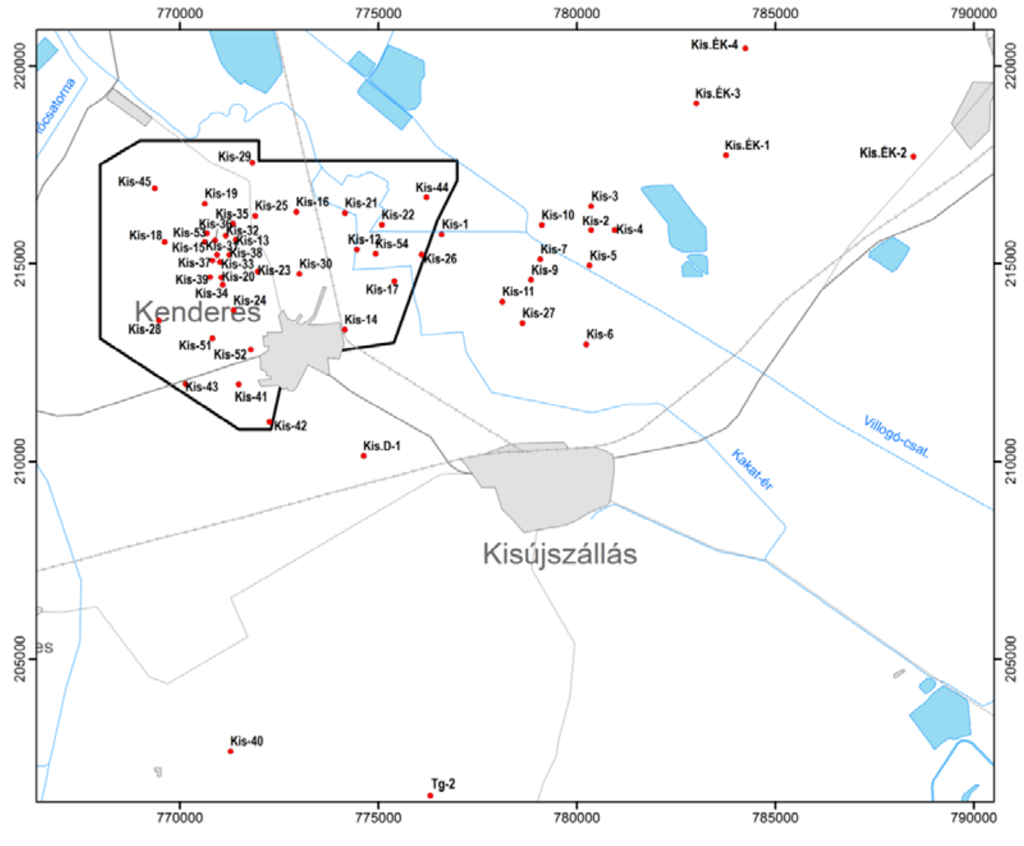

Figure 6. Hydrocarbon exploration wells in the pilot area

The deposition of the Pannonian sediments was related to two delta systems in the area. The older delta system approached the area from NE. Sediments representing the delta slope are found NE to the pilot area in the Pannonian sandstone unit. Because of the distance the pilot area was only reached by distal marl of the delta foreland *(Endrőd Marl Formation)*. These units are insignificant as reservoirs, however, they could be potential source rocks. This marl unit thins regionally towards West.

From the aspect of hydrocarbon exploration, the sand layers of the delta system approaching from the NW, overlying this deepwater marl formation are the most significant. The sandy delta slope and delta foreland facies layers of this delta system serve as natural gas reservoirs. The youngest delta slope sediments are found in the boreholes of the easternmost part of the area near Kisújszállás, because the delta was approaching from the NW.

The Szolnok Sandstone Formation, composed of delta foreland sandstones that represent deeper water sedimentation environment is only present in the northern foreland of the pilot area in greater thickness. Sandstone bodies only reach the pilot area in the deeper embayments of the basement. Among the sandstone bodies only the Pl1-12 sandstone groups (Lower Pannonian sandstone group No. 12) and those below belong clearly to the formation. Sandstone bodies in the southern foreland of the pilot area are suggested to originate from other basin filling processes, namely from a sediment source with Mezőtúr and Endrőd center.

The eastern part of Kisújszállás is in an elevated position. In the pilot area the distal marl (Endrőd Formation) is overlain by sandy delta slope sediments. Heading from Kisújszállás towards Nagykörű the thickness of the delta slope sediments is continuously increasing from 400-500 m to 700-900 m. The lower portion of the delta slope was the most favorable for the accumulation of sand-rich sediments transported on the delta slope. Where delta foreland sandstones are voluminous, the lower part of the delta slope is sand poor.

Reflection seismics along the Kis-21 and Kis-11 boreholes (Figure 6) indicated closure structures. The hydrocarbon productivity of the area is determined by the overlying Lower Pannonian domal sandstones.

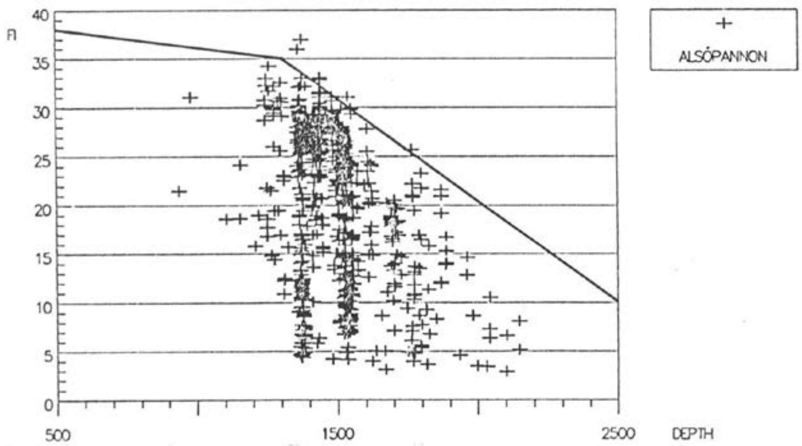

Figure 7. Porosity vs. depth in the Kisújszállás area
(FI: effective porosity) (Bujdosó et al. 1990) ALSÓPANNON - Lower Pannonian

Porosity of the sandstones decreases with depth (Figure 7).

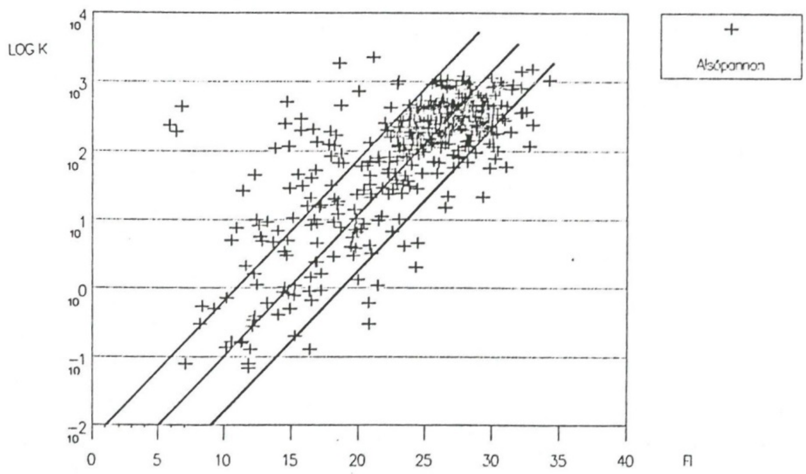

Figure 8. Porosity vs permeability in drill cores from the Kisújszállás area (FI: effective porosity, K: permeability coefficient) (Bujdosó et al. 1990) Alsópannon - Lower Pannonian

Effective (FI) porosity in the shallowest reservoirs of Kisújszállás is approximately 0.1, whereas those lying deeper at Nagykörű and Fegyvernek are 0.08 and 0.075, respectively (Figure 8).
The gas reservoirs in the elevated E-W structure mainly belong to sandstones deposited in the delta slope environment. Sandstone layers of Pl1-11 are all delta slope sediments, whereas those with higher number in the series represent the delta foreland environment and are found in the northern foreland of the elevated structural zone.

- Kisújszállás East, the area of topographic maximum No. I.. This is the zone where the Pannonian reservoirs are found in the central part of the delta slope.
- Kisújszállás center and West, where topographic maximums II. and III. are found.

Production history

Gravimetric surveys, carried out with the Eötvös torsion balance have been carried out in the 1920s and 1940s. The surveys indicated a gravity maximum near Kisújszállás. This gravity indication was further explored by reflection seismics. Based on the seismic analysis a 300 m high elevated zone was identified on the bottom of the Pannonian. This was the target of several exploration wells (Kisújszállás-East). The exploration shifted to the West, where exploration wells hit reassuring units from hydrocarbon point of view. These early results were followed by more detailed seismic analysis to better understand the structures in the area.

Exploration wells were drilled in the vicinity of the pilot area after 1958. Nine wells were drilled until 1968. These indicated a remarkable hydrocarbon reserve in western direction. Sixteen further exploration wells in the pilot area had been drilled until 1976. These wells discovered 2 Miocene and 13 Lower Pannonian reservoirs with flammable gas content. Most of the reservoirs are found in the western part of the area. Nine additional wells had been drilled until 1981, these are the following: Kis- 31, -32,-33,-34, -35, -36, -37, -38, -39. In four cases drill cores were also sampled. Unfortunately, water analysis had not been carried out in these newer wells. The wells explored 16 hydrocarbon occurrences, out of which 11 fall on the western part of the gravity maximum and only 5 on the eastern side.

The 16 hydrocarbon occurrences that fall in the pilot area represent 12 reservoirs. The two Miocene reservoirs are different in their rock and gas compositions. The gas is stored by fine grained sandstone with tuff intercalations in one of the Miocene reservoirs, whereas the other reservoir consists of volcanic tuff and tuffite. The trap type of the Miocene reservoirs is unclear. Based on pressure, the reservoirs are overpressured.

Fourteen Lower Pannonian natural gas occurrences are known in 10 reservoirs that fall between ~1200-1700 m depth ranges. The reservoir lithology is dominantly clayey and aleuritic, with high variability even in short distance. The interrelation between occurrences and reservoirs in the area is highly complex. Clay marl layers separating sandstone bodies may wedge out. This results in connectivity between the sandstone layers in the productive zone of the pilot area. Two overlying small, but clearly distinct reservoirs developed in the vicinity of the western gravity maximum. On the other hand, in some cases reservoirs can show weak to moderate interconnection resulting in a complex reservoir system. Sandstone bodies are separated by WNW-ESE faults. Lower Pannonian reservoirs are all stratigraphic traps that developed atectonically, as a result of pseudo dome formation in connection with compaction. Phase boundaries are practically subhorizontal. The composition of the natural gas varies in each reservoir. Hydrocarbon content falls between 46.53-83.22% whereas carbon dioxide content falls between 0.3-32.45%. The highest carbon dioxide content is found in the III/Pl1-5ABCD reservoir. Pore water composition in the reservoirs is mainly alkaline (Palmer I.).

There are 56 producing wells operating on 18 hydrocarbon occurrences in and near the pilot area. Over 5000 Mm^3 natural gas has been produced until 2017 with approximately 26 Mm^3 produced in 2017. There are four reservoirs in the pilot area that are responsible for over 90% of the gas production. The original gas-water-boundary (GWB) falls between 1334-1440 m. There are some small reservoirs where the original GWB falls below 1500 m. The larger reservoirs contain CO_2 rich natural gas, that may reach 30%. The original gas in place well exceeds the 5000 Mm^3.

Dome No. II. (Kisújszállás-W field)

III/Pl1-5.

The production of this largest reservoir, which we selected as target for pilot injection, started in 1983 in its central part (A) using the Kis-36-37-39 production wells (Table 2). The southern dome (C) was discovered in 1983. No interconnection was suggested between the two occurrences, because of the differences in gas composition and reservoir pressures. However, in 1986, based on pressure measurement it has been proved that the two occurrences form a single hydrodynamic system.

The analysis of gas composition in the Kis -30 well (B) showed strong similarity with the southern (C) occurrence. Nevertheless, pressure measurements indicated that the interconnection between (A) and (B) reservoir units is significant. The well Kis-45 confirmed that there is a refilling source of good quality gas from the NW. The reservoir pressure measurements indicated that there are two moderately and one strongly confined zone concerning water refill. One of these zones is the fault zone between A and C reservoir units. The pressure difference between the two reservoir units had increased to 10 bar between 1983-1985 and remained such high until 1988. Later on the pressure difference gradually decreased. Nevertheless flow is still in the direction of the A reservoir unit.

Over 20% of the gas had been produced until 1990. The pressure drop was significant and indicates a straight, closed reservoir. Water flow was not observed.

Table 2. Name of wells penetrating different subunits of the target reservoir for pilot injection

Reservoir:	**III/Pl1-5ABC**	
Exploration wells:	A –reservoir unit	Kis-13-15-18-19-20-31-32-33-34-35-36-37-38-39-53
	B - reservoir unit	Kis-23-24-25-30
	C- reservoir unit	Kis-40-41-51-52
	D- reservoir unit	Kis-45

2.5. Structural evolution

Main faulting in the area occurred in the Pannonian (Middle to Late Miocene). These faults also affect the reservoirs. Faults were identified based on the following observations:

- Borehole Kis-11: stratigraphic gap between 1280-1300 m. Approximately 50 m of Pannonian sandstone is missing.
- Borehole Kis-21 where the II/Pl1-5 gas reservoir contains gas in footwall/hanging wall position. More favorable structures towards the East are only aquifers, as demonstrated by Kis-22, -44 boreholes. We suggest that the different exploration wells penetrated different blocks, resulting in very different recent characters (Figure 6).

- According to the seismic interpretation the Late Pannonian or younger faults with NE-SW strike were developed. These fault played a major role in the development of the hydrocarbon traps. There are two main faults in the pilot area. One of the fault zones is found on the gravity maximum No. III. in its western zone, south of Kis-28, -24 wells and north of Kis-51. The fault zone crosses the gravity maximum No. II. towards the NE and runs somewhat north of the Kis-12, -22, -44 wells and somewhat south of Kis-30, -21 wells. The other fault zone runs through the gravity maximum No. I. on its eastern part. The fault zone was hit by the Kis-11 well at the depth of the Pl1-4,-5 gas reservoirs. It runs north of the Kis-9, -7, -3 wells and south of the Kis-10 well.

It is suggested that the antithetic fault running between the KB-2 and Kis-ÉK-2 boreholes is responsible for the trap development. Based on the seismic interpretation the largest reservoirs are found at the outer periphery of the collapse zone related to this fault.

3. Injection project concept

In this chapter we will discuss two independent approaches applied to develop the injection concept in the pilot area. The selected reservoir for pilot injection (namely the III/Pl1-5ABCD) has been described in detail concerning its geological and structural setting.

The following table (Table 3) summarizes some of the most important reservoir geological parameters. Those that are publicly available are shown in the table (Table 3; Bujdosó et al., 1990), and that were used for injection model development. Some of the values used are confidential, their values are not shown:

Table 3. Some of the relevant reservoir parameters of the target reservoir at the pilot site

Parameters	
Year	2016
Area [km^2]	15.29
Average porosity [%]	27.21
Average water saturation [%]	50.07
Reservoir temperature [°C]	90
GWB [m]	1343.5
Initial reservoir pressure [MPa]	14.21
Volume factor of the reservoir [m^3/m^3]	7.19
N_2 content [%]	6.8
CO_2 content [%]	46.94
Original gas in place [Mm^3]	5314
Original producible gas [Mm^3]*	
Cumulative production [Mm^3]*	
2016 production [Mm^3]*	
Gas resource [Mm^3]*	
Producible gas resource*	

* confidential

The main concept of the pilot project is to use this reservoir for pilot operations and if found appropriate, upscaling the injection project to industrial levels.

3.1. *Cumulative production based injection concept*

Most of the earlier assessment studies carried out in the region (EU GeoCapacity [http://www.geology.cz/geocapacity], CO2Stop [https://ec.europa.eu/jrc/en/publication/reserves-and-resources-co2-storage-europe-co2stop-project]) used the cumulative production approach, when estimating the amount of injectable CO_2 in the potential storage sites. The concept is based on the assumption that most of the pore volume of hydrocarbon produced from the reservoir remains available for CO_2 injection.

The available pore volume in a conventional gas reservoir is calculated as shown below:

$$\Delta V = B_{gi} G_p$$

where: G_p – Cumulative gas production (m^3)

ΔV – pore volume available for storage (m^3)

B_{gi} – volume factor of the gas reservoir (m^3/m^3)

Substituting for the given values in the table: **ΔV= 2.968*10^7 m^3**

The overall injectable CO_2 in mass (kg) unit is calculated multiplying ΔV with the density of CO_2 at given reservoir conditions (p, T) that was calculated based on Span and Wagner equation of state (1996).

$$M_{CO2} = \Delta V * \rho_{CO2}$$

where: M_{CO2} – mass of injectable CO_2 (kg)

ρ_{CO2} – density of CO_2 at reservoir conditions (387.08) (kg/m^3)

Substituting for the given values in the table: **M_{CO2}= 1.15*10^{10} kg**

Our results indicate that the overall CO_2 storage potential of the selected reservoir most likely exceeds 10 Mt, if the entire pore volume of the produced hydrocarbon becomes available for CO_2.

Concerning the pilot study the amount of CO_2 to be injected in the pilot phase of the project will not exceed 100 000 tons in coherence with the relevant regulations. The pilot project is planned for 36 months duration with annual injection of maximum 33 000 tons.

At normal conditions this amount refers to 1.76*10^7 Nm^3 of CO_2 to be injected annually. To make this possible, this requires an injection rate of 7*10^4 Nm^3/day (calculating with 250 days of operation annually). Based on the exploration and production reports from the field (Bujdosó et al., 1990) gas yields in the producing wells in the target formation range from 1.0*10^4 – to over 1.0*10^5 m^3/day (average yield: 7*10^4 m^3/day). This implies that a single, adequately placed well could be capable of injecting the required amount of CO_2 for the pilot project. However, upscaling to industrial levels will definitely require additional injection wells.

3.2. *Injection of dissolved carbon dioxide*

The concept of injecting dissolved carbon dioxide is not new (e.g., Eke et al., 2011; Randi et al., 2017). Several ideas have been discussed supporting and against dissolved carbon dioxide injection. Recently the CO2-DISSOLVED project (http://co2-dissolved.brgm.fr/) is focusing on the possibility of injecting CO_2 dissolved in water, thereby enabling enhancement of geothermal heat production.

In order to gain a reliable knowledge about the target reservoir we have carried out the reinterpretation of archive geophysical well-logs (mostly resistivity; see Figure 9). We have focused on the estimation of the most relevant physical parameters of the target reservoir, namely the thickness and the effective porosity.

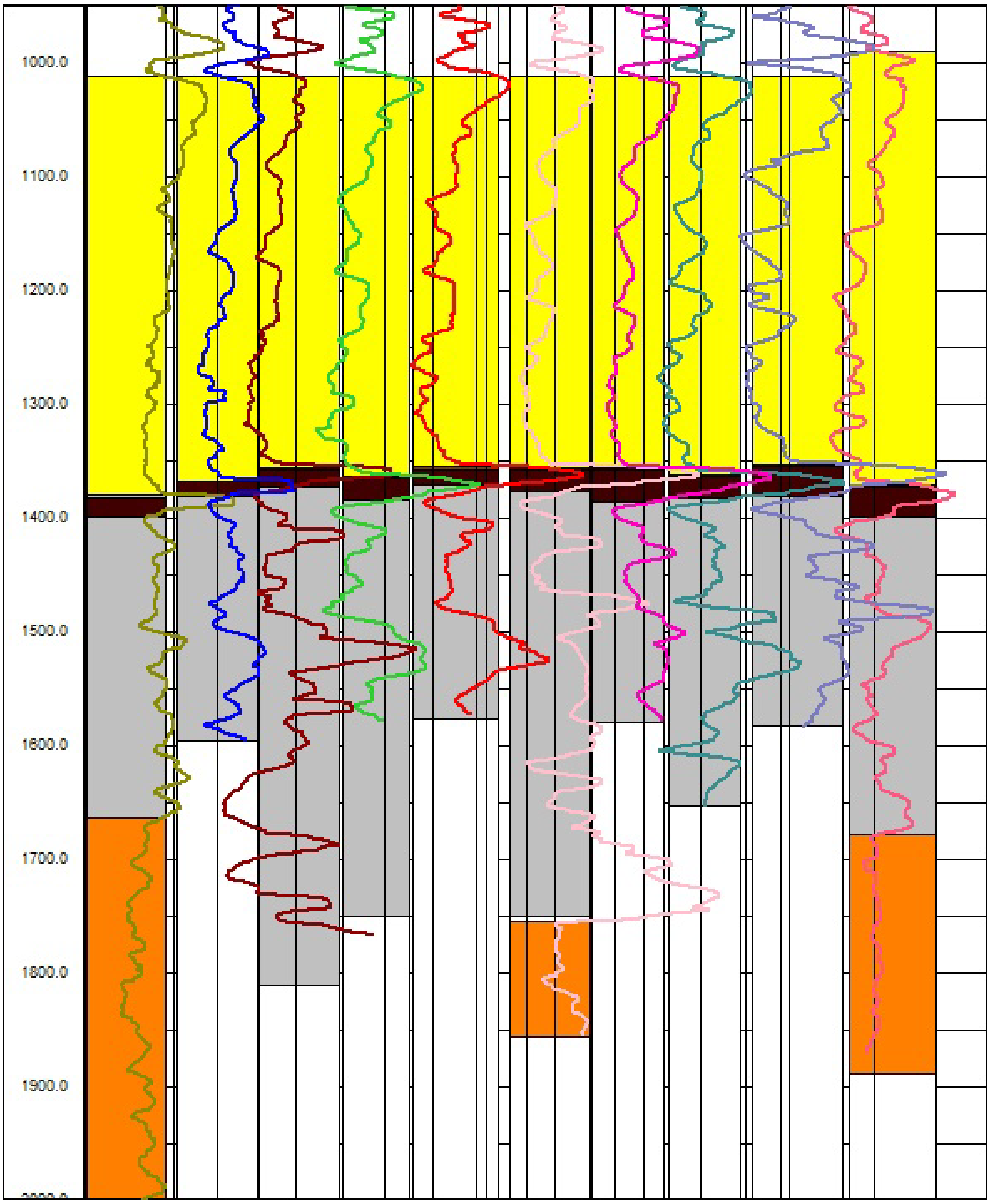

Figure 9. Resistivity well-logs from the pilot area. orange color indicates Endrőd, grey - turbiditic Szolnok Sandstone, yellow - Algyő Formation; black zone indicates target reservoir. Scale 1 m : 5 000 m

We have analyzed geophysical well logs from 20 boreholes in the pilot area. Thickness and effective porosity data derived from these well logs was subjected to Monte-Carlo simulation. The Monte Carlo simulation is one of the **random**-based methods. With the help of MC problems of high complexity become solvable, which are otherwise unsolvable with analytical methods. The key issue for the effective solution is the application of sufficient quality of random number generators, that are used in most commercially available program features. The generated random numbers correspond to a statistical distribution with given expected value and standard deviation.

Results of the Monte-Carlo simulation (Table 4) were used to calculate the cumulative effective pore volume (V_{effp}) of the target reservoir using the following formula:

$$V_{effp} = Area \ x \ thickness \ x \ effective \ porosity$$

Reservoir area was derived from Table 3 whereas, thickness and effective porosity originate from the Monte-Carlo simulation described above.

The total storage capacity can be determined by the following formula:

$$Total \ storage \ capacity = S_{CO2,w} \ x \ \rho_{CO2} \ x \ P_{reservoir} \ x \ V_{eff}$$

where $S_{CO2,w}$ – solubility of CO_2 in water at normal conditions (0.00145 kg/kg)

ρ_{CO2} – density of CO_2 at normal conditions (1.98 kg/m^3)

$P_{reservoir}$ – initial reservoir pressure (derived from Monte-Carlo simulation)

V_{eff} – cumulative effective pore volume

A more realistic storage capacity was calculated multiplying *Total storage capacity* by 0.8. This corresponds to the production efficiency of gas from the pore space (producible gas volume / original gas in place)

Table 4. Reservoir parameters derived from well logs and Monte-Carlo simulation

Parameter	Median value	Standard deviation
Thickness (m)	15.58	8.58
Effective porosity (%)	13.16	3.3
Effective pore volume (m^3)	$32.51*10^6$	$18.24*10^6$
Total storage capacity (Mt)	13.02	7.3
Realistic storage capacity (Mt)	10.4	

Two scenarios based on final carbon dioxide saturation are discussed in detail.

Scenario 1 (carbon dioxide saturation 100%)

At reservoir conditions in the pilot area, approximately 257.8 kg carbon dioxide can be dissolved at the bottom hole of a potential injection well. This results in 178.7 bar pressure at the bottom hole of the injection well. This pressure exceeds original hydrostatic reservoir pressure by 25.7 % at approximately 1400 m depth. Considering average etage height and permeability of the reservoirs, and calculating with transmissivity of water, this overpressure would result in a maximum of 15 782 t injected carbon dioxide.

However, there is a remarkable (orders of magnitude) difference between the transmissivity for carbon dioxide due to its significantly lower viscosity compared to water, implying that when injected carbon dioxide saturated water reaches the reservoir, carbon dioxide would separate from the injected water mass and rapidly diffuse in the pore water of the reservoir.

Assuming an unchanging concentration gradient during the injection project, approximately 1.6 Mt carbon dioxide could be injected in the reservoir annually. If we assume realistic conditions for the injection i.e., heterogeneity, it is better to assume somewhat lower rates: approximately 0.8 Mt/annum.

However, the diffusivity of carbon dioxide is expected to continuously decrease during the injection project because the concentration gradient between saturated injected water and reservoir pore water is gradually decreasing. This infers that the amount of injectable CO_2 is gradually reduced to zero, when saturation is complete in the reservoir. In practice, this means that the theoretical maximum of 10.4 Mt overall storage capacity could only be reached in infinite time.

Scenario 2 (carbon dioxide saturation 25%)

Following the same logic, but assuming that only 25% saturation will be achieved at the bottom hole of the injection well. In this case the bottom hole pressure will be 151.25 bar, resulting in 9.15 bar overpressure compared to initial reservoir pressure. Considering average etage height and permeability of the reservoirs, and calculating with transmissivity of water, this would result in a maximum of ~1000 t injected carbon dioxide annually.

However, there is a remarkable (orders of magnitude) difference between the transmissivity for carbon dioxide due to its significantly lower viscosity compared to water, implying that when injected carbon dioxide saturated water reaches the reservoir, carbon dioxide would separate from the injected water mass and rapidly diffuse in the pore water of the reservoir. Assuming an unchanging concentration gradient during the injection project, approximately 98 400 t carbon dioxide could be injected in the reservoir annually. If we consider realistic conditions for the injection i.e., heterogeneity, it is better to assume somewhat lower rates: approximately 50 000 t/annum.

Conclusion of the two scenarios with dissolved CO_2,

The following statements can be made:

- The theoretical maximum of injectable CO_2 in a single well, when considering realistic reservoir conditions is approximately 800 000 t/annum, although maintaining this injection rate would become practically impossible, due to saturation of reservoir pore water in carbon dioxide and reduction of diffusivity
- The pessimistic estimation indicates approximately 50 000 t/annum of injectable CO_2 in a single injection well.
- The higher the final saturation in the reservoir pore water the more CO_2 could be injected in the reservoir

3.3. Summary of the injection project concept

Preliminary estimations using the cumulative production and dissolved CO_2 concepts revealed that the target reservoir is highly potential to store the provisional < 100 000 t CO_2 injected during the pilot project and has the potential to be upscaled to small-medium scale industrial project with a maximum of approximately 10-11 Mt CO_2 capacity. Maximum injection rates are variable, but even in the most pessimistic case could reach 50 kt/annum rate in a single well.

4. Sources of CO_2

The concept of the pilot injection project strongly builds on the upscaling potential of the reservoir, when proven successful. For the pilot project, carbon dioxide is planned to be purchased from CO_2 producers (LINDE GAS, or MESSER) or from one of the CO_2 reservoirs operated by MOL Plc. The transport of CO_2 will most likely be road transport, because of its flexibility.

However, if pilot injection project is successful upscaling of the site and its use as storage for industrial emission could be realized. Therefore, we mapped potential industrial sources that could use the storage potential. Primarily we were focusing on utilities in the relative vicinity (< 100 km) of the pilot area. Sources with > 50 000 t/annum emissions were selected in this radius. There are 10 large emission sources with cumulative annual emission of over 7.5 Mt (Table 5). In the following we provide a list of these facilities that have been operating in 2018.

Table 5. Large point source emissions in the vicinity (<100 km) of the pilot site

Name, city	type	Verified emission in 2018 (t CO_2)
Borsodchem Corp, Kazincbarcika	boiler (for hot water and steam for the chemical reaction processes)	87 713
Borsodchem Corp, Kazincbarcika	power plant	296 881
Borsodchem Corp, Kazincbarcika	chemical industry	132 119
Columbian Tisza Soot Plant, Tiszaújváros	chemical industry	217 988
Guardian Glass Factory, Orosháza	glass industry	113 412
Linde Gas, Kazincbarcika	gas processing	153 776
Mátra Power Plant, Visonta	power plant	5 245 773
TVK plant, Tiszaújváros	chemical plant	1 062 658
TVK power plant, Tiszaújváros	power plant	139 485

No transport network for CO_2 is known in the region.

5. Budgets

Technological steps of carbon dioxide geological storage are more or less mature, and - although with the aim of enhanced hydrocarbon production, have been done for over 50 years. On the other hand, due to its earlier use solely for enhanced production, business models for *storage only* activities are not really available. Up to now only a few *storage only* projects in a handful of countries has been realized. Furthermore, even these projects struggle to become profitable and have failed to provide robust business models applicable worldwide.

It is therefore vital to understand what costs are expected in a storage pilot project, that has the purpose to demonstrate the feasibility of this activity (and not only technically).

In the following section we provide cost estimation for the proposed pilot project at Kenderes area. There are certain steps of the project that will be elaborated in detail. However some of the cost items are derived from literature. In many cases the values linked to certain elements are only a matter of speculation, linear upscaling or other considerations. These are indicated in the text.

In the following section we summarize cost items related to the planned pilot storage activity at Kenderes, based on the study of Vidas et al. (2009)

Analysed cost items:

- Geological site characterization
- Injection well construction
- Well operations
- Monitoring
- Mechanical integrity tests
- Carbon dioxide for injection
- Post injection monitoring and maintenance
- General, administrative communication and “marketing” costs.

5.1. Geological site characterization

The main goal of site characterization is to decide whether a given site is suitable and safe for geological storage. The activity includes geologic, geophysical, and engineering evaluation to determine reservoir porosity, permeability, and continuity and its adequacy for long term injection. The ability of overlying units to trap and retain injected CO_2 is also evaluated. Other assessment includes the mechanical properties of the reservoir, geochemical reactivity of reservoir and cap rock, information on any earlier activity affecting target reservoir and cap rock, i.e., past drilling penetrations. Significant components of site characterization costs include 3-D seismic data acquisition, including processing and interpreting as well as evaluating geomechanical and geochemical data.

Detailed cost estimate of seismic survey

One of the basic requirements of seismic exploration is the 1) Exploration permit. The permit fee is 2000 kHUF (approx. 7000 €). There may be additional cost for 2) assurance. The 3) preparation process form seismic exploration includes the following tasks: - the acquisition of ownership information;

- official notification of owners
- negotiation with utilities
- personal visiting of main land owners and land users

costs approximately 4000 kHUF (14 000 €).

The 4) 3-D seismic exploration (on 20 km^2, approximately 1500 - 2000 m target depth) - cost of 3-D seismics: 60 000 kHUF (182 000 €). Associated 5) damage fees in agriculture: approximately 5 000 kHUF (17 500 €).

6) Data processing costs are estimated to fall around 5 000 kHUF (17 500€), whereas 7) interpretation costs are also around 5 000 kHUF (17 500€).

Injection well construction (including plugging of old wells)

Injection wells are the key infrastructure for storage projects. Their design and construction does not differ considerably from other injection wells (e.g., those used for natural gas storage), however cements, casings and other related infrastructure must be resistive to corrosion and high pressures. The construction includes the design, the drilling and completion of the well.

Drilling and completion of injection well

The following cost estimate is provided for a well that includes the following features:

- partly directional drilling
- gas tight completion including TENARIS coils
- 9 5/8” casing until approximately 1000 m
- 7” casing below 1000m
- 2 3/8” tubing for precise volume flow rate
- liners
- cementing
- well bore geophysics
- WARP drilling mud
- drilling rig costs
- other costs

The estimated costs including all listed features sum up to 700 000 kHUF/well (2 130 000 €)

Plugging of abandoned wells (based on Osundare et al., 2018) has an estimated cost of approximately 1.1 - 1.3 M€/well.

Other significant cost items

According to Vidas et al. (2009) - among other important cost items, the most important ones are the following:

- Well operations
- Monitoring
- Cost of carbon dioxide

Well operations

Well operations include all activity related to operation in wells throughout and after the injection project, from maintenance to repair and replacement. Risks associated to well failure and relocation of a new well are also included. Hence this complex cost item is the most significant among all related costs. It may reach almost 50 percent of the whole injection project.

Monitoring

Monitoring activity is something required for the whole duration of the project. Ideally, it predates any field activity related to the injection, in order to have a good baseline for the monitored parameters. Furthermore, some of the monitoring activity should go on for decades after the ceasing of the injection, in order to demonstrate that injected CO_2 is behaving as modelled. Monitoring is the tool to demonstrate the safety of the site, the entrapment and retainment of the injected carbon dioxide. Furthermore, if necessary, this is the primary tool to start corrective measures.

There is a whole set of monitoring possibilities and requirements listed in the Governmental Decree 145/2012, hence the precise cost estimation for monitoring is not possible. According to Vidas et al. (2009) overall monitoring costs are in the range of well construction.

Cost of carbon dioxide

A key element of the pilot project is the availability of injectable carbon dioxide on site. There are several options for the source. The most obvious would be to use food quality grade carbon dioxide produced in NW Hungary by LINDE GAS, or MESSER and transport it to the pilot site with road transport.

Food quality CO_2 has an advantage that its road transportation is not problematic. Any substance could be added, that could be used as tracer to understand the behavior of the injected carbon dioxide. The major disadvantage of food quality carbon dioxide is its high cost (approximately 5-10 % of the pilot project) and its limited availability.

Other CO_2 rich gases from the vicinity of the pilot area are well known to occur (e.g., Szarvas). Their costs are assumed to be significantly lower than food quality CO_2, however its transport to the pilot site could be problematic. Related permitting may pose unsolvable risk to the pilot project, because the regulation of road transport of such gases (with currently undefined composition) is not available. Pipeline transport for the pilot is not cost effective.

Summary of costs related to pilot project

Most of the significant cost items have been described in detail. Furthermore, where available, we have estimated their absolute or relative quantity. A broad approximation of the full cost of the pilot project can be made, on order of magnitude level, which sums up to **5 000 - 8 000 MHUF** (~15 - 25 M€). If proven successful, some of these costs (part of the monitoring and the well operations) could be compensated by the industrial partners interested in reducing their emissions.

6. Potential impacts of this pilot

Pilot projects are general measures in commercialization of novel, large scale industrial procedures. In case of storage pilots the purpose of such projects is similar. However, beyond this effect it is anticipated that general stakeholder attitude towards carbon sequestration could dramatically change in case of a successful projects.

There are certain specific aspects of CO_2 geological storage that are of remarkable importance and which could serve as best practices for further (commercial) deployment of storage projects in case of successful pilots. These specific aspects are the following:

General impacts

- site characterization, including reliable estimation of storage capacity
- risk assessment and risk management in case of on-shore CO_2 storage
- operation of storage projects including
- transport
- injection
- monitoring (baseline, down-hole, areal)
- stakeholder communication (from the planning and permitting phase, injection phase and abandonment phase)

Site specific impacts

- small-scale business model for CO_2 capture and storage
- best practice.

General impacts
Site characterization, including reliable estimation of storage capacity

There has been a long record of storage potential assessment in Europe. These activities are mostly related to EC financed research projects that were in some cases and countries continued by commercial companies. These latter studies have developed more sophisticated methods for site characterization, mostly building on the practice and experience of oil and gas industry exploration. The different assessment activity resulted in very different level of knowledge and reliability of information about potential storage formations. This discrepancy could be overcome and best practice for assessment pre-feasibility, feasibility, planning and testing phase could be developed to effectively estimate storage capacity of target formations.

Stakeholder communication

One of the key aspects and obstacles in carbon geological storage is the low level of knowledge and resulting distrust in stakeholders. The involvement of stakeholders from site selection procedure through pre-feasibility and feasibility studies, planning and realization phase. Sharing all relevant information and involving stakeholders in planning and decision making is expected to build trust in carbon dioxide geological storage. Experience in the communication during the project could be used as best practice in further projects.

7. Stakeholder mapping in the region

Stakeholder mapping is one of the key activities to understand and engage all types and levels of stakeholders to the project. Stakeholder mapping is a collaborative process of research, debate, and discussion that draws from multiple perspectives to determine a key list of stakeholders across the entire stakeholder spectrum.

Stakeholder mapping is normally broken up to different activities that are listed in the following [based on BSR methodology]:

- Identification of stakeholders
- Analyzing stakeholder perspective and interest
- Mapping
- Prioritizing stakeholder relevance

7.1. Identification of stakeholders

In the stakeholder identification process the following stakeholder groups were identified:

1) ***Local entities***: (1i) involved municipalities, (1ii) local industry, (1iii) land owners, (1iv) inhabitants

2) ***Government and governmental bodies***: (2i) responsible authorities, (2ii) governmental research institutes, (2iii) Ministries in charge, (2iv) local members of the Parliament, (2v) related councils within the Parliament

3) ***Industry***

3a) *directly related industrial actors*: (3ai) (potential) operator(s), (3aii) technology providers, (3aiii) local emitters, (3aiv) potential competitors for pore space

3b) *indirectly related industrial actors*: (3bi) potential operators not providing service in the region, (3bii) emitters out of the region

4) ***Financial actors***:

4a) *directly related financial actors*: - (4ai) banks financing the project, (4aii) insurance companies providing coverage

4b) *indirectly related financial actors*: (4bi) banks planning to finance other projects, (4bii) insurance companies planning to provide coverage for other projects

5) ***Non-governmental organizations*** (NGOs)

5a) *local/regional NGOs*: (5ai) acting in the geographic area of the project with focus on any aspect of the project

5b) *national/international NGOs*: (5bi) energy-environment-climate change focused organizations acting country wise and/or internationally.

7.2. Analyzing stakeholder perspective and interest

We will now analyze the list of stakeholders concerning the following aspects (based on BSR methodology):

- influence and legacy of stakeholder = **EXPERTISE**
- readiness of stakeholder to engage to the project = **WILLINGNESS**
- potential role and significance in the project = **VALUE**
- necessity of involvement

In the following table (Table 6) these aspects are indicated for the different stakeholder group

Table 6. Analysis of stakeholder expertise, willingness and value in the pilot storage project aspect

Stakeholder	**Stakeholder influence and legacy**	**readiness of stakeholder to engage to the project**	**potential role and significance in the project**	**necessity of involvement**
SH1 - local entities				
involved municipalities	**significant**: unless it is accentuated, they have the right to stop project	**moderate:** low level of knowledge, strongly motivated for local investment and employment	**minor:** except for stopping project no significance in the project	**moderate:** not necessary to involve to greater degree than what is required in the legislation
local industry	**significant:** have large influence due to local tax paying and employing / No direct influence in the permitting procedure	**significant:** low level of knowledge, but easily motivated with benefits	**significant:** lobbying for the project towards decision makers as well as employees	**significant:** could be the key players in technology application as well as among the first beneficiaries
land owners	**significant:** strong capability to stop project through protesting	**moderate:** low level of knowledge, motivation challenging	**moderate:** Without engagement the project realization becomes impossible	**moderate:** Without engagement they might prevent project realization

Stakeholder	Stakeholder influence and legacy	readiness of stakeholder to engage to the project	potential role and significance in the project	necessity of involvement
inhabitants	**minor:** limited capability to stop project through protesting	**minor:** low level of knowledge, indirect relation to project	**minor:** indirect motivation or adverse motivation	**minor:** minor player
SH2 - Government and governmental bodies				
responsible authorities	**significant:** licensing	**minor:** follows regulations	**significant:** critical role and primary significance	**significant:** primarily important (up to the level it is possible)
governmental research institutes	**significant:** Strong influence on ministerial and parliament decisions as well as expertise for authorities	**significant:** Remarkable readiness	**significant:** Credible, unbiased opinion towards governmental as well as civil stakeholders	**significant:** primarily important to involve
Ministries in charge	**significant:** Strong policy control on authorities, decision preparation for parliament decisions	**moderate:** moderate level of knowledge, strongly relies on research institute	**significant:** ability to tackle legislative problems	**significant:** primarily important (up to the level it is possible)
local members of the Parliament	**significant:** recommendation to the parliament decision is prepared	**minor:** strongly influenced by overall policy of the party as well as local opinion	**significant:** final decision and representation in parliament	**moderate:** at a certain point it could become significant, when local support achieved

Stakeholder	Stakeholder influence and legacy	readiness of stakeholder to engage to the project	potential role and significance in the project	necessity of involvement
related councils within the Parliament	**significant:** primarily important (up to the level it is possible)key player in final decision making	**minor:** should be independent	**significant**: recommendation is significantly influencing parliament decision	**minor:** council in charge will approach project preparation to orientate
Industry				
directly related industrial actors				
(potential) operator(s)	**significant:** has the capability and willingness as well as the financial interest and probably the lobbying tools to have positive decision	**moderate**: has to be convinced that project participation is within the companies interest	**significant:** once convinced, the company(ies) would have major role in project realization	significant
technology providers	**high:** these companies operate on the market, they participate if financially (or other aspect) viable	**low-moderate**: depends on project financing	**significant-moderate**: adequate technology in due time	**moderate**: involvement already during planning and feasibility study
local emitters	**significant**: medium to large companies with financial power and lobbying tools	**moderate**: low level of knowledge, needs to be educated and motivated	**significant**: these companies provide the CO_2, they are the commissioners as well as primary beneficiaries of the project	**significant**
potential competitors for pore space	**significant**: in case of more beneficial use of pore space or stronger lobbying activity inhibit project realization	**minor**: as competitors these entities are counter-interested in project	**significant**: must be convinced about mutual benefits	**significant**
indirectly related industrial actors				

Stakeholder	Stakeholder influence and legacy	readiness of stakeholder to engage to the project	potential role and significance in the project	necessity of involvement
potential operators not providing service in the region	**moderate:** has the capability and willingness as well as the financial interest and probably the lobbying tools to have positive decision for other projects	**moderate**: has to be convinced that participation in subsequent project is within the companies' interest	**moderate:** once convinced, the company(ies) would have major role in realization of following projects	**moderate**
emitters out of the region	**moderate**: medium to large companies with financial power and lobbying tools	**moderate**: low level of knowledge, needs to be educated and motivated	**moderate**: these companies provide the CO2, they are the commissioners as well as primary beneficiaries of the project	**moderate**
SH4 - Financial actors				
directly related financial actors				
banks financing the project	**moderate**: financing is critical in CCS-projects, however the motivation is solely profit-related	**minor-moderate**: low level of knowledge, lack of experience in financing such projects	**moderate**: bank guarantees are required, could provide financial stability, liquidity	**moderate**: at a certain stage, the involvement of a commercial financing entity is important; new aspects of project planning are expected

Stakeholder	**Stakeholder influence and legacy**	**readiness of stakeholder to engage to the project**	**potential role and significance in the project**	**necessity of involvement**
insurance companies providing coverage	**moderate**: the involvement of such entity(ies) is solely profit-related	**moderate**: level of knowledge is low, however, getting experience on small scale might be motivating	**moderate**: involvement necessary, role might be important during project planning	**moderate-significant**: credibility and assurance for the project
indirectly related financial actors				
banks planning to finance other projects	**minor**: financing is critical in CCS-projects, however the motivation is solely profit-related	**minor**: low level of knowledge, lack of experience in financing such projects	**minor**: bank guarantees are required, could provide financial stability, liquidity	**minor**: at a certain stage, the involvement of a commercial financing entity is important; new aspects of project planning are expected
insurance companies planning to provide coverage for other projects	**minor**: the involvement of such entity(ies) is solely profit-related	**minor**: level of knowledge is low, however, getting experience on small scale might be motivating	**minor**: involvement necessary, role might be important during project planning	**moderate-**: credibility and assurance for the project
SH5 - Non-governmental organizations				
local/regional				

Stakeholder	Stakeholder influence and legacy	readiness of stakeholder to engage to the project	potential role and significance in the project	necessity of involvement
acting in the geographic area of the project with focus on any aspect of the project	**moderate-significant**: strong influence on public voice but unclear legacy	**significant**: environmental NGOs have a strong position against any CCS; locals may have positive attitude	**significant**: mostly in forming a public voice	**significant**
national/ international				
energy-environment-climate change focused organizations acting country wise and/or internationally	**moderate-significant**: strong influence on public voice but unclear legacy	**significant**: environmental NGOs have a strong position against any CCS	**significant**: mostly in forming a public voice	**significant**

7.3. Mapping and prioritizing stakeholder relevance

The following figure (Figure 10) summarizes the results of preliminary mapping and prioritizing of stakeholders in relation to the pilot storage project.

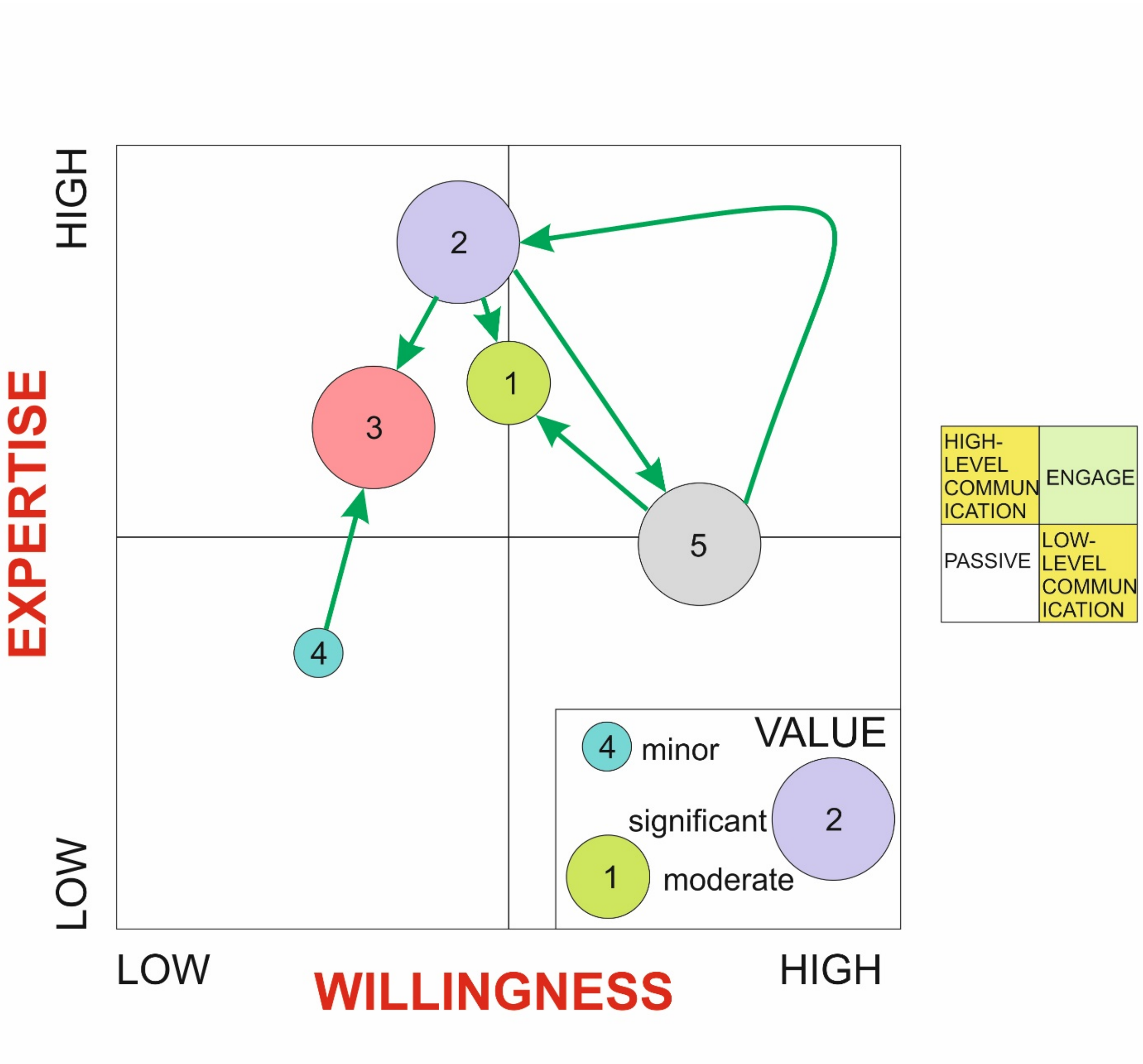

Figure 10. Stakeholder mapping in the pilot area. Colors used on the figure are the same as used in the table. Potential influences are indicated by green arrows Stakeholder groups were joined to simplify the figure

8. Provisional timeline and funding opportunities

Project schedule

The Kenderes depleted gas field has been found to be a potential site for carbon dioxide geological storage. The assessment of the site and its more detailed analysis confirmed its potential for storage. Owing to the general geology of the Pannonian Basin system, the structure of the field and the relative vicinity of large emission point sources, Kenderes area has been selected for pilot project conceptual study.

The provisional timelines discussed in the following are based on the experience of other pilot projects worldwide and imply that the timelines and risks associated to permitting procedures are similar to projects, already on the run. There are more detailed time estimations for the seismic survey part of the project realization, these will be presented in detail.

Supposing that increasing carbon prices, the tightening of emission regulations and the increasing trust for CCS/CCUS options pushes large emitters to seriously consider geological storage of carbon dioxide we may assume the requirements for a pre-feasibility study in 2020. The pre-feasibility study could build on information of assessment and screening activity by the Mining and Geological Survey of Hungary and its predecessors. A more complex and detailed feasibility study, still based on earlier investigations and involving publicly or commercially available data from earlier hydrocarbon exploration could be carried out in 2021. This would be followed by conceptual studies building on reprocessing and reinterpretation of archive geological and geophysical data (mostly well logs, 2-D and 3-D seismics). This information would provide the basis for the front-end engineering design (FEED) study, followed by the final investment decision (FID) around 2024-2025 (Figure 11).

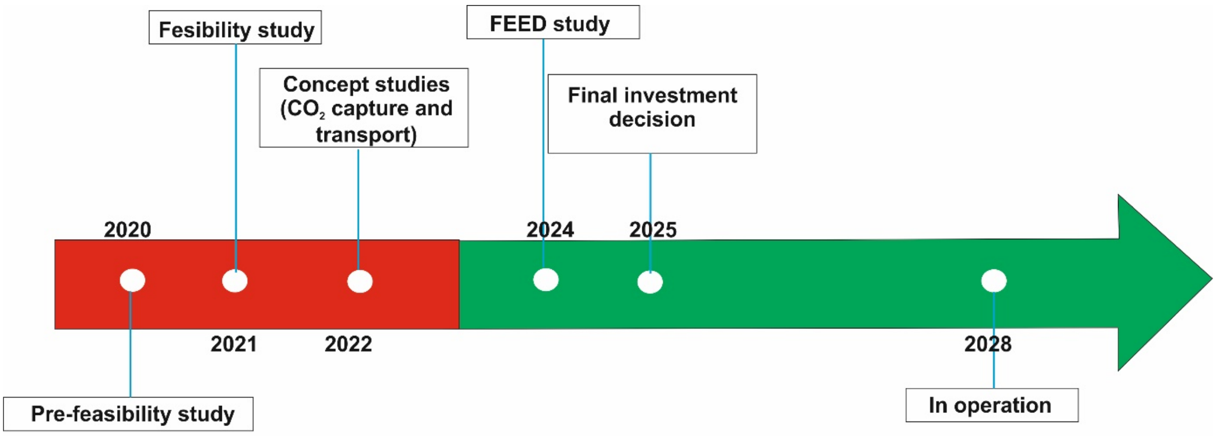

Figure 11. Provisional timelines of the pilot project (after Northern Lights)

Field projects would follow starting with geological mapping and seismic surveying. To start the survey an exploration permit is necessary. This includes the exact allocation of the measurement. The required time for exploration permitting is approximately 2 months. The field measurement preparation phase including:

- the acquisition of ownership information;
- official notification of owners
- negotiation with utilities
- personal visiting of main land-owners and land users

Field measurement with 20 km^2 target area takes about 1 month. Processing of data is time consuming and could take up to 3 months as well as interpretation, which is also estimated to take about 3 months.

Drilling related activity (new injection well, observation well, well abandonment) is estimated to take 4-6 months, depending on well conditions and drilling success.

Operation phase may start some 3 years after FID, presumably in 2028.

Funding opportunities

Funding is currently believed to be one of the most problematic issues related to any CCS/CCUS activity. Most of the large-scale demonstration projects in Europe have referred to the lack of funding or the uncertainty of funding sources. In the last year carbon dioxide prices increased dramatically, which could be a good way to make CCS/CCUS commercially viable. However, even in this favorable case of carbon prices pilot projects are expected to be partially funded by EU and national funds in order to reduce economic risk of such an investment.

Because of the financial needs of such a pilot project, conventional R&D funding schemes could only minimally contribute to financing the project. On the European scale financing by the Innovation Fund seems to be desirable for such projects. On the national scale “Contract for difference” (CFD) type funding could ensure the motivated segment of the industry to invest in a storage pilot project.

9. Project risk assessment

In the following section we present some of the elements studied during risk assessment. Still far from all the aspects that should be studied during risk assessment. The presented list rather represents topics studied in the last years.

9.1. Condition of wells in the pilot area

The highest potential risk related to a CO_2 geological storage project is represented by insufficient condition of earlier wells penetrating the target reservoir. In order to assess the risk related to the wells, we have studied 23 wells from the target area in detail. The main objective of the study was twofold:

- general assessment of well conditions;
- to determine if the wells are suitable or could be made suitable for carbon dioxide injection.

In this study we provide the summary of the well analysis:

- The technical status of the wells that were drilled 30-35 years ago is out-of-date. The built-in equipment is mostly strongly corroded;
- Cementing of the wells has been problematic already during drilling. Cement logs frequently indicate damage or the lack of cement bond in certain zones;
- During the long history of production there have been several new perforations. Although, old perforations were plugged/cemented with pressurized cementing, still, these perforated zones represent weaknesses and zones of high leakage risk;
- Water invasions resulted in similar activity, namely pressurized cementing and perforation of new producing layers;
- There have been technical problems with some of the producing wells already during the operation (flow-through within the wells, etc….);
- Hydraulic communication between different reservoirs as a result of damage or lack of cement.

Conclusion of risk assessment on wells

1. Technical condition of wells penetrating the target reservoir in the pilot area do not enable their use for CO_2 injection, because of
    - the poor condition of the built-in equipment
    - the damaged or lacking cementing
    - hydraulic communication between penetrated layers
    - technical condition of well-head equipment

1. Some of the wells are appropriate to be operated as observation wells of the following features:
    - movement of the CO_2 plume
    - concentration changes in the water and gas phase
    - change of reservoir pressure.

9.2. Reactivity modeling

The Storage Directive prescribes the modeling of geochemical reactivity as a consequence of carbon dioxide injection into reservoir pore water. In the following we present an equilibrium model for the Kenderes pilot area. Parameters used for the model are the following:

depth: 1305 m

p=pCO_2= 142.1 bar

T= 90 °C;

average porosity= 27.21 %

The mineral composition of the storage rock is from Kisújszállás-52 well from the target reservoir (Table 7). Water chemistry is derived from Kisújszállás-13 well, also from the target reservoir.

The thermodynamic equilibrium reaction model indicates the following reactions (Figure 12, Table 7). As a result of CO_2 injection: albite dolomite and illite of the reservoir rock are completely dissolved, whereas K-feldspar and ankerite show only partial dissolution. Calcite, quartz and kaolinite are formed associated with the precipitation of minor goethite. New mineral phases dawsonite and chlorite also precipitate.

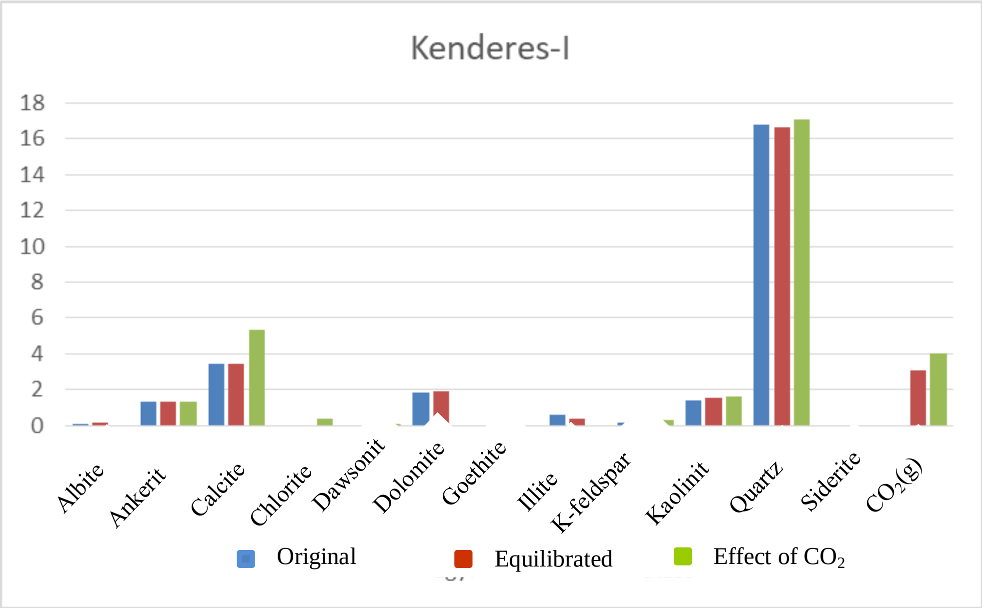

Figure 12. Reactivity model of the target reservoir at Kenderes pilot area

Table 7. Mineral composition of the Kenderes pilot area modelled by equilibrium reactivity modeling

	Original	Equilibrium	Effect of CO_2	Absolute change
	mol/kg water			Δ mol/kg water
Albite	4.90E-02	1.22E-01	0.00E+00	-1.22E-01
Ankerite	1.31E+00	1.31E+00	1.31E+00	-1.33E-08
Calcite	3.46E+00	3.44E+00	5.32E+00	1.88E+00
Chlorite	0.00E+00	0.00E+00	3.97E-01	3.97E-01
Dawsonite	0.00E+00	0.00E+00	6.50E-02	6.50E-02
Dolomite	1.86E+00	1.88E+00	0.00E+00	-1.88E+00
Goethite	0.00E+00	0.00E+00	1.64E-06	1.64E-06
Illite	6.25E-01	4.12E-01	0.00E+00	-4.12E-01
K-feldspar	1.81E-01	3.07E-01	3.02E-01	-5.54E-03
Kaolinite	1.39E+00	1.53E+00	1.64E+00	1.09E-01
Quartz	1.68E+01	1.66E+01	1.71E+01	4.18E-01
Siderite	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO_2(g)	0.00E+00	3.10E+00	4.01E+00	9.11E-01

9.3. Storage permits

Storage permits for storing CO_2 permanently or temporarily in geological reservoirs have not yet been granted to any operator, and up to now have never been initiated by anybody in Hungary. The goal of the pilot project is to limit overall injection throughout the project duration to 100 000 t. Hence, permitting will remain solely in national competency and will follow prescriptions of the storage directive.

The lack of experience in permitting CO_2 storage projects both for Environmental Authority and the Mining Authority implies that the involvement of international experts is foreseen.

No additional risk associated to permitting the storage pilot project is predicted.

9.4. Natural reserve areas, Natura2000 network areas other protected areas

National parks protected natural reserves do not fall in the area. Some protected territories are found in the northern part of the pilot area.

There is an ecological corridor as the only element of the National Ecological Network in the area, which is largely overlapping with the Natura 2000 area in the northeastern most zone of the pilot area.

As indicated earlier a special area of conservation Natura 2000 (SAC) is found in the northeastern part of the area, which is the Kenderes Grass-Land (HUHN20144). Special protection areas (SPA), i.e., bird reserves are not found here. Ramsar areas are not found here either. Among other "*Ex lege*" protected areas only Tumuli are found in the pilot area, north of Kenderes village.

9.5. Introduction of the pilot area under the Water Management Plan

We will discuss the surface and subsurface water bodies (~aquifers), their conditions, monitoring networks, subsurface water production and protective zones based on the Water Management Plan prescribed in the governmental decree dealing with the legislation of water management. In the evaluation we will focus on the *sensu stricto* pilot area, however the near vicinity of the area will also be discussed, because the injection activity envisaged might affect these zones. Our summary is based on the Water Management Plan developed for this area in 2009.

Surface and subsurface water bodies

Surface water bodies, water flows and stagnant waters

The pilot area and its surroundings belong to the Tisia partial water catchment area and are in contact with one surface catchment subunit, namely the Nagykunság unit (2–18). The eastern part of the area has a dense network of modified and artificial water flows (Table 8). Water flows falling in the water body category are the Kakat- and the Villogó-channels, the latter only touching the area. There are 8 further flatland artificial water flows in the area. There is no water body category stagnant water in the area, however there is a small storage-lake used for fishing.

Table 8. Surface water bodies in the area

Name of the surface water body	Code	Type
Kakat-channel	AEP624	flatland, calcareous, modified
Villogó-channel	AEQ111	flatland, calcareous, modified

The Figure 13 shows the surface waters and their usage in the area, indicating stagnant waters water flows and water catchment.

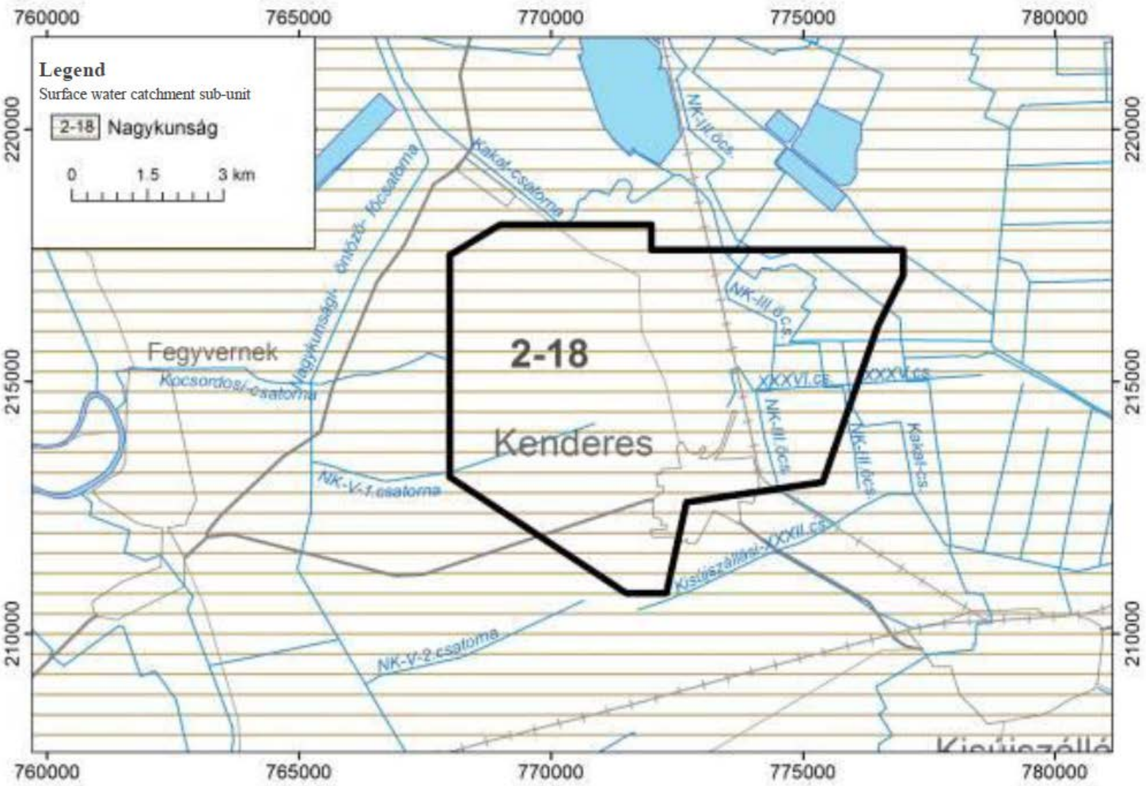

Figure 13. Surface water catchment sub-units

Subsurface water bodies in the area

The pilot area lies in a regional upward flow zone. The ground water producing upper 20-40 m belongs to the Danube-Tisza interfluve, Middle Tisza valley (sp.2.10.2.) water body, whereas the northeastern part of the area belongs to the Jászság, Nagykunság water body (sp.2.9.2).

Similarly to the shallow water bodies, those that provide lukewarm (< 30°C) waters also belong to the Danube-Tisza interfluve, Middle Tisza valley (sp.2.10.2.) and Jászság, Nagykunság water bodies (sp.2.9.2). The water body that provides water warmer than 30°C is the Észak-Alföld (pt.2.2) porous thermal water body. (Figure 14).

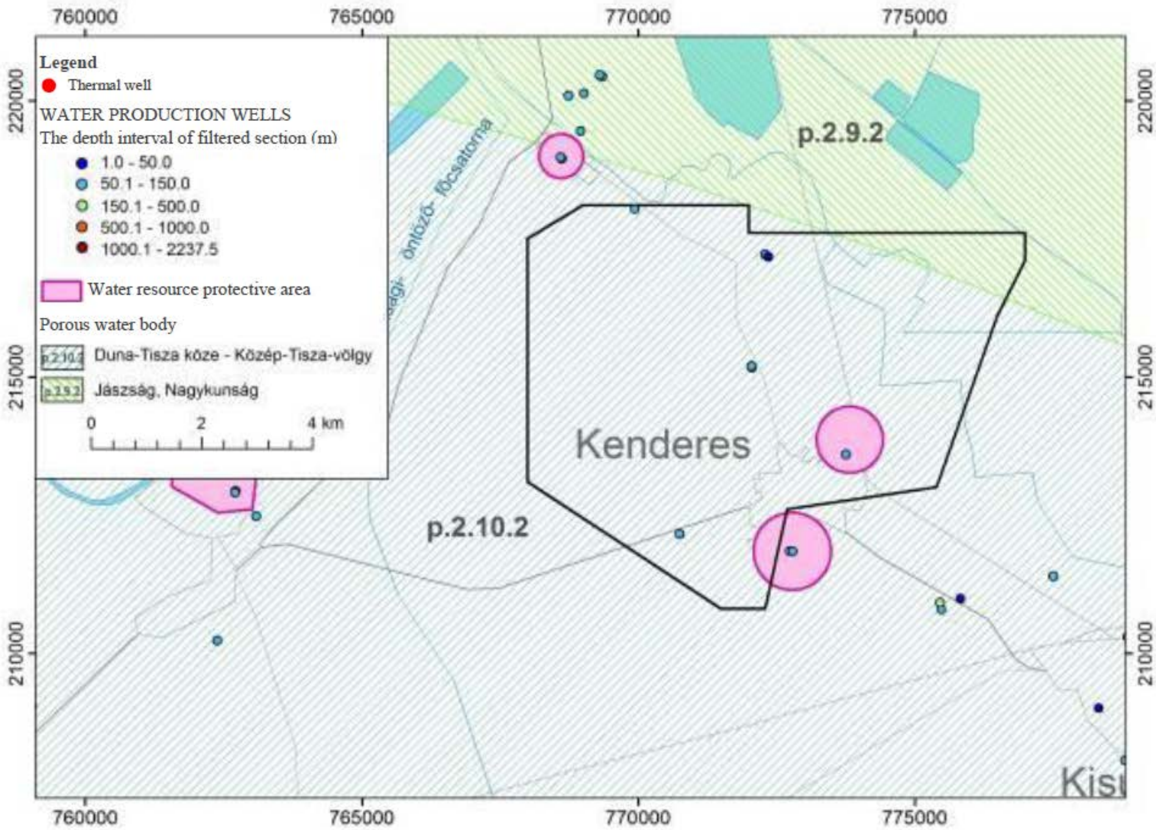

Figure 14. Sub-surface water bodies in the pilot area indicating water producing wells and water resources

Protected areas

Among the different protected areas, those ecosystems that are dependent on the subsurface waters (groundwater-dependent ecosystem) could be sensitive to the change of subsurface water quality and quantity. In the middle part of the area the Kenderes grass land"Kenderesi-legelő" is a protected groundwater-dependent ecosystem (Table 9)

Table 9. Groundwater-dependent ecosystem in the area

Type of protected area	Identifier	Name of the protected area
Natura2000 nature conservation area	HUHN20144	Kenderes grass land

Protective zones of water resources also belong to protected areas

Surface and subsurface water production

There is no significant registered production of surface waters for drinking or any other purpose. The protective zones of the water production wells of the Kenderes water works fall in the area (Table 10). Invulnerable water bodies in the area have delineated protective zones. The delineation of these protective zones is based on finished computed diagnostics.

Table 10. Water resources in the area

Water resource	Code	Goal of production	Status	Digital availability of protective zone	Vulnerability	Protected production (m^3/day)	produced water body
*Kenderes water works	ALG169/15 044-40	drinking water	in operation	only computed finished	no	438	p.2.10.2
Kenderes Bánhalma settlement water works	ALG168/15 044-30	drinking water	in operation	only computed finished	no	438	p.2.10.2, p.2.9.2

* water resource in the area

There is no water production for mineral water and medicinal water purposes in the area based on the record of OGYFI 2010. In the broader zone there is a mineral water well (B–63) and two medicinal water wells (B–110, B–102) in Kisújszállás. These latter two are used for spas. Other wells in the record are shallow observation wells (filtering depth < 50 m). Deeper wells in the area produce with agricultural purposes.

There is no well in the area producing water with temperatures exceeding 30°C. Thermal wells are only found in the broader zone of the pilot area, namely in Kisújszállás (described above).

Cross-border water bodies

Water bodies in the area are neither part of any bilateral negotiation nor part of any accentuated water body agglomeration on ICPDR level. However, the shallow porous water body is the subject of international evaluation of the Tisza water catchment

Monitoring of water bodies

The monitoring of surface water follows the Water Framework Directive (2000/60/EC) implemented in the 31/2004. (XII.31.) KvVM regulation. There is no surface monitoring in the pilot area. There is water quality monitoring southwest of the protected area on the Nagykunság main channel, and northwest on the Nagykunsági-II-2 irrigation channel (Figure 15).

Shallow layers are monitored north of Kenderes. There are no monitoring wells for deeper water bodies, only in the broader zone, from the area of Kisújszállás and Kenderes (Figure 15).

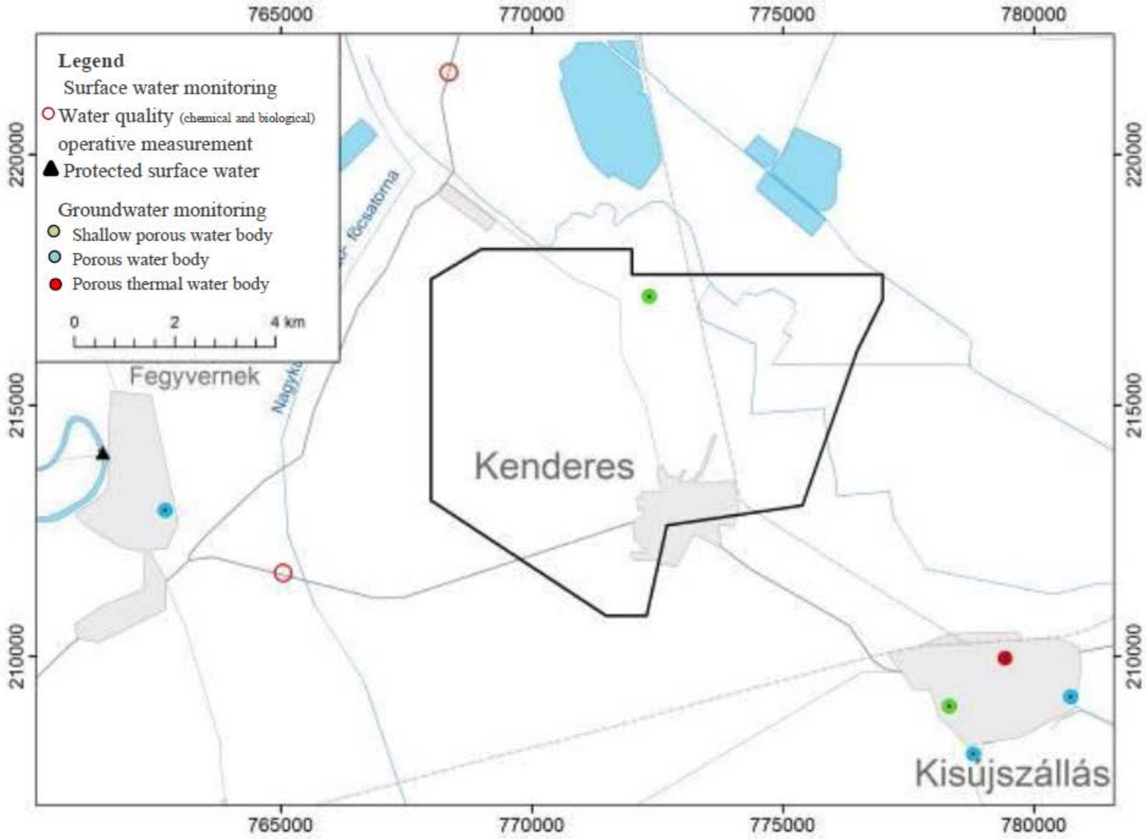

Figure 15. Monitoring points of surface and subsurface water in the area following the Water Framework Directive

9.6. Seismic risk assessment

The pilot area and its surroundings are inactive - even in Hungarian perspective. In the last 30 years, when high sensitivity monitoring network was deployed, and unfelt events were also registered, no event has been documented in approximately 20 km radius. This indicates that seismic risk is extremely low in the area.

10. Summary

Detailed analysis on the Kenderes depleted gas field site has been carried out in order to study its adequacy for potential storage pilot in the future.

Detailed geological studies revealed that the target reservoir for the pilot project developed in the Pannonian sedimentary sequence and is formed by delta foreland sandstones that are covered by thick delta slope facies marls and clay marls. Such sequence of sediments is widespread in the Pannonian Basin due to uniform basin filling process during Late Miocene Pliocene.

Exploration of the target area started already in the 1950s. The production of natural gas culminated in the 1980s and is still ongoing, but is extremely limited.

Storage capacity of the target reservoir was estimated using 2 independent approaches. The first approach was applied in earlier assessment projects e.g., EU GeoCapacity, CO2Stop and are based on cumulative production. The second method was based on basic reservoir parameters, determined using re-interpreted well logs. In the second case, we used a probability-based approach (Monte-Carlo simulation). Despite the different approaches both estimation methods revealed approximately 10 Mt storage capacity. Considering earlier production of the production wells, it is highly probable that the pilot injection (100 kt of CO_2 in 3years) is realistic over a single well.

Cost estimates, with detailed cost analysis of geophysical exploration and drilling revealed that the approximate cost of the storage pilot project would fall in the range of 15-25 M€. Timelines are highly speculative, but building on the experience of other projects it is likely that it would take approximately 8 years for the project from the pre-feasibility study to become operational.

Funding of the pilot project was found to be one of the most critical aspects. Currently it is unlikely that, despite drastically increasing carbon prices, such a project could be realized without EC/state funding. One of the funding sources of the EC could be the Innovation Fund that is aiming to support CCS/CCUS related projects. On the national scale “contract for difference” type of funding is foreseen.

Preliminary stakeholder mapping was carried out for the pilot project. In general it can be stated that the overall readiness of stakeholders is at an acceptable level, however the willingness to participate in any form in a storage pilot is at low level. There is plenty of space for communication, mostly at high-level.

Risk assessment studies showed that the condition of old wells in the pilot area is poor. Most of the wells will have to be abandoned and adequately plugged. There are certain wells that could be transformed to monitoring wells. On the other hand protected water bodies and nature protected areas are found only on the periphery of the pilot area. Seismic risk is very low.

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Appendix IV

Gamtos tyrimų centras Nature Research Centre

Vilkyciai pilot project study

This work (report) has been carried out under the subcontracting agreement between University of Zagreb, Faculty of Mining, Geology & Petroleum Engineering (UNIZG-RGNF) and Nature Research Centre (NRC), signed on April, 01, 2019. The work was subcontracted in the frames of ENOS project (EU program Horizon 2020; coordinator BRGM, France), under the task WP6.3 lead by UNIZG-RGNF.

Project manager for NRC

Saulius Šliaupa

Deputy Director for Science

Miglė Stančikaitė

1. Aims of the Vilkyciai pilot project

CO_2 is commonly used in oil fields to increase the oil recovery. This technology is well developed and rather old. There are, however, sites containing large resources of oil below the oil fields. Due to long geological history of the mature oil provinces some oil was spilled out due to tectonic movements (tilting), but a reservoir may still contain some residual oil. It is called the Residual Oil Zone (ROZ) (Fig.1). Formation of the ROZ is believed to be related mainly to a tectonic tilting after the main oil generation/migration stage. The water flooding has no effect for oil exploitation as oil saturation in such the zone typically is 40-60% of oil. Application of CO_2 in such zones can be effective to increase the oil recovery, as such zones are much larger then overlying oil accumulation (oil fields). The field experiment is planned in the Gargzdai ROZ applying CO_2 for oil recovery. The zone contains a number of small oil fields, including Vilkyciai oil field which is selected for the field experiment.

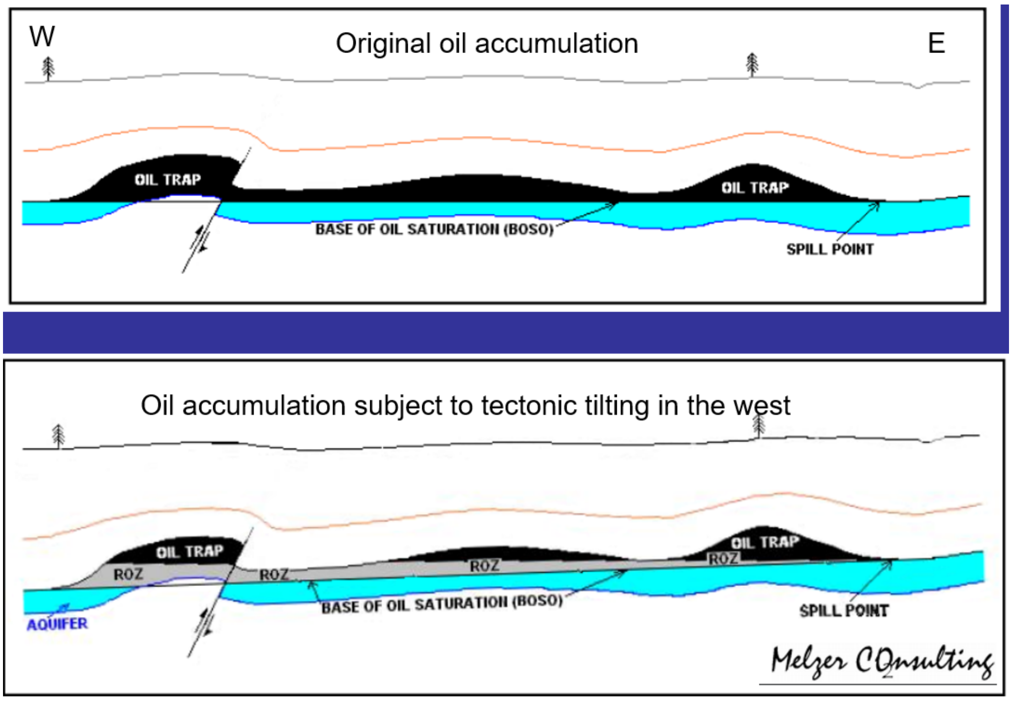

Fig. 1. Concept of formation of the ROZ

2. Review of geology

The Vilkyciai site is located in the central part of the Baltic sedimentary basin (Figs. 2, 3). The basin overlies the western part of the East European craton (structure of very low tectonic activity).

The sedimentary basin is a bowl-shaped with crystalline basement (Palaeoproterozoic-Archean) depths increasing westwards (Fig. 4). The basin comprises Ediacaran and all Phanerozoic geological systems (Fig. 5). The most complete stratigraphy is documented in Lithuania, including Vilkyciai oil field (Fig. 5).

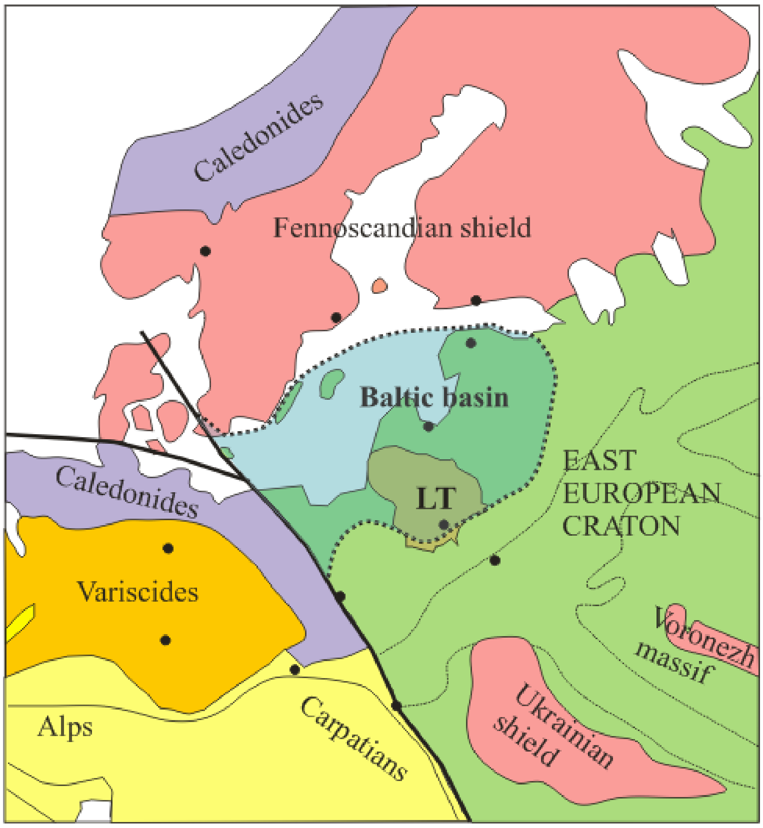

Fig. 2. Tectonic map of Central and Eastern Europe

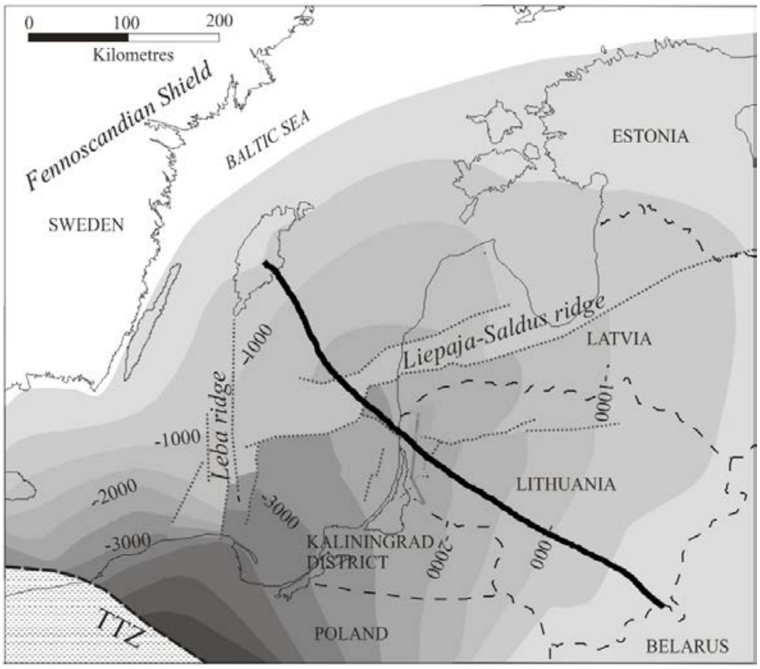

Fig. 3. Depths of top of the crystalline basement. Major faults of the sedimentary cover are indicated by dotted lines (after Sliaupa, Hoth, 2011). Bold line indicates line of cross-section (see Fig.4)

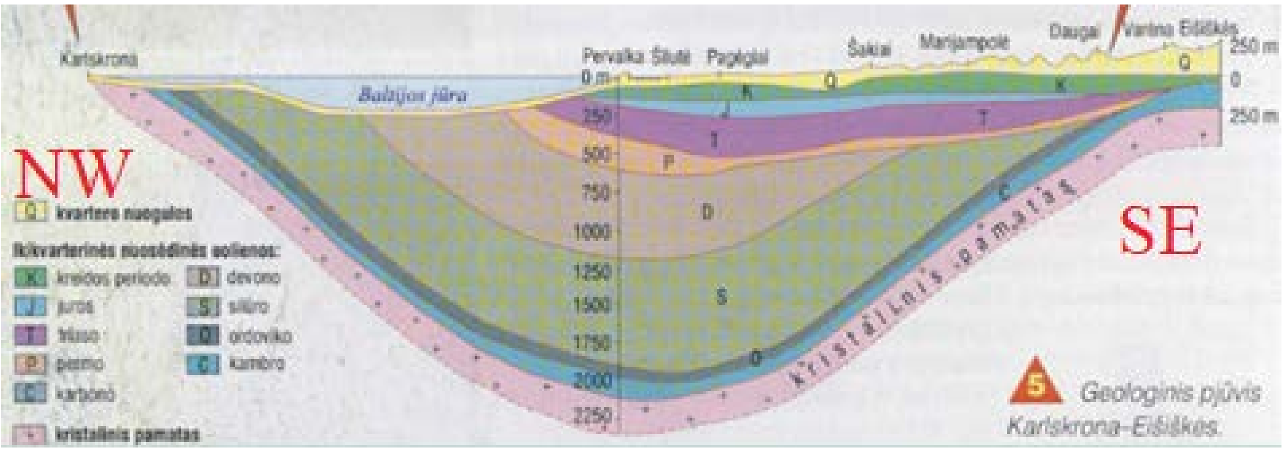

Fig. 4. Cross section NW-SE across the Baltic sedimentary basin (line is indicated in Fig. 3)

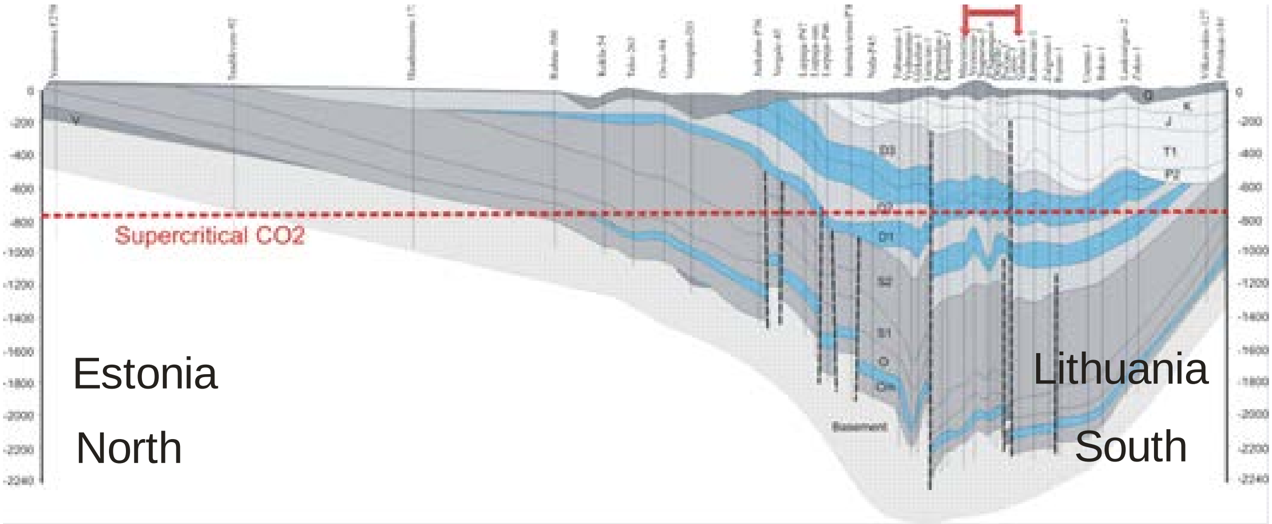

Fig. 5. Geological cross section North-South (Estonia-Lithuania). Gargzdai zone is marked in red. Blue layers indicate major aquifers. Oil fields are related to the deepest Cambrian reservoir in west Lithuania (after Sliaupa et al., 2008)

There is a number of small oil fields in the sedimentary basin, including Lithuania (Figs. 6, 7) (Brangulis, 1993). The hydrocarbon play of the Baltic sedimentary basin is represented by the Cambrian sandstones and shales, Ordovician and Silurian carbonates and organic rich shales).

The lower part of the Cambrian section of west Lithuania is represented by 60-80 m thick shales and siltstones with subordinate sandstones that are overlain by the Middle Cambrian quartz sandstones of about 50-75 m thick, hosting numerous oil fields in west Lithuania, as well as in the Kaliningrad District and Polish offshore (Sliaupa, Hoth, 2011).

The thickness of the Ordovician succession ranges from 35 m to 200 m in Lithuania (Laskovas, 2000). The eastern lithofacies are predominated by the shallow marine carbonates that systematically grade to marlstones in west Lithuania. Two distinct black shale layers containing up to 20% of organic matter are attributed to the Mossen and Fjäka Regional Stages (RSts) of about 4-5 m thick. They are considered as two prospective oil and gas shale layers. Oil shows were identified in the Upper Ordovician in the middle Lithuania and Latvia. The oil fields related to the Upper Ordovician mud mounds are exploited in the Gotland Island.

The thickness of the Silurian succession reaches 700-800 m in west Lithuania (Lapinskas, 2000). The westward thickening associates with a distinct lithofacies trend changing from predominating shallow water carbonates in the east to deep water graptolitic shales in the west. The maximum depth of the base of the Silurian succession reaches 2100 m in westernmost Lithuania. Some oil fields were discovered in 35 to 90 m thick bioherms in middle Lithuania, while several oil shows were reported from the fractured Lower Llandovery limestones in west Lithuania.

The petroleum system is overlain by up to 1 km thick Devonian succession of variable lithological composition in west Lithuania. The subsidence modelling suggests that the main oil generation stage took place during the Late Devonian and Early Carboniferous, well after formation of major faults. The subsidence considerably decelerated since the end of the Devonian. The Upper Palaeozoic-Cenozoic succession is only 20-40 m thick in northwest Lithuania and reaches up to 600 m in southwest Lithuania.

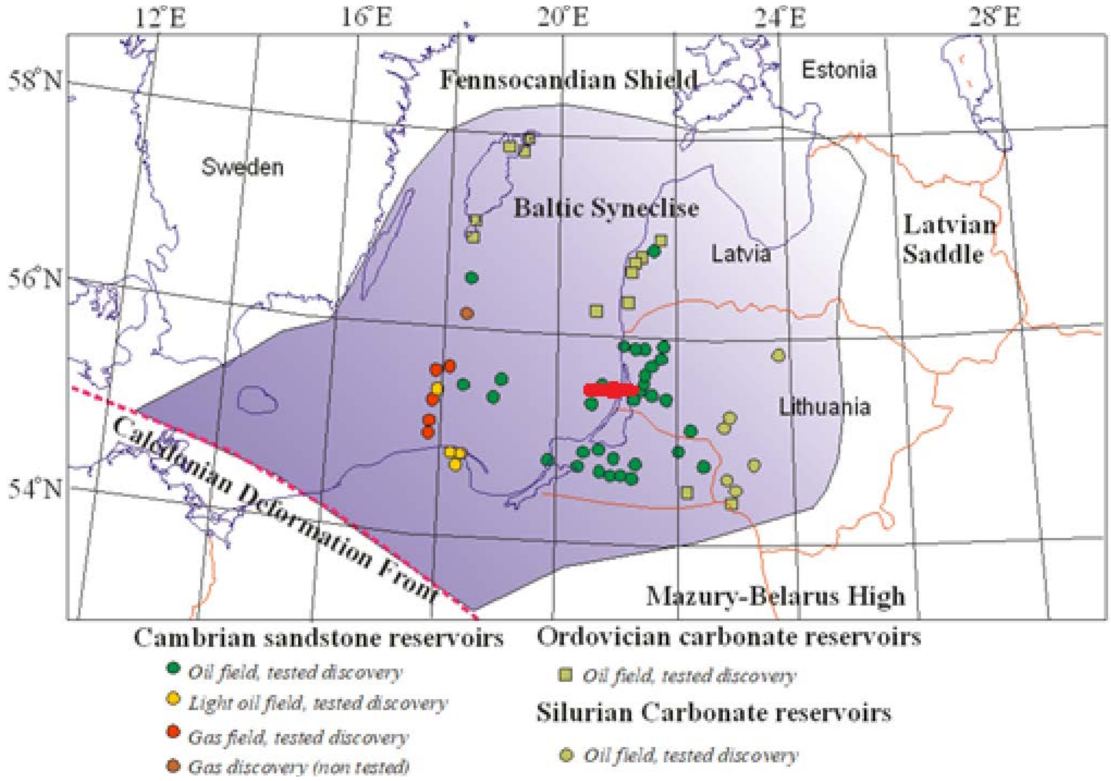

Fig. 6. Oil and gas fields of the Baltic sedimentary basin (after Sliaupa, Hoth, 2011)

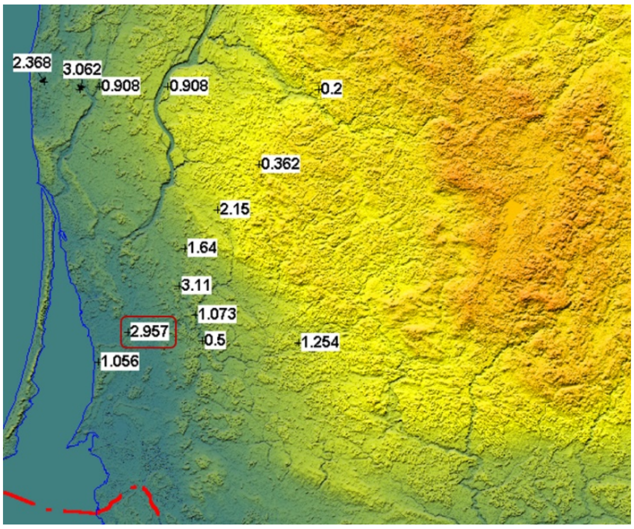

Fig. 7. Oil fields reserves in west Lithuanian oil fields (LIDAR topography is a background). Vilkyciai oil field is marked by red contour

The Vilkyciai oil field is located in the southern part of the Gargzdai uplift (Figs. 8, 9). The oil field is split by the Gargzdai fault zone into a larger field in the west and smaller field in the east. The latter segment is considered as non-commercial area. The acreage of the main segment is about 3*5 km. The depth to the top of the Cambrian oil reservoir in the crestal part of the structure is -1931 m, the deepest part is -2088 m. The thickness of the Middle Cambrian that represents a reservoir part of the Cambrian succession is 66 to 75 m. The total thickness of the Cambrian succession is 135-146 m. The amplitude of the structure is about 50 m.

The structure associates with the Gargzdai fault. The amplitude of the thrust fault is about 150 m. It was formed during the earliest Devonian, owing to a collision of the Baltica and Laurentia continents. The oil generation modelling suggests formation and migration of main oil volumes during the Late Devonian-Carboniferous times. It should be mentioned that the southern part of the basin started lifting up at that time. It can explain formation of the Gargzdai ROZ, as the southern part of the zone, according to the 3D seismic survey, is not closed by any fault.

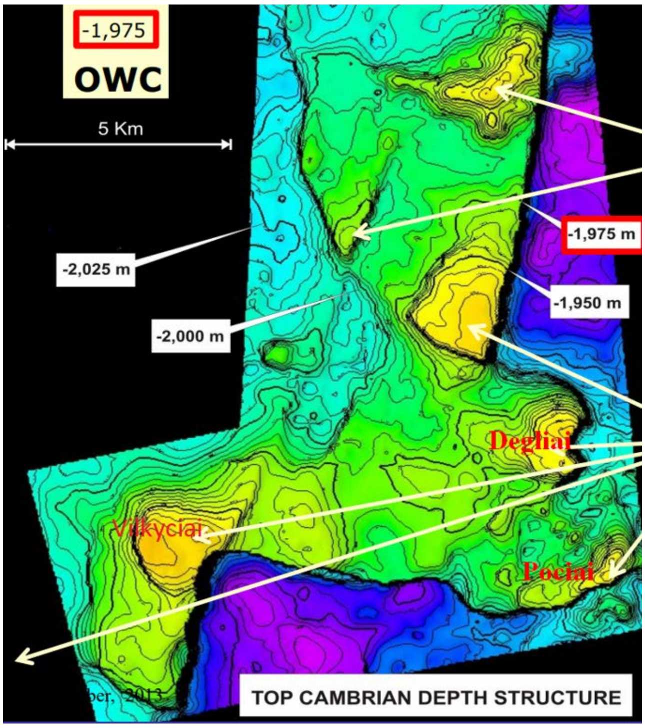

Fig. 8. Top Cambrian depth structure (3D seismic survey). Red rectangle indicates OWC depth in the first oil field discovered in the Gargzdai zone

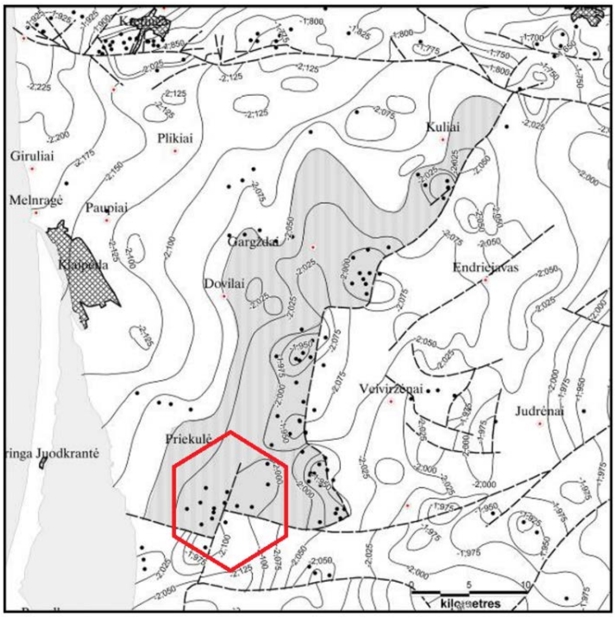

Fig. 9. Top Cambrian depth structure (2D old seismic survey). Grey area shows Gargzdai ROZ zone, potential for CO2-EOR

Two major lithological units are defined in the Cambrian section. The lower part, attributed to the Lower Cambrian-lowermost Middle Cambrian, is composed mainly of shales and siltstones with subordinate sandstones. This part of the section does not contain the oil. The Middle Cambrian (the Deimena RSt) is the main oil reservoir in the Baltic sedimentary basin (and in the Vilkyciai oil field as well). It is composed of quartz sandstones with rare shale and siltstone interlayers. Sandstones are fine grained, strongly cemented by late diagenetic quartz cement which reduces considerably the reservoir quality.

Due to severe quartz cementation sandstones have rather poor reservoir quality of the oil fields. There are only several good reservoir quality layers in the upper part of the succession (Fig. 10). The best properties are reported from the lower portion of the Middle Cambrian (to which ROZ associates). It should be mentioned that there is an excellent isolation of the Middle Cambrian reservoir from other aquifers. The reservoir is overlain by 750 m package of shale. Furthermore, the presence of the oil is a good evidence of the isolation of the Vilkyciai oil field from a leakage risk.

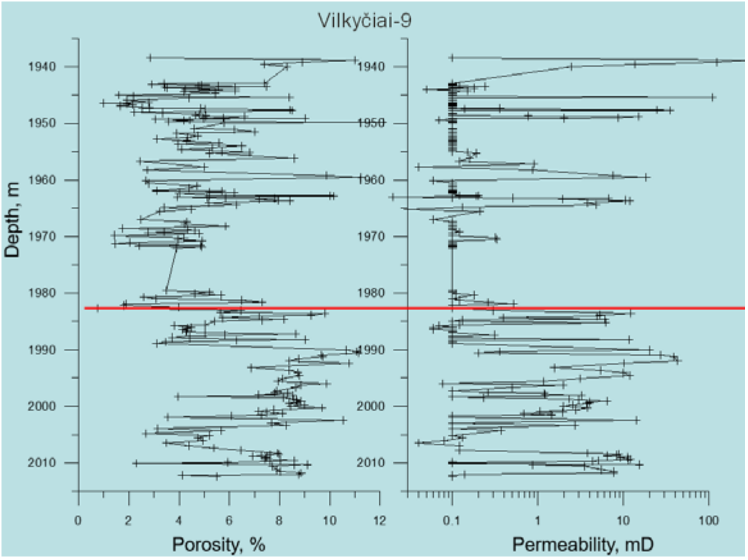

Fig. 10. Porosity and permeability of Middle Cambrian sandstones. Red line marks transition low and higher reservoir properties. Only scarce interlayers have permeability >0.1 mD, while the lower part is dominated by permeable layers, permeability reaching 50 mD

The Vilkyciai oil field was discovered as early as 1972, but was not exploited until 1990. Since than it was reopened for exploitation. The oil characteristics of the Vilkyciai field are similar to other oil fields in the Gargzdai zone. The oil is light (0.817 g/cm^3), of low viscosity (7.3 cSt), there is a low content of gas (50 m^3/t of oil) (Zdanaviciute, Sakalauskas, 2001). The OWC is located at the depth of -1973 m (Figs. 11, 12). The ODT (base of oil saturation) is confined to the underlaying shales at the depth of -2040. The thickness of the ROZ is 65 m.

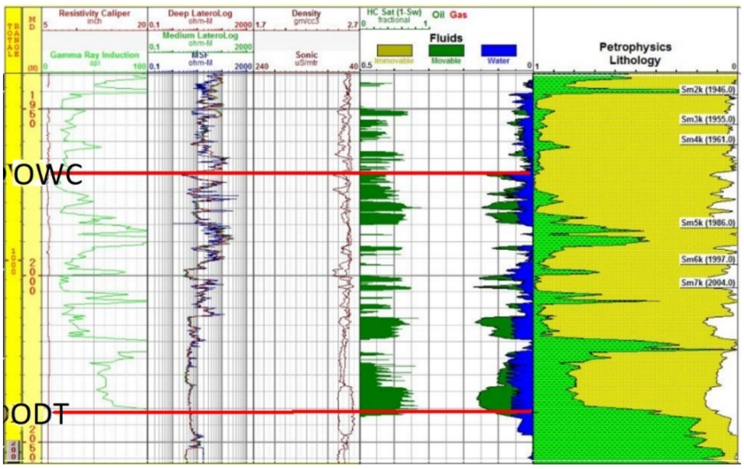

Fig. 11. Interpretation of well logging data (Vilkyciai-15). OWC-oil water contact, ODT-oil down to

Already the first oil exploration wells drilled in seventies suggested the presence of the unsaturated zone (ROZ) (Fig. 12). ROZ was identified in all wells of the Vilkyciai site.

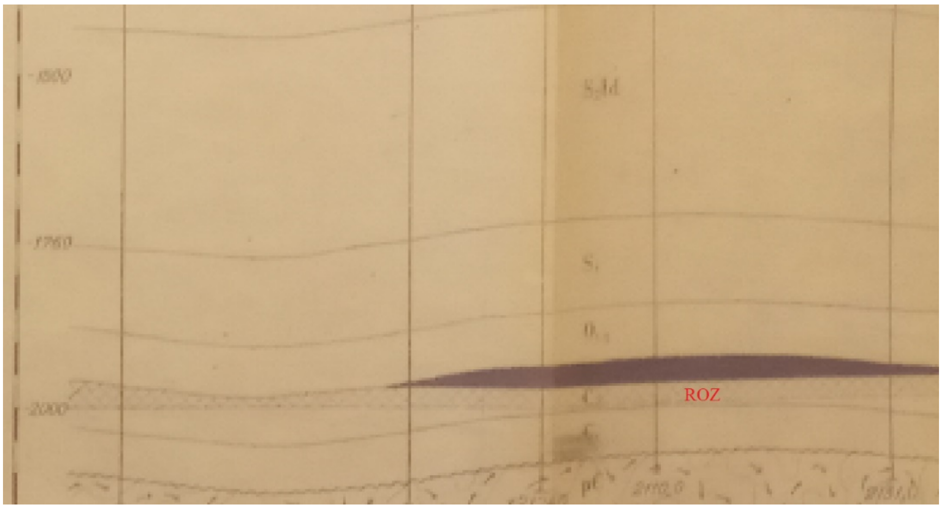

Fig. 12. Fragment of geological profile copied from old (1972; Geological Archives at Geological Survey of Lithuania) report. ROZ is marked

The zone was investigated in more detail after reopening the oil field using more sophisticated well logging tools (Fig. 13). The presence of the ROZ below the oil field is evidenced by oil shows while drilling, the well tests indicate some presence of oil in the water. Also, the well logging data indicate the presence of the oil in the ROZ.

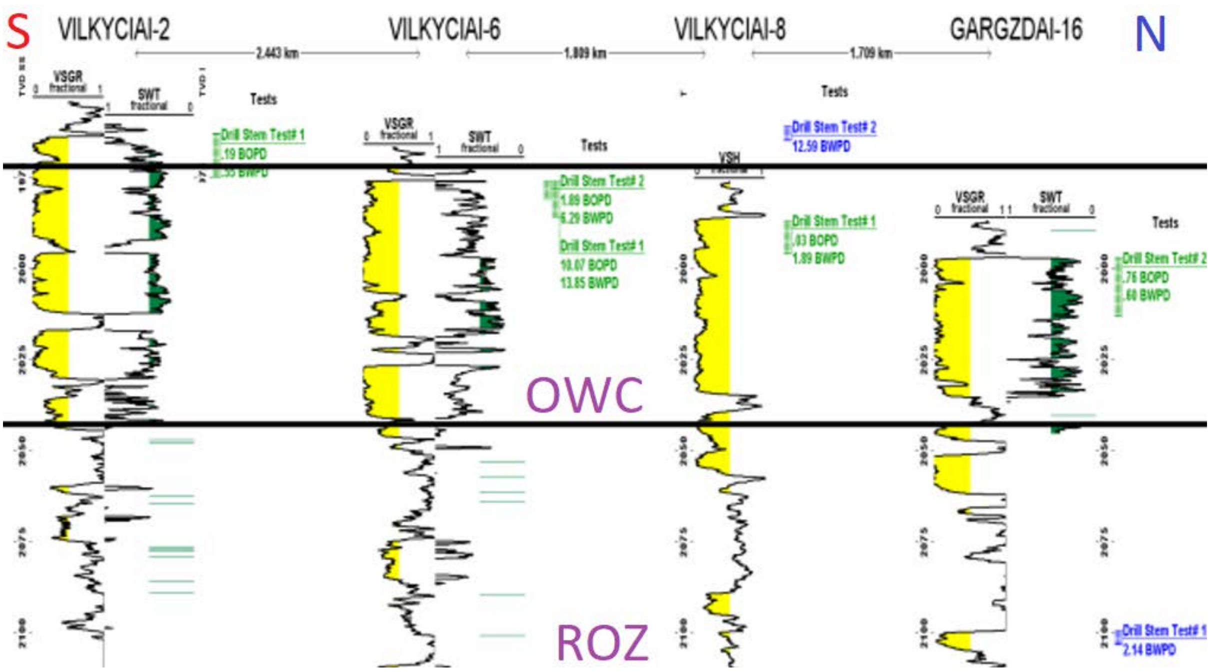

Fig. 13. Interpretation of well logging data. Yellow indicates presence of oil (saturation). Calculations suggest 40-50% of oil saturation in ROZ zone (Haselton, 2013 presentation)

3. Injection project concept

There are already 23 wells drilled in the Vilkyciai oil field. Most of wells are drilled through a whole section of the Middle Cambrian (therefore reached the ROZ), some wells are drilled down to the crystalline basement underlying the Cambrian succession. The average spacing distance between the wells is 1.5-2.5 km. The field is located in geographically favorable environment that allowed high quality 3D seismic survey. There are no woods and no larger villages nearby (Fig. 14). Therefore, no additional field studies are required.

The concept envisages performing the CO_2 injection experiment as a main part of the experiment. The CO_2 injection well will be selected together with Minijos Nafta specialists when project is started.

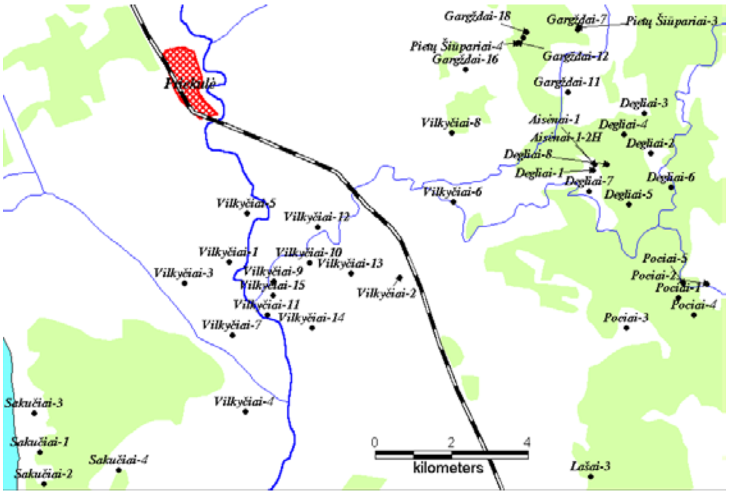

Fig. 14. Location of Vilkyciai wells. Neighboring wells are also shown.

The wells have the typical well completion (Fig. 15). It is a positive factor for the field experiment.

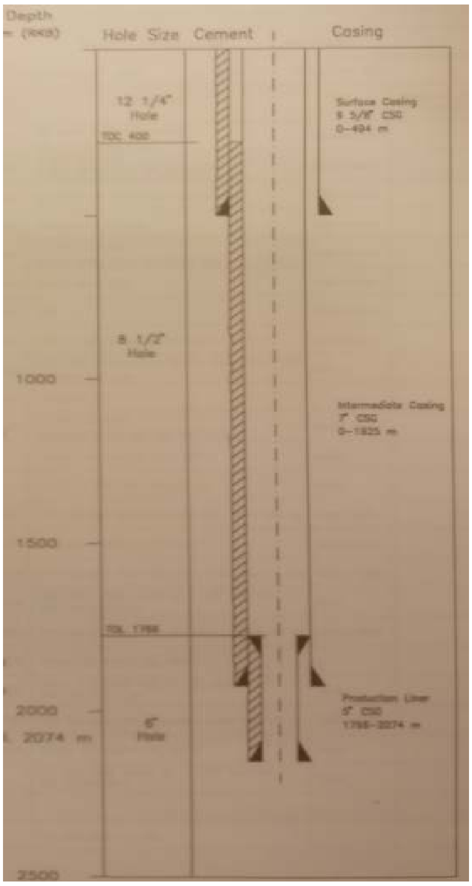

Fig. 15. Typical well completion in the Vilkyciai oil field (industrial report)

Abundance of wells is considered as a risk factor for the upward leakage along the wells. However, the monitoring of the site did not show any indications of the oil or gas at the Vilkyciai site.

4. Sources of CO_2

JSC Azotas LT was founded in 2014 considering that agriculture is fast developing sector. Companies main activity is producing and trading of fertilizers and chemical materials. As a byproduct CO_2 is produced and sold. The distance to the Vilkyciai oil field is about 200 km (Fig. 16). CO_2 might be transported by tracks. Alternatively, there is a train connection between Jonava and close to Vilkyciai site, which is considered as a positive factor for CO_2 transportation.

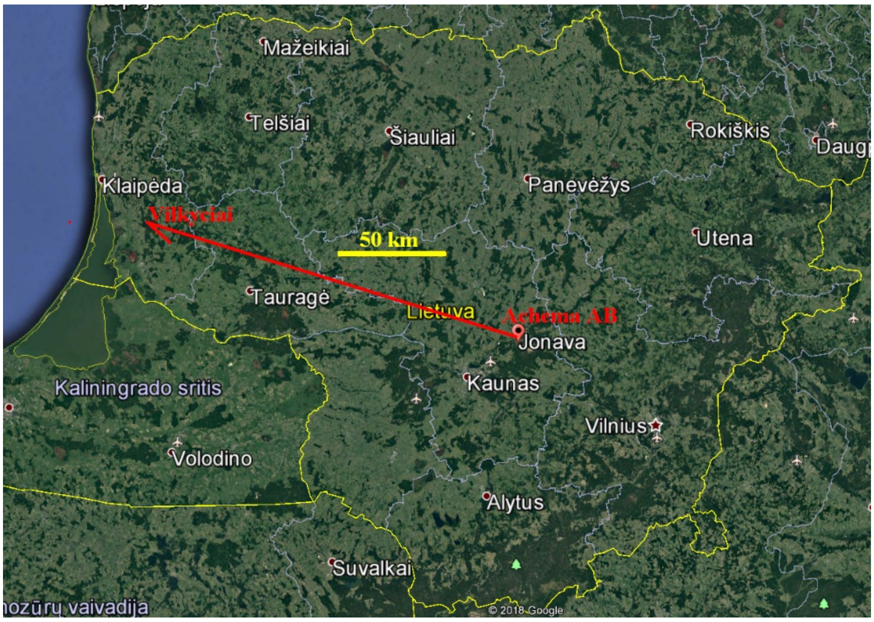

Fig. 16. Location of Azotas LT and Vilkyciai oil field

5. Budgets (site investigation costs – initial and detailed, drilling and workover cost estimates – means investment costs and operational costs when applicable)

- Site investigations costs – no expenses. The area is covered by 3D seismic survey. There are 23 wells drilled in the Vilkyciai oil field. Abundant core material is available and stored in Vievis drill core store owned by the Geological Survey of Lithuania and can be accessed for free (https://www.limis.lt/muzieju-kontaktai/-/museumSearch/view/805284?page=1&rowsOnPage=0).
- Drilling -no expenses. As mentioned above 23 wells were drilled and logged. Preparation of the injection well and monitoring well – 100,000 EUR
- Workover – logging for monitoring, 50,000 EUR.
- Sampling of water/oil in the wells to trace changes and trace migration of CO_2 – 50,000 EUR.
- Investment costs and operational costs. Injection of 1000 t of CO2 is planned. 80,000 EUR to by (60 EUR per ton and 20 EUR for transportation per ton) and transport CO_2 from Azotas plant. Pump leasing costs 200,000 EUR. Leasing of the containers for CO_2 storage costs 2,000 EUR per month. Preparation of the injection and monitoring wells 10,000 EUR.

6. Potential impacts of the Vilkyciai pilot

There are national and international aspects of the experiment.
The exploited oil volumes dramatically decreased in Lithuania and application of CO_2 in ROZ would allow to increase (revive) the oil production in a country (Fig. 17).

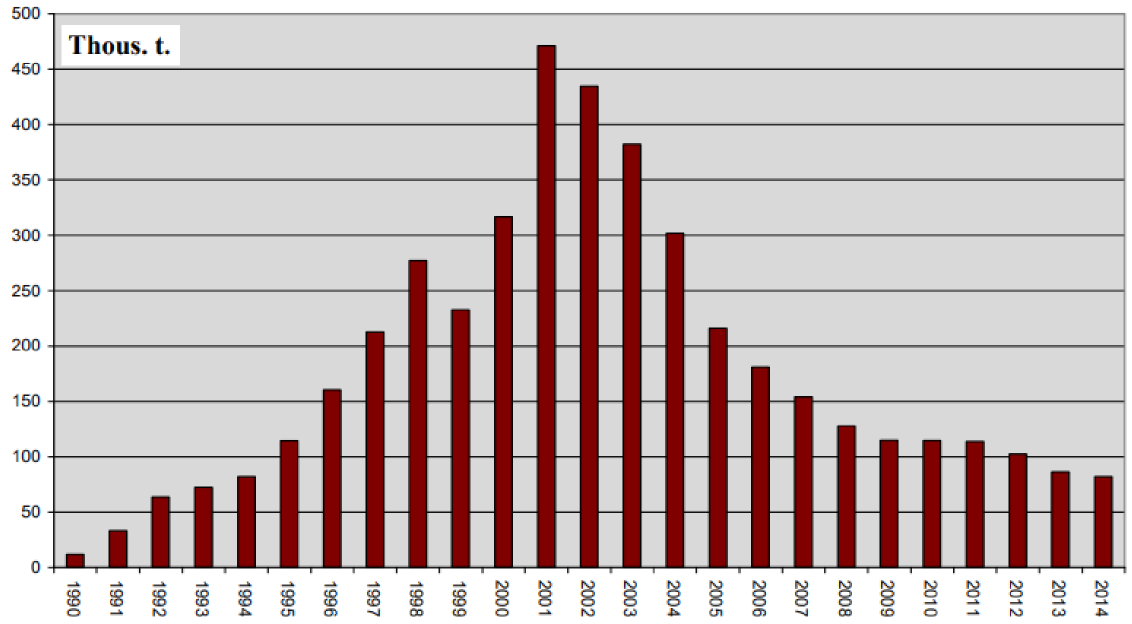

Fig. 17. Oil production history in Lithuania (provided by Geological Survey of Lithuania)

The results of the project are important for oil industry in general (international aspect, the most important impact of the project). The exploitation of ROZ is still at a very low incipient level. Therefore, good praxis example would encourage other oil companies to investigate and finally exploit ROZ in other regions. The exploitation of ROZ is stressed, for example, by the Department of Energy of USA (Petzet, 2012).

7. Stakeholder mapping in the region

- Oil company Minijos Nafta (operator of the Vilkyciai oil field) (Fig. 18). The Vilkyciai oil field is at the tail stage, therefore utilization additional resources are important for the company.
- Gargzdai municipality. Vilkyciai oil field is located in the Gargzdai administrative region. It is responsible for supervising the environment state (e.g. pollution) of the region. Also, some taxes are payed to the municipality by the company.
- Local community. Population of this region is quite sensitive as regards any new geological innovations. Also, some local part of the population is employed by the company.
- Central government. Injection of 100,000 t of CO_2 is allowed by Law. In any case, this experiment will have to be agreed to the central institutions.

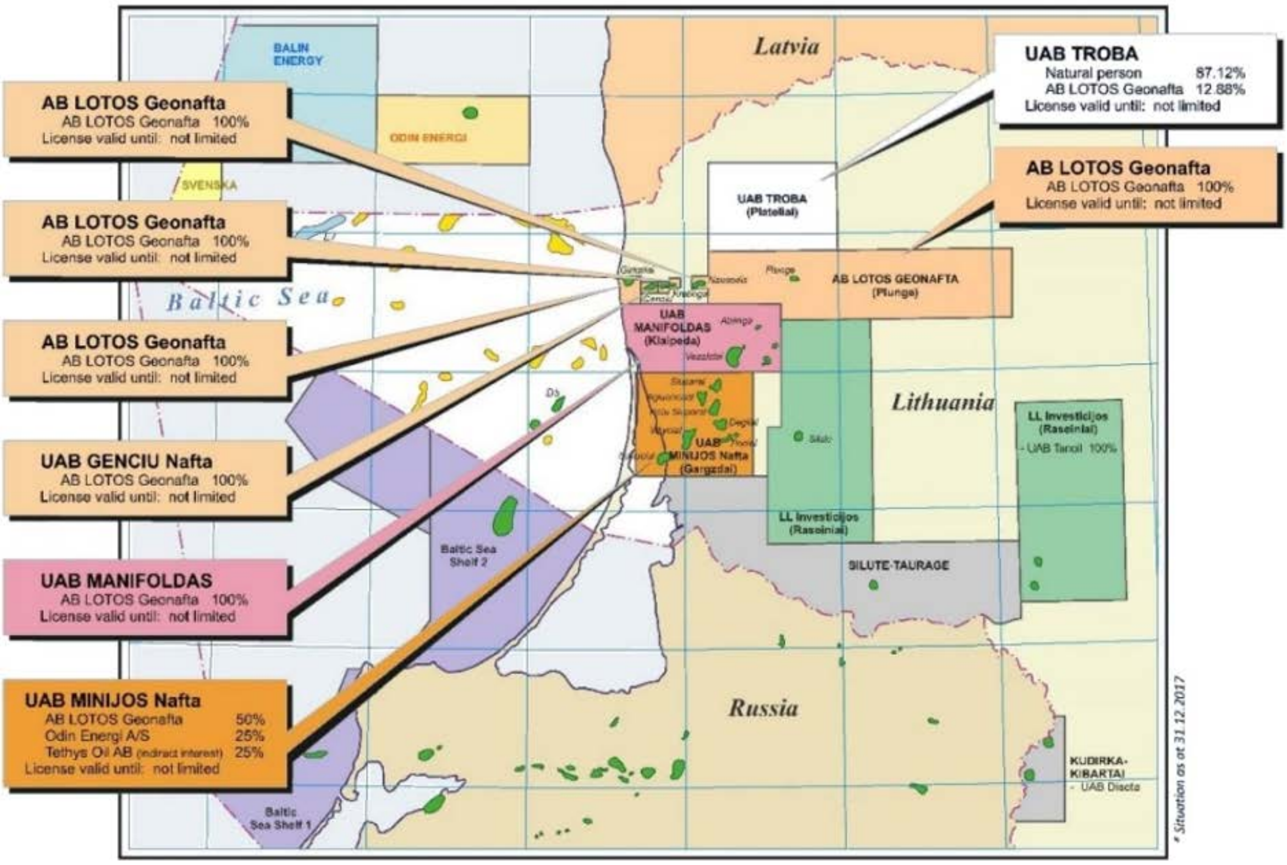

Fig. 18. Oil fields license areas of Lithuania. License area of Minijos Nafta is shown. Vilkyciai oil field is located in the Minijos Nafta company's license area

8. Provisional timeline and funding opportunities

Some additional funding can be expected from Minijos Nafta oil company which operates the Vilkyciai oil field. As it was mentioned, the oil production is in the tail stage, therefore the company would be eager to utilize the ROZ using CO_2. The ROZ resources are very large and its application would compensate for the production decline in the oil fields.

The experiment would take 1.5 year. It is a selection of the well most suitable for the CO_2 injection based on revision of available geological and geophysical material. The special injection mechanisms have to be installed at the site. Buying and transportation of CO_2 to the site. Injection of CO_2 into the well and documentation of the oil production. Monitoring of the site.

The leakage of CO_2 is of low risk as there is a good geological isolation (about 800 m thick Ordovician and Silurian shale package overlying the Middle Cambrian reservoir rocks. The leakage might be potentially related to the numerous wells drilled in the oil field and around. However, no accidents were reported from the oil field.

9. Project risk assessment (permitting, construction, policy)

Permitting – low risk, as injection of 1000 tons of CO_2 is allowed by the Lithuanian Law.
Construction – no risk.
Policy – such the project can be positively accepted by Ministry of Economy, low risk.
Leake of CO_2 along abundant wells – low risk, as there are no indications of the methane gas leakage along wells according to monitoring of the Vilkyciai site. As regards geological

conditions, the Cambrian oil reservoir is covered by about 1 km thick Ordovician-Silurian package – no risk.

Leakage of CO2 along the fault bounding the main part of the oil field in the west – some risk

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CONCEPTUAL STUDY OF CO_2 INJECTION IN DZIWIE SALINE AQUIFER IN WEST-CENTRAL POLAND

The work has been carried out under the subcontracting agreement between University of Zagreb, Faculty of Mining, Geology & Petroleum Engineering (UNIZG-RGNF) and Polish Geological Institute – National Research Institute (PGI-NRI), signed on April, 1, 2019. The work was subcontracted in the frames of ENOS project (EU programme Horizon 2020; coordinator BRGM, France), under the task (WP6.3) lead by UNIZG-RGNF.

Project manager for PGI-NRI

Adam Wójcicki

Warsaw, July 2019

Table of Contents

Introduction

In the frames of EU H2020 ENOS project (http://www.enos-project.eu/) the project leaders have committed to prepare a publicly available report "Study on new pilot and demonstration project opportunities in Europe". Basic information on ongoing, planned and/or cancelled pilot CO_2 injection projects in Europe had been collected by the relevant task leader of ENOS project (UNIZG-RGNF - University of Zagreb, Faculty of Mining, Geology & Petroleum Engineering) and, among others, the cancelled pilot CO_2 injection project at Dziwie site (near Kłodawa, in west-central Poland; originally planned in connection to the Polish CCS demo project Bełchatów and EU CCS Flagship Programme) was selected for a conceptual study. The work was subcontracted to PGI-NRI by UNIZG-RGNF under the agreement signed on April, 1, 2019.

1. Aims of the pilot (and its origin and connections)

The Polish CCS demo project Bełchatów and EU CCS Flagship Programme

In 2007, after the EU heads of state and government had endorsed the goal of constructing a set of industrial-scale CCS demonstration projects (during the EU Spring Council in March 2007), the European Commission began to create an economic and legal framework to support up to 12 flagship demonstration CCS power-plant projects and thus the EU CCS Flagship Programme was launched (Corless et al., 2011; ZEP, 2007). These demonstration projects were expected to start operation by 2015, and all were aimed to show the potential of CO_2 capture and storage while testing the technology and gaining valuable know-how – 10-12 full scale, integrated CCS projects covering a wide variety of CCS technologies, Europe-wide. The original goal of the EU CCS Flagship Programme was to ensure that CCS is viable for all new fossil fuel power plants by 2020. In years 2009-2010, the EU awarded 1 billion EUR to six such demonstration projects under the European Energy Programme for Recovery (EEPR), ensuring a diverse technological and geographical spread of the projects. It was also decided to competitively allocate (in 2011) 300 million EU Allowances from the ETS New Entrants Reserve (hence its acronym "NER300") to CCS and innovative renewable energy demonstration projects. One of the flagship demonstration CCS power-plant projects was the Polish CCS demo project Bełchatów which received 180 million euro – the EEPR grant agreement was signed in May 2010 (Corless et al., 2011; PGE website).

Hence, in 2009 PGE Elektrownia Bełchatów S.A. initiated works aiming at construction of a demonstration CCS installation. The installation was to be integrated with the 858 MW unit which has been since September 2011 operated in PGE GiEK SA Oddział Elektrownia Bełchatów (Bełchatów Power Plant). It was planned the CCS installation would comprise the following key components which constitute the full value chain in the validation process of the CCS technology (PGE, 2015; PGE website-CCS demonstration plant):

- Post-combustion Carbon Capture Plant (CCP) of size equivalent to 260 MWe and the CO_2 capture efficiency of at least 85%, utilizing the Advanced Amine Process (AAP) & its integration with the 858 MW unit. The CCP was to capture approximately 1,8 million tons of CO_2 per annum. The task included also modifications of the new 858 MW unit for the needs of the CCP construction, in order to obtain the status „Capture Ready" (completed in 2010). The key modifications included tie-in for off-take and return of cooling water required for the CCP as well as flue gas to the main flue gas ducts. A comprehensive FEED study (feasibility analysis) for the selected post-combustion capture plant option based on advanced amines was prepared in years 2009-2011 then the environmental decision and the building permit were obtained.
- CO_2 Transportation: this component was to consist of a pipeline (of diameter 300 mm) and the associated infrastructure to transport the compressed CO_2 from the Carbon Capture Plant to the storage site. Pipeline routes to each storage site considered in CO_2 storage component were designed and a prefeasibility study on the transport component was completed. For the selected storage site (at the beginning of 2012) a pipeline of total length of 140 km, running across 16 communes was designed, then during 2012 the pipeline route was proposed to be included in the local plans of spatial development, the relevant environmental impact assessment report was prepared and submitted as well as the public

tender specification for selection of the pipeline construction contractor was prepared and published. Also briefing meetings in this topic with representatives of 16 Commune Councils from the area of the planned CO_2 pipeline route were organized.

- CO_2 Storage: this was to inject pressurized CO_2 underground (within deep saline aquifers) for permanent storage. In 2009 three possible CO_2 storage sites were identified (basing on the input from the Polish national research project "Assessment of formations and structures suitable for safe CO_2 storage including the monitoring plans"), located in Łódzkie voivodeship (province) in central Poland, within a radius of 120 km from the Bełchatów power plant: (1) Lutomiersk-Tuszyn-Pabianice-Bełchatów, (2) Budziszewice and (3) Wojszyce (see also Wójcicki et al., 2014). Following comprehensive geological works, analyses and examinations carried out in years 2009-2011 (new field works – including detailed 2-D seismic and gravity surveys as well as appraisal wells, processing and interpretation of new and archive data, construction of geological models of the considered storage sites and their surroundings) and basing on experts' recommendations Wojszyce structure (located in northern part of Łódzkie voivodeship) in saline Jurassic sandstone aquifer was finally selected in the beginning of 2012 as the most suitable storage site for the CCS demo project Bełchatów. As the second phase of the storage component detailed site characterization of Wojszyce structure was scheduled (including 3-D seismic and the appraisal well(s); the next phase would be the demo storage site development, basing on previous activities, provided the site characterization confirms the feasibility and safety of storage there) and the public tender specification for selection of the site characterization coordinator contractor was prepared and published in March 2012. Additionally informative campaign among authorities from regional and local level (with representatives of Łódzkie voivodeship, counties and communes where possible CO_2 storage sites were considered), which consisted in several meetings and workshops, was organized in years 2009-2010. These events were followed by external public engagement campaign for local communities where new field works (of the first phase of the storage component) were carried out (detailed 2-D seismic and gravity surveys as well as appraisal wells). Last but not the least in March 2012 numerous briefing meetings with representatives of local administration aiming at spreading information about the actions planned in the second phase of the demo CCS Project were organized (PGE, 2015; PGE website).

PGE sought as much non-refundable financial support as possible. In February 2011 an application to ETS "NER300" programme was submitted, in June 2011 Memorandum of Understanding was signed with the Norwegian Trading Mechanism and together with the Polish government efforts towards developing a domestic CCS support scheme were undertaken (PGE, 2015; PGE website).

In the beginning of 2013 a decision was made to close the Bełchatów CCS demo project. There were many reasons of such decision: financial (e.g. a failure of a domestic CCS support scheme – hence the lack of domestic contribution which was necessary to obtain NER300 grant), legal risks (delayed implementation of the CCS directive into Polish law, no law enabling a feasible implementation on the transport component, obligation to apply the public procurement law during the contracting process), problems with public acceptance (protests during field works conducted at one of possible storage sites, therein also the lack of public acceptance for the underground CO_2 storage in general, at least in one area out of three, as well as the lack for public acceptance for CO_2 pipeline routing there), problems with selection of the coordinator contractor for the second phase of the storage component (site characterization) and numerous technological risks (PGE, 2015; PGE website).

The national project

The Polish national research project "Assessment of formations and structures suitable for safe CO2 storage including the monitoring plans", ordered by Polish Ministry of Environment (which is also the permitting authority and, in case of CO_2 storage, the competent authority in accordance with the CCS Directive 2009/31/EC of 23 April 2009 as well as the relevant Polish law implementing the Directive) was carried out in years 2008-2012 by a research consortium led by PGI-NRI (Wójcicki et al., 2014).

The project was intended to identify and assess the geological formations and structures suitable for geological storage of CO_2 from large industrial emission sources in Poland. The results of the study were to be used for the purposes of CCS demonstration projects of zero-emission power plants till 2015 horizon (at the start of the project, in 2008, two such projects had been planned in Poland - PGE Bełchatów and PKE & ZAK Kędzierzyn, then only PGE project started in 2009 and was cancelled in 2013), entities applying for permission to build new "CCS ready" power blocks, required to identify potential CO_2 storage sites and provide pre-feasibility studies, commercial CCS installations planned for construction after 2020, and by research institutions.

The goals of this project included (Wójcicki et al., 2014):

1. Summary of the current state of knowledge on geological storage of CO_2, taking into account previous studies and projects (in Poland, Europe and world-wide);

2. Consulting for the Ministry of the Environment regarding the implementation of the CCS Directive;

3. Assessment of geological formations and structures suitable for geological storage of CO_2 from industrial emission sources with an estimate of national needs and capabilities;

4. Integration of results and plans for R&D in the field of CO_2 geological storage conducted in Poland and cooperation with key stakeholders in this field in Europe and around the world;

5. Development of multi-variant (alternative) scenarios for the purposes of CCS demonstration projects of power plants with reduced CO_2 emissions and possibly other CCS installations;

6. Development of monitoring programs for selected geological structures.

In 2009, basing on available archive geological-geophysical data, geological formations and structures in central Poland – possible CO_2 storage sites for the Bełchatów demo CCS project were characterized and the relevant report was elaborated (Wójcicki (ed.), 2009) and then utilized by PGE (the demo project and Bełchatów power plant operator) as the starting point for the storage component of the demo project.

Pertaining to goals 5 and 6 listed above the assumptions and geological work plans for several possible pilot CO_2 injection projects, mostly in Bełchatów area (central Poland) were completed (Wójcicki (ed.), 2013). These results were utilized by an initiative on the Polish CO_2 injection pilot project suggested by the Ministry of Environment and established in 2009 by key Polish energy operators, research partners and service companies. The initiative considered several locations for the pilot CO_2 injection into saline aquifer in central Poland and finally selected the injection site at Dziwie located not far from (but outside) the CO_2 storage site intended for the Bełchatów demo CCS project (Wojszyce structure – see Fig. 1.1) and managed to obtain the injection permit in 2011 (Wójcicki, 2013).

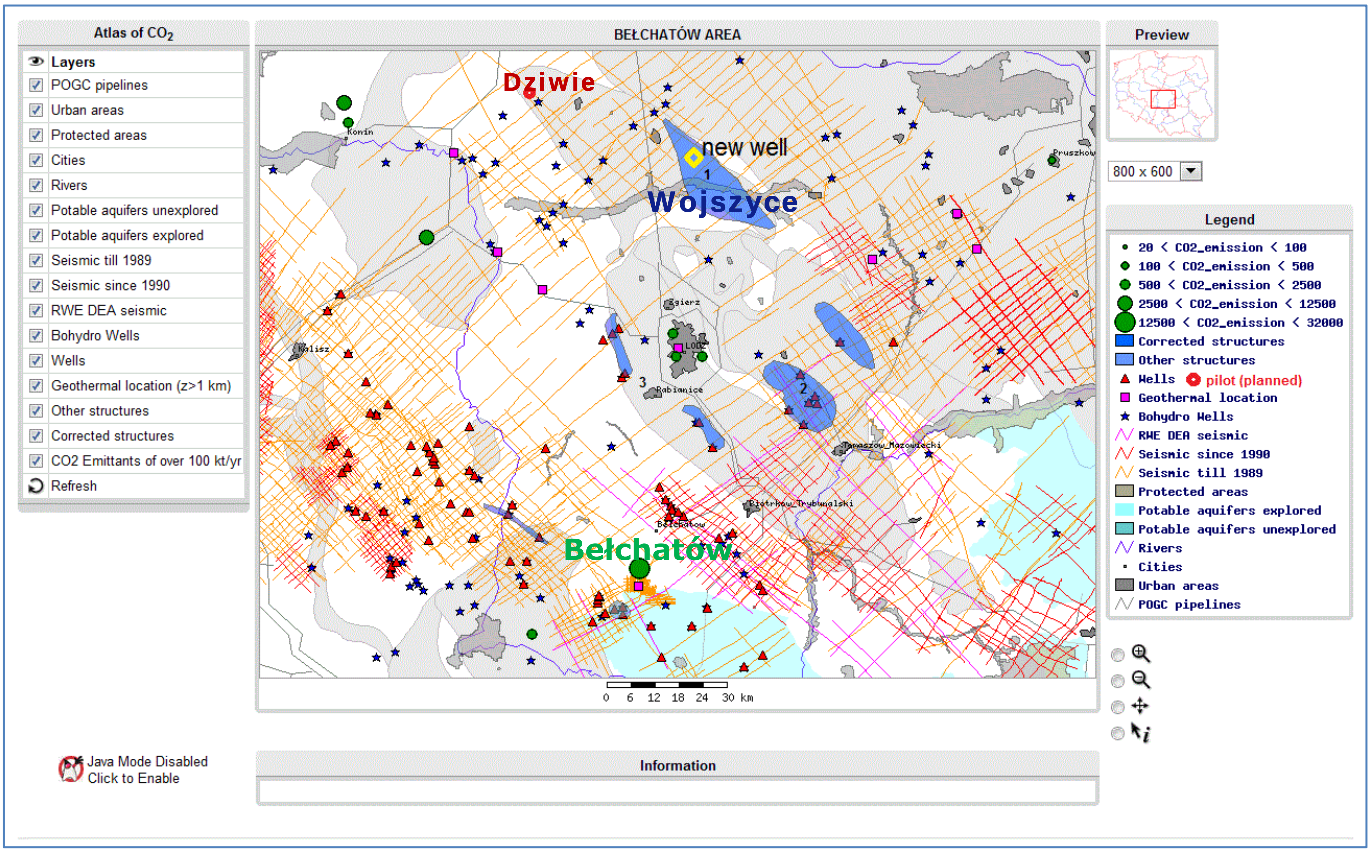


Fig. 1.1 Location of the planned pilot CO_2 injection site (Dziwie), CO_2 storage site of the demo project (Wojszyce) and CO_2 capture installation (Bełchatów) (Wójcicki, 2013).

The pilot injection project

The initiative on the Polish CO_2 injection pilot, the research-industrial consortium GeoCO_2 was initiated in 2009 by key power companies in Poland, members of Economic Society Polish Power Plants, and research partner and service companies were invited (Filipowicz in: Hinc, 2011; TGPE/ESPP website). The power companies were entities applying (or planning to apply in not too distant future) for permission to build new "CCS ready" power blocks, required to identify potential CO_2 storage sites and provide pre-feasibility studies (on possible future large scale CCS projects) in accordance with the CCS directive and its guidance documents (being implement at that moment into Polish law). Present members of TGPE/ESPP are (after TGPE/ESPP website) the following companies, providing electricity and heat to the vast majority of country population: PGE (1st domestic energy operator, the demo CCS project operator), Tauron (2nd domestic energy operator), Enea, PAK, Energa, CEZ, Polenergia, PGNiG Termika.

The goals of the pilot injection project (regardless of location – the consortium considered several locations in central Poland, where the saline aquifer most suitable for the demo CCS project and possible future large scale CCS projects appears – Wójcicki et al., 2014 – and finally Dziwie site was selected where issues like funding, land ownership and public acceptance seemed to be solved) were as follows (Filipowicz in: Hinc, 2011):

- Testing the CO_2 injection technology (intended to be applied in the frames of the demo project, but not until after the second phase of the storage component, as well as in future large scale projects) and CO_2 migration/injectivity within the saline aquifer in Jurassic sandstones (same aquifer as in the case of the demo CCS project and likely in many future large scale CCS projects in Poland);
- Verification of the assumed CO_2 migration models and integrity of the clayey caprock (regarding risks on CO_2 and/or brine leaking through the caprock into shallower aquifers);
- Proving the safety of CO_2 injection and storage into the aquifer intended to be used in case of the demo CCS project and possible future large scale CCS projects in Poland (at least in pilot project scale);
- Decreasing financial risks pertaining to implementation of CCS technologies by Polish energy sector (the key Polish energy operators participating in the initiative agreed to provide financial contributions proportional to their electricity production and CO_2 emissions);
- Providing reliable data on the pilot CO_2 injection and monitoring as the basis for project reports and scientific publications intended for the following end users: permitting and mining authorities, energy operators, NGOs and research community (a platform for a not unfounded discussion of proponents and adversaries of CCS).

It was assumed the knowledge and experiences acquired during the pilot project would be utilized to improve the CO_2 injection, storage and monitoring technologies and would make a contribution of Polish research community and industry to solve the global issue on reduction of CO_2 emissions (Filipowicz in: Hinc, 2011).

2. Review of geology (the Jurassic aquifer and its caprock)

The study area and the planned pilot injection site is located within North-European Permian-Mesozoic basin, the biggest European sedimentary basin in question, which extends from eastern Poland to eastern England, covering Denmark, a large part of Germany and the Netherlands. The basin was a subject of studies in the frames of numerous national and EU-funded research projects – for example EU Geocapacity (Vangkilde-Pedersen et al., 2009) where formations and structures suitable for CO_2 storage within the basin were assessed in regional scale in countries in question.

In northern, north-western and central Poland, Cretaceous, Jurassic and Triassic sedimentary rocks comprise sandstone aquifers suitable for CO_2 storage (Tarkowski in: Allier et al., 2009; Fig. 2.1, 2.2).

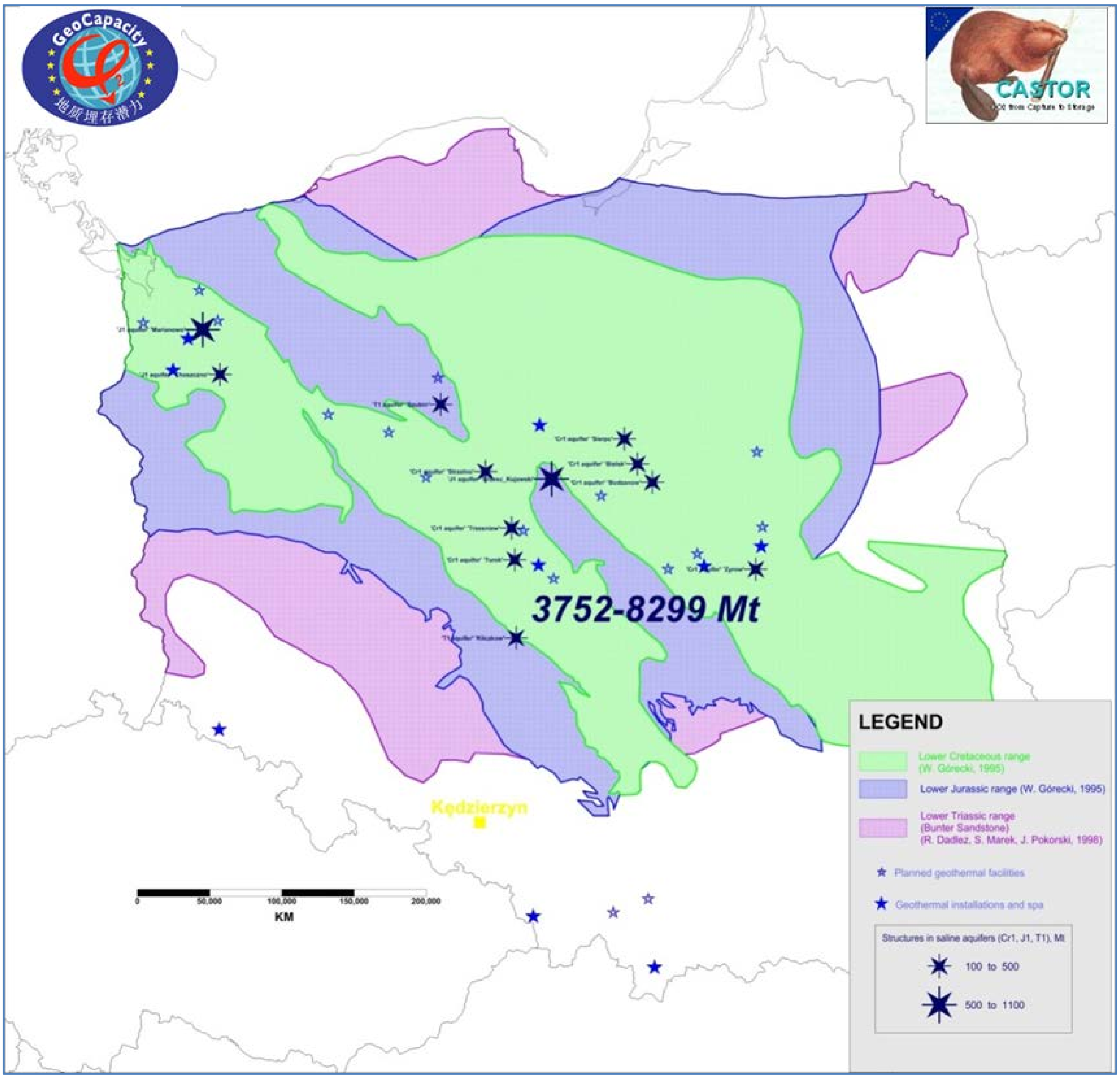


Fig. 2.1 The extent of Mesozoic aquifers in Poland (information collected in CASTOR and EU GeoCapacity projects).

Within Cretaceous the aquifers are represented mainly by Lower Cretaceous Barremian-Albian sandstone and sand and carbonate-sand deposits of very good reservoir properties located at depths from 0 (outcrops) to 2,800 m below surface level, usually overlain by low-permeability Upper Cretaceous carbonate rocks. The entire Lower Cretaceous succession thickness is up to 500 m in central parts of the basin.

In Jurassic sedimentary rocks several saline aquifers of good to very good reservoir properties are known: sandstone complexes of Hettangian, Sinemurian, Upper Pliensbachian, Lower Toarcian & Lower Aalenian (i.e. Lower Jurassic and the lowest part of Middle Jurassic). Depth to the top of Lower Jurassic sequence varies from 0 (outcrops) to more than 3,900 m below surface level. Porosity of Jurassic aquifers is usually within the range 15-33% and permeability 100-10,000 mD (though it varies depending on depth, and within the supercritical range for CO_2 the lower end values are more likely to appear than the upper end values; a realistic average value for the entire complex is about 500 mD).

Regarding Triassic Sedimentary rocks the saline aquifer in Middle Buntsandstein (Lower Triassic) sandstones is the main target which lies at about 1,500-5,300 m below surface level. The saline aquifer is sealed by 100-200 m thick Roethian silty and clastic-carbonate-evaporitic sediments. Reservoir properties of this deep saline aquifer are usually worse than in case of Jurassic and Cretaceous aquifers (Tarkowski in: Allier et al., 2009).

As mentioned in Chapter 1 the Jurassic sandstone aquifer were the target in case of the Bełchatów demo CCS project. Precisely, in case of the structure selected as the most suitable storage site (Wojszyce structure) the primary reservoir was the sandstone complex of Upper Toarcian & Lower Aalenian (no seal in between) and secondary – Upper Pliensbachian (Wójcicki et al., 2014). The primary caprock in case of the primary reservoir is the Upper Toarcian claystone, mudstone and heterolite complex and there are a couple of similar complexes within Middle Jurassic. In case of the secondary reservoir the primary caprock is a far thicker complex of Lower Toarcian claystone, mudstone and heterolites (see also Fig. 3.1).

The importance of the Jurassic saline aquifer for the problem of large scale CO_2 storage in Poland consists in the facts that the reservoir is extensive and covers a large part of country (Fig. 2.1) and in large parts of central and north-western part of Poland appears within the supercritical range of carbon dioxide, e.g. at depth of about 1 km and deeper (Fig. 2.1, 2.2 and 2.3). Also a very important issue is the presence of a relatively thick, regional continuous caprock of impermeable claystone, mudstone and heterolites complex of Lower Toarcian (Hesselbo and Pieńkowski, 2011). The complex is a good seal for Upper Pliensbachian reservoir (and then Sinemurian and Hettangian). As mentioned above the primary seal for the sandstone complex of Upper Toarcian & Lower Aalenian is relatively thin, though there are a couple of secondary seals above, within formations of Middle Jurassic. Regarding Lower Cretaceous aquifer it should be noted the reservoir does not appear within the supercritical range of carbon dioxide to such extent as in case of Jurassic aquifer(s). The caprock for Lower Cretaceous aquifer is very thick but mainly consists of carbonate rocks, so in case of presence of natural leakage paths the storage of carbon dioxide there might be not always safe and permanent.

These facts are reasons for the scope of the planned pilot project described in chapter 3.

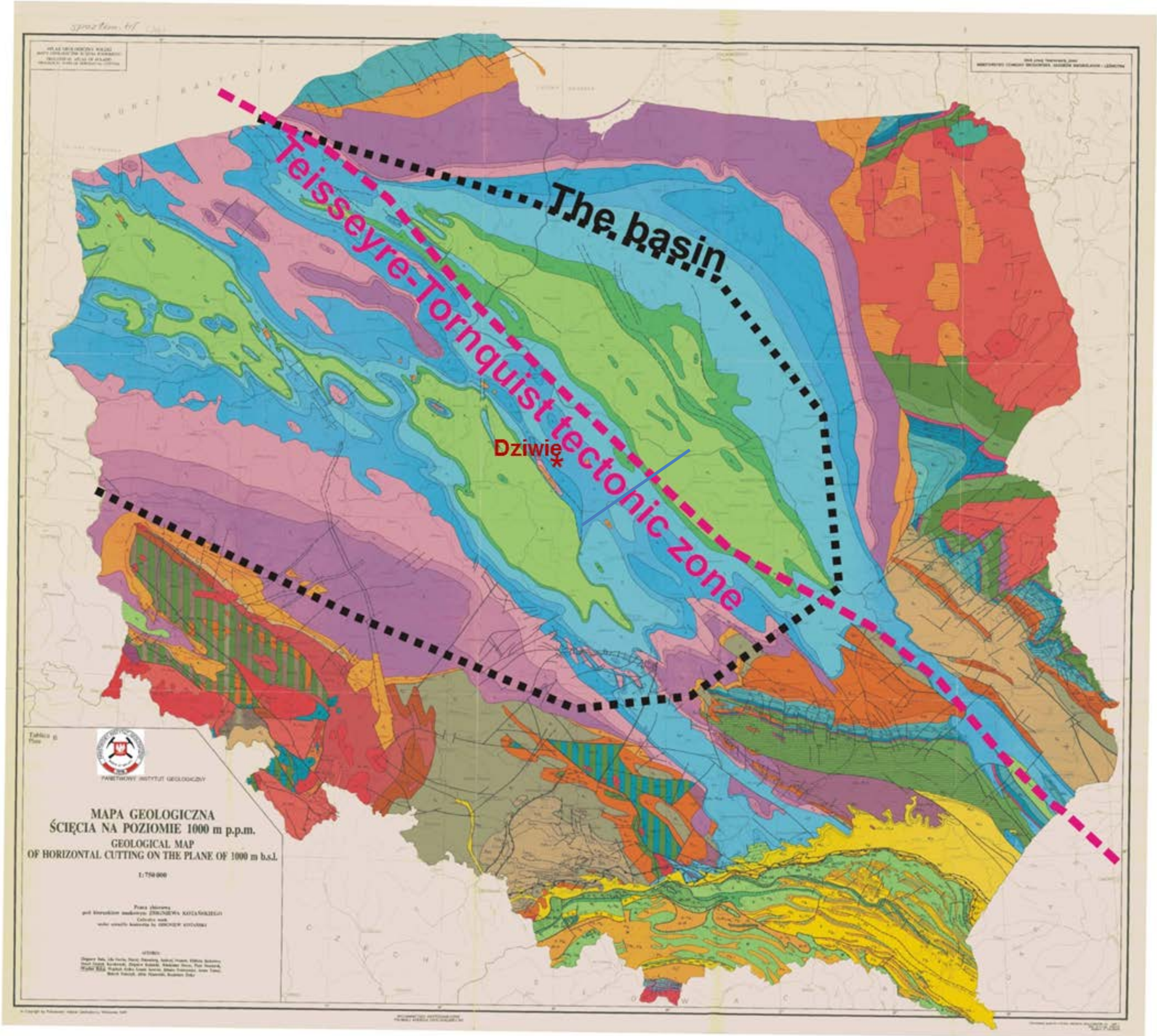


Fig. 2.2 Location of the planned pilot site (Dziwie) on the background of geological horizontal section map at depth of 1,000 m (Kotański, 1997).

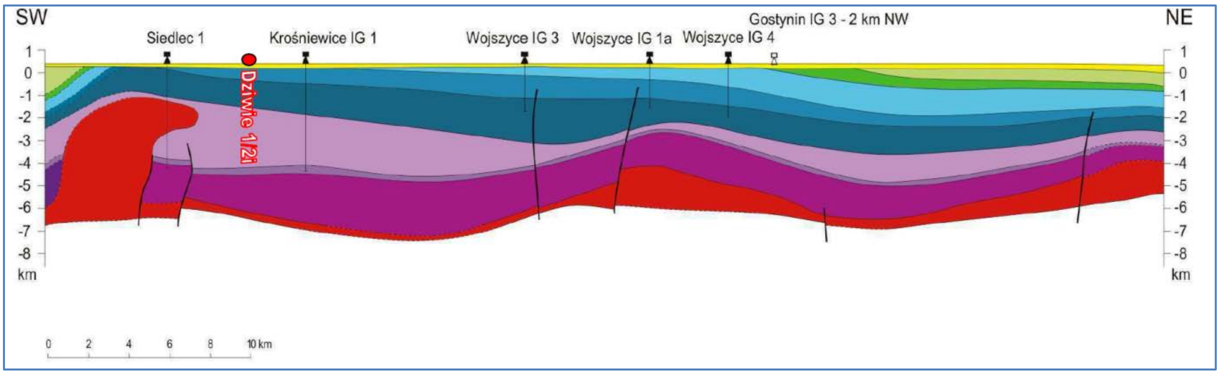


Fig. 2.3 Geological cross-section after Dadlez (2001) with the planned injection site cast to the profile.

3. Injection project concept

The original design of wells planned in the frames of pilot CO_2 injection project at Dziwie site in central Poland, as well as the anticipated geology (based on the geological wells located nearby, results of seismic interpretation and regional geological maps and cross-sections) is presented in Fig. 3.1. The distance between monitoring well and injection well is about 60 meters.

The target reservoir was Upper Pliensbachian sandstone (Lower Jurassic) with mudstone and heterolite inserts (132 m thick in total) of average porosity about 20% and permeability 200-500 mD. The primary caprock was the claystone, mudstone and heterolite complex of Lower Toarcian (110 m thick in total).

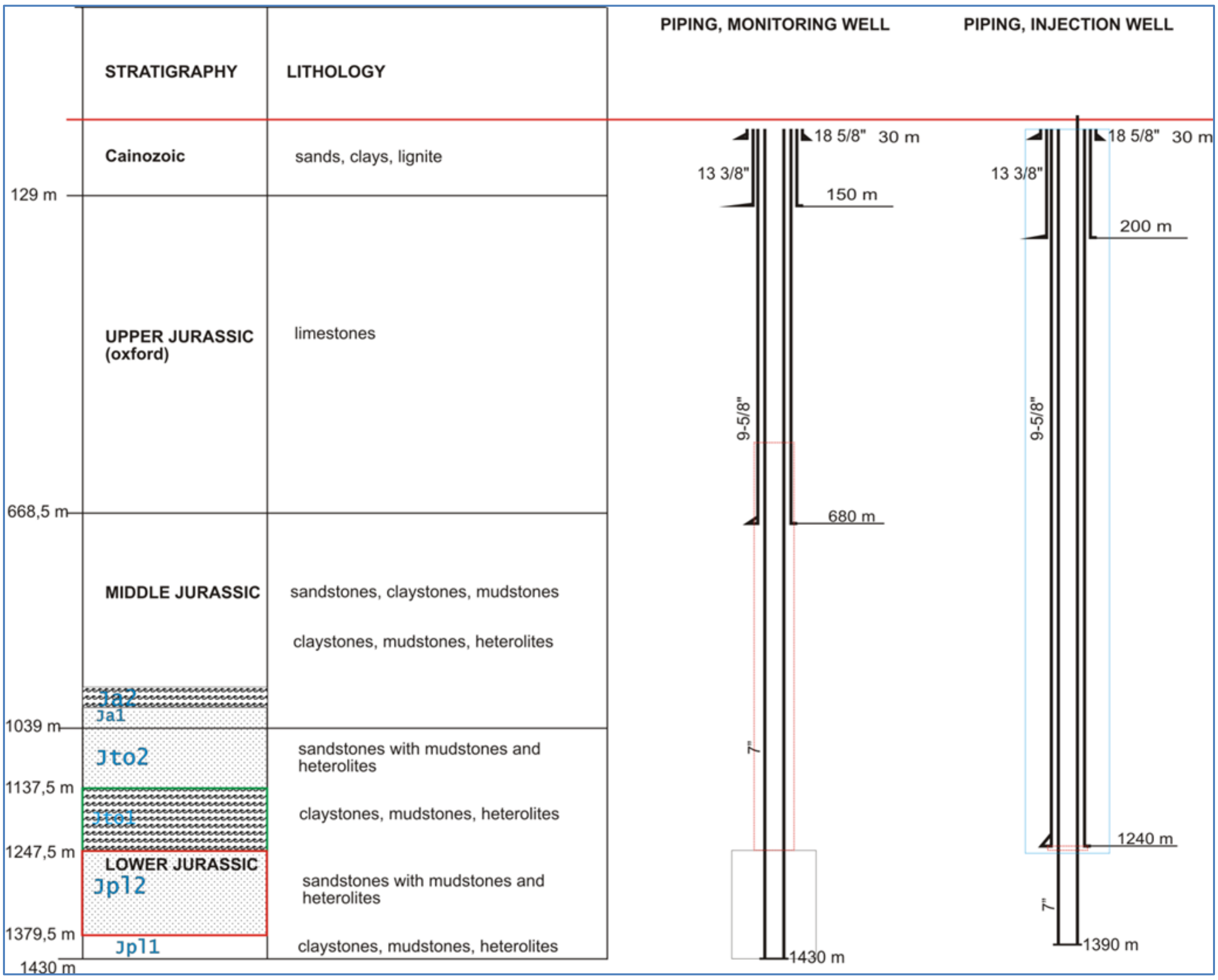


Fig. 3.1 Original design of wells planned in the frames of pilot CO_2 injection project at Dziwie site in central Poland (Wójcicki, 2013).

The planned amount of CO_2 injected was about 27 kt (precisely 27,072 t according to the geological workplan mentioned in Chapter 8 and Fig. 8.1).

The injection timeframe was assumed for 24 months (since January 2012 till December 2014 were the project start in January 2012).

The injection infrastructure (storage tanks, pump, chiller, heater, control panel, etc.) was designed according to experiences of the pilot injection project at Ketzin, Germany. The consortium made contact researches from GFZ Potsdam involved in Ketzin project and visited the site at Ketzin in 2010. The description of the relevant Ketzin project facilities (and monitoring infrastructure) is given in presentation of Streibel et al. (2013).

The monitoring infrastructure was designed to be as minimal as possible for the scheduled 3-year period of the project duration (with possibility to expand in next phase of the project). Only general assumptions were elaborated, the detailed blueprint of the monitoring (and drilling and injection) was to be submitted for approval to the regional mining authority.

The monitoring was to include:

- Cross-hole seismic (VSP) monitoring and electromagnetic monitoring (between the injection and monitoring well in Fig. 3.1);
- Gravimetric monitoring around the injection site;
- Passive seismic (seismometry) around the injection site;
- Geochemical monitoring of soil and groundwater (small diameter shallow wells to collect soil gas, piezometers to reach groundwater table and collect water samples);
- Biomomitoring (samples of microorganisms).

4. Sources of CO_2

Regarding carbon dioxide acquisition similar situation as in case of Ketzin project occurred (Streibel et al., 2013). A relatively pure stream carbon dioxide is a byproduct of industrial processes in chemical works (e.g. Haber-Tropsch processing, ammonia plant) which is usually vented into atmosphere. Sometimes CO_2 is captured and refined to food grade purity in order to be used in food industry, agriculture, etc. The oldest such installation working in Poland, located in Kędzierzyn ZAK chemical plant (located in southern Poland, about 250 km from the planned injection site) has been built in 1998 by ZAK and by the end of 2002 was acquired Messer Poland – the company invested a substantial financial contribution in order to expand the scope and volume of products. The plant annual production capacity is 35,000 t of CO_2 and carbon dioxide is used as carbonic acid in the beverage industry and in the horticultural sphere (supplying CO_2 to growing plants; Messer Group websites). In the original pilot project it was planned to acquire CO_2 of food grade purity produced in Kędzierzyn chemical plant and transport carbon dioxide by trucks. These plans covered the 3-year original project only, not a possible next phase (to be agreed later by the consortium partners).

According to press releases the market of capture and refining of carbon dioxide from chemical plants is growing recently in Poland and a couple of new facilities have been constructed.

The characterization of CO_2 industrial sources within the wider region is presented in chapter 7 (Table 7.1) along with the stakeholders operating these installations. It should be noted that two chemical plants in the wider region around the pilot injection site (in Włocławek and Janikowo) produce carbon dioxide stream which can be easily captured (and refined). According to press releases, in Janikowo the CO_2 used to be produced and in Włocławek a capture and refining facility was completed last year.

5. Budgets

The budget agreed by the consortium of Polish energy companies and research institutions and service companies for the scope of pilot project (Wójcicki, 2013; Filipowicz in: Hinc, 2011) was circa **19-20 M€.** The cost was valid to the period when the latest version of the geological workplan (the basis for the research/injection permit) was completed and then submitted to the permitting authority (Ministry of Environment) for approval i.e. in first months of 2011.

Obviously since year 2011 the prices on the services and goods necessary to perform such project did not remain unchanged and technological developments in drilling and monitoring technologies might have changed the whole picture as well.

Hence the approximate investment costs and operational costs taking into consideration current prices of drilling services (cheaper drilling services) and monitoring expenditures for the 3 year period (practically unchanged) are listed below.

<u>The investment costs (the site development, baseline monitoring):</u>

Preparatory works at the site –	0.6 M€
Drilling the appraisal/monitoring well –	0.9 M€
Collecting core and brine samples –	0.2 M€
Well logging –	0.2 M€
Completing the appraisal/monitoring well –	1.1 M€
Drilling the injection well –	0.9 M€
Well logging (incl. nonstandard), downhole –	0.9 M€
Completing the injection well –	1.1 M€
Surface gas survey and environmental monitoring (incl. completing piezometers and shallow small-diameter wells) –	0.3 M€
Production and (other in situ) tests –	0.8 M€
Baseline surface and cross-hole monitoring –	0.4 M€
Laboratory analyses of core, brine and cement samples –	0.4 M€
Interpretation of data, initial model elaboration –	0.3 M€
Injection infrastructure –	0.7 M€
Other –	0.9 M€
SUBTOTAL	9.7 M€

The operational costs (mainly the injection phase)

Laboratory analyses of brine and cement samples –	0.1 M€
Surface gas survey and environmental monitoring –	0.2 M€
Surface and cross-hole (and downhole) monitoring –	2.1 M€
Interpretation of data, model calibration –	0.1 M€
Media, energy (incl. transformer), personnel, other –	0.7 M€
CO_2 for injection (27 kt X 74 €) –	2.0 M€
Other –	1.1 M€
SUBTOTAL	6.3 M€
The site abandonment (optional)	(1.0 M€)
TOTAL COST	16.0 M€
	(17.0 M€)

6. Potential impacts of this pilot

At this moment there is no visible interest among Polish energy companies in development of pilot CO_2 injection project. The issue is somehow connected to the failure of Bełchatów demo project and current status of Polish permitting and legal policy described in chapter 9.

Regarding the status of "CCS readiness" in Poland it should be noted that around (and before) year 2012 the power companies applying for construction permits on new power blocks fueled by lignite, hard coal, oil fuel or gas were required to provide as an attachment a full CCS chain prefeasibility study (e.g. Tymowski et al., 2010). In many cases the "CCS readiness" meant more or the same as in case of the Bełchatów demo project described in Chapter 1 (a "Capture ready" post-combustion technology, the capture installation to be added later along with the full CCS chain when required). Such a study included an assessment of storage options, more or less detailed and based on interpretation of archive geological-geophysical data. After 2013 such studies became rare and vague, partly because so few (large) new power blocks are planned by power companies. The environmental activists strongly oppose construction of new power blocks fueled by lignite and hard coal.

However, before 2012 the situation differed significantly. The rationale for Polish energy companies establishing the consortium in order to carry the pilot CO_2 injection project was included in the demosEuropa report (Filipowicz in: Hinc, 2011):

- Hoping the EU would abandon the policy on reducing CO_2 emissions, or including the emission penalties or connection to trans-boundary pipelines towards North Sea reservoirs in energy prices did not seem to be an option;
- Modernization of Polish energy sector, development of clean coal technologies, distributed energy (co-)generation (including renewables) and development of CCS technologies seemed to be a more realistic option;
- Along with research projects and prefeasibility studies the Polish demo CCS project "Bełchatów" was carried out, but none of these activities included pilot CO_2 injection into formations which would likely be used in future CCS projects of Polish energy industry;
- Such pilot injection would help the decision makers in the energy sector in decisions on planning and implementation of "CCS ready" projects, especially on construction of the most expensive part of CCS full chain – capture installations;
- The decision makers might then learn CO_2 whether storage is possible, safe and accepted by general public – they usually do not read research papers on CO_2 geological storage nor attend scientific conferences.

7. Stakeholder mapping in the region

The Dziwie site is located in central Poland. In the region of central Poland (within a radius of approximately 150 km around the planned pilot CO_2 injection site) there are, according to ETS data and national registry, 23 industrial installations emitting at least 100 kt of CO_2 per year (Fig. 7.1). These installations are characterized in Table 7.1.

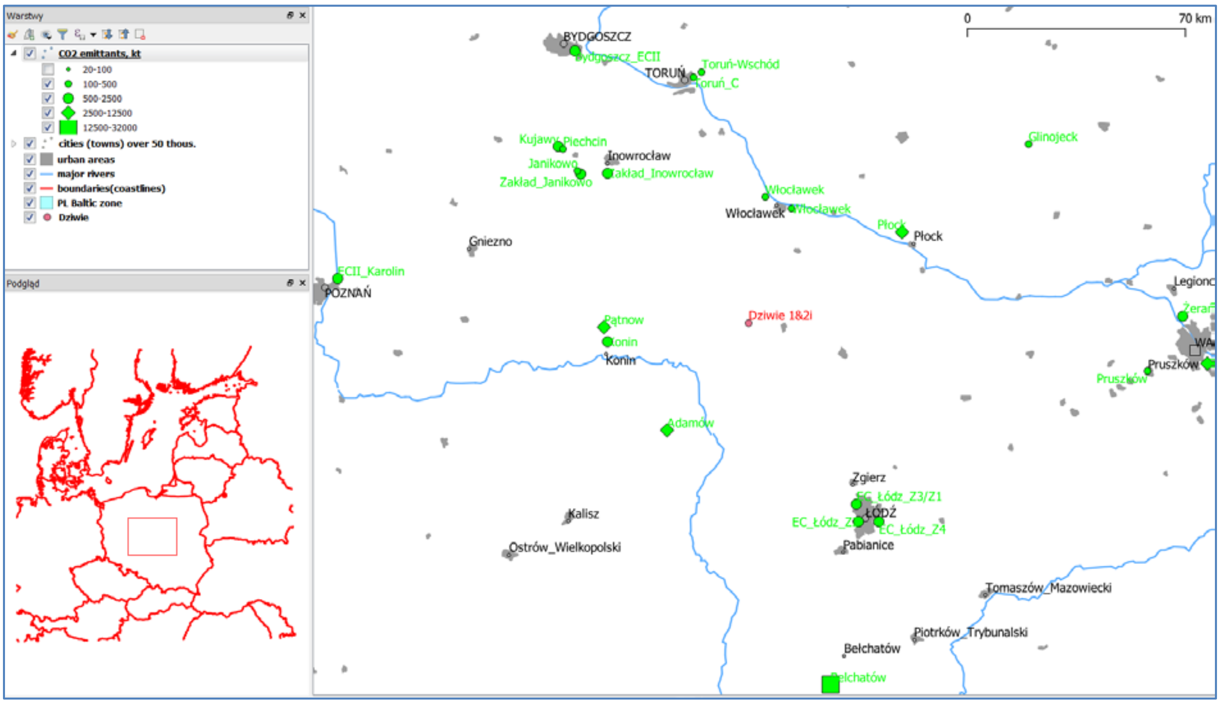


Fig. 7.1 CO_2 emittants located in the region of central Poland (over 100 kt/a; after ETS data).

Table 7.1 Characterization of CO_2 emittants located in the region of central Poland (over 100 kt/a; approximate emissions after ETS data and company websites).

No.	Name of installation	Operator	Type	Emission [kt]	Status	Fuel	Cap1	Unit	Cap2	Unit
1	Adamów	(ZE PAK)	Power	(3,977)	closed in 2018	lignite	600	MWe		
2	Belchatów	PGE GiEK	Power	37,180	operational	lignite	5,472	MWe		
3	Bydgoszcz	PGE EC	CHP	766	operational	hard coal, fuel oil	177	MWe	564	MWt
4	EC_Łódz_Z2	(Veolia)	CHP	(539)	closed in 2015			MWe		MWt
5	EC_Łódz_Z3(/Z1)	Veolia	CHP	944	operational	hard coal, fuel oil	206	MWe	804	MWt
6	EC_Łódz_Z4	Veolia	CHP	994	operational	hard coal, fuel oil	198	MWe	820	MWt
7	ECII_Karolin	Veolia	CHP	1,659	operational	hard coal, fuel oil & biomass	276	MWe	843	
8	Glinojeck	ZGK	Heating	101	operational	hard coal, biomass			35	MWt
9	Janikowo	Soda Polska	Other chemical	104	operational	hard coal	550			

		Ciech								
10	Konin	ZE PAK	Power	<1,000	operational	Lignite, biomass	198	MWe	212	MWt
11	Kujawy	LafargeHolcim	Cement	917	operational	hard coal	1,383	Kt of clinker		
12	Pątnow I	ZE PAK	Power	5,900	operational	lignite	1,200	MWe		
13	Piechcin	LafargeHolcim	Cement	192	operational	fuel oil	641	Kt of clinker		
14	Płock	PKN Orlen	CHP	3,178	operational	fuel oil	345	MWe	2,153	MWt
15	Płock	PKN Orlen	Refineries	2,307	operational	fuel oil	13,351	Kt of oil		
16	Pruszków	PGNiG Termika	CHP	131	operational	hard coal	9	MWe	186	MWt
17	Toruń_C	Elana - Energetyka	CHP	279	operational	hard coal, fuel oil	293	MWe		
18	Toruń-Wschód	PGE Toruń	CHP	231	operational	hard coal	2	MWe	314	MWt
19	Włocławek	PKN Orlen	CHP	262	operational	gas	463	MWe		
20	Włocławek	MPEC	Heating	130	operational	hard coal, gas			146	MWt
21	Zakład_Inowrocław	Soda Polska Ciech	CHP	664	operational	hard coal	0	MWe	356	MWt
22	Zakład_Janikowo	Soda Polska Ciech	CHP	931	operational	hard coal	0	MWe	350	MWt
23	Żerań	PGNiG Termika	CHP	2,500	operational	hard coal, fuel oil	386	MWe	1,580	MWt

The biggest emittants in the region in question are large power plants of PGE (Bełchatów), and ZE PAK (Patnów, Konin). Then there are big CHP plants of PGNiG Termika in Warsaw (e.g. Żerań) and Veolia in large cities of Poznań (ECII-Karołin) and Łódź (EC_Łódź_Z3, Z4). There are also big emittants in Płock – oil refinery of PKN Orlen accompanied by an industrial CHP plant and a smaller industrial CHP plant of PKN Orlen in Włocławek (providing energy to chemical works where carbon dioxide stream is a byproduct of industrial processes), both not far from injection site. Further NW of the site there are chemical works in Inowrocław and Janikowo (producing sodium carbonate, salt and also carbon dioxide stream – as a byproduct vented into atmosphere) of Soda Polska Ciech and cement works Kujawy of LaFargeHolcim in Piechcin – the emittants listed in Table 7.1 are big industrial CHP plants of these works. In northernmost part of the region city and industrial CHP plants in Bydgoszcz (of PGE) and Toruń (of Elana and PGE) are located. Since 2012 till now some industrial installations were closed (Adamów power plant, EC_Łódz_Z2) and some were replaced entirely (in Włocławek a fuel oil powered plant was replaced with a gas powered one) or partly (in Konin biomass was introduced instead of lignite in case of one power blocks, in ECII-Karołin biomass is being introduced).

Putting all together the stakeholders in the region in question belong to the power sector, CHP, refineries, chemical and cement industries.

PGE (together with its subsidiaries) is the biggest energy provider in Poland and operates large power plants (lignite and hard coal fueled; also operates lignite mines providing fuel to their lignite powered plants), city CHP plants, renewables – standalone (wind farms) and in co-generation (biomass) all over Poland (PGE website-who we are).

ZE PAK is the fourth energy producer in Poland and operates one large and one big power plant in central Poland (Pątnów and Konin, mentioned above – fueled by lignite and in second case – partly by biomass; ZE PAK Website).

Veolia (Polish branch of an international company) provides heat and electricity mainly to cities of Łódź and Poznań (CHP plants fueled by hard coal and to lesser extent fuel oil and biomass; Veolia website).

PGNiG Termika is a part of Polish Oil and Gas Company (PGNiG Termika website) and provides heat and electricity to Warsaw and the city surroundings (CHP plants fueled by hard coal and to lesser extent fuel oil; PGNiG Termika website).

PKN Orlen, together with its subsidiaries, is the biggest Polish fuel producer and distributor, operating also in Czech Republic and Lithuania. The company operates three oil refineries in Poland (the biggest one – Płock is within the region and listed in Table 7.1), two in Czech Republic and one in Lithuania as well as two oil terminals in ports in Poland (Gdańsk) and Lithuania (PKN Orlen website).

LaFargeHolcim (Polish branch of an international company) operates several cement plants in central and south central Poland as well as produces concrete and aggregates (LaFargeHolcim websites).

Putting all together the stakeholders in the region in question belong to the power sector, CHP, refineries, chemical and cement industries.

Soda Polska Ciech (a part of Ciech group – a major player in chemical industry in Poland with subsidiaries located in Germany and Romania) is a chemical company operating mentioned above chemical plants in Inowrocław and Janikowo in north-central Poland and distributing produced sodium carbonate, salt and other products (Soda Polska Ciech website).

8. Provisional timeline and funding opportunities

The duration of the planned pilot CO_2 injection project at Dziwie site was assumed to be 3 years (Wójcicki, 2013). The injection phase was expected to last 2 years (27 kt of CO_2 in total). The 3-year project might have been continued upon decision of the project consortium provided additional funding was secured. For the 3-year period the entire cost of the project was to be covered by the industrial partners of the consortium (the key power companies in Poland, members of Economic Society Polish Power Plants – see Chapter 1). It was tentatively assumed that during the project injection phase the consortium partners would apply for funding in the frames of EU and other international programmes, in order to sustain the project activities.

Were the project started in the beginning 2012 the following provisional (approximate) timeline can be provided (the scope of the project was assumed using lessons learned from Ketzin project, and other similar projects, and, because of financial constraints, a minimal suite of monitoring techniques was selected):

May 2011 – the geological workplan accepted by Ministry of Environment (Decision of May 20, 2011 and the first page of the geological workplan – attached below – Fig. 8.1[1])

January-February 2012 – after the consortium agreement is signed preparatory works at the site are carried out.

February-June 2012 – drilling the appraisal well (to be used later as the monitoring well); well logging within the appraisal/monitoring well; surface gas survey and environmental monitoring before and after drilling of the appraisal/monitoring well; collecting core samples for laboratory analyses; collecting brine/formation water samples for laboratory analyses, collecting of mud, other fluids and cement samples for laboratory analyses; completing the monitoring well; groundwater survey (piezometers).

June-October 2012 – drilling the injection well; well logging within the injection well (and downhole seismic); surface gas survey and environmental monitoring before and after drilling of the injection well; collecting brine/formation water samples for laboratory analyses, collecting of mud, other fluids and cement samples for laboratory analyses; completing the injection well; groundwater survey (piezometers).

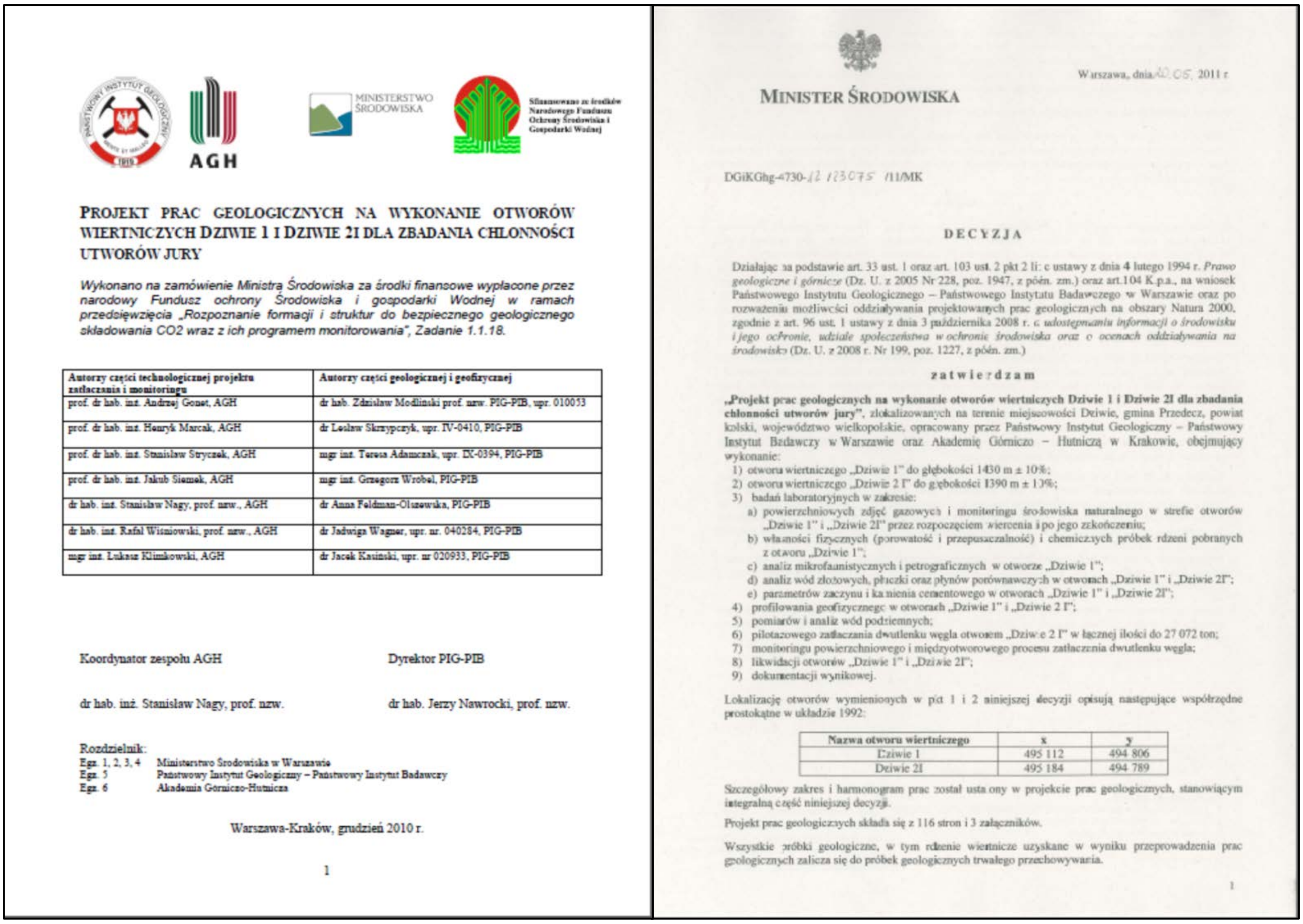
[1] The contents of the geological workplan is as follows:
- drilling of the appraisal/monitoring well;
- drilling of the injection well;
- laboratory analyses and baseline field surveys (surface gas survey and environmental monitoring before and after drilling of both wells; petrophysical/reservoir and chemical analyses & microfaunal and petrographic analyses of core samples collected in the appraisal well; analyses of brine/formation water, mud and indicative fluids collected in both wells; parameters of cement paste & stone used in both wells);
- well logging to be applied in both wells;
- groundwater survey and analyses;
- pilot CO_2 injection (up to 27 072 t);
- surface monitoring (seismic, other geophysics, geochemical) and cross-hole monitoring of CO_2 injection;
- abandonment of monitoring and injection wells (in case the project is stopped after injection of 27 kt CO_2);
- final project report.

November-December 2012 – production tests in the injection well, completing the injection infrastructure, baseline (pre-injection) surface and cross-hole monitoring, interpretation of results laboratory analyses and well logging, elaborating of the pilot injection site model.

January 2013-December 2014 – test injection commenced and ongoing, surface (geophysical, environmental/groundwater & soil) and cross-hole monitoring during injection, calibration of pilot injection site model, seeking for additional funding in EU and other international programmes in order to sustain the project after 2014.

January 2015 – depending on the consortium decision the project is either closed or continued (in case additional funding is secured, e.g. from EU programmes – in such case the geological workplan might have been amended previously and submitted for approval to the permitting authority – Ministry of Environment).

Fig. 8.1 Decision of the permitting authority and the approved document permitting the project activities (Wójcicki, 2013)



MINISTERSTWO ŚRODOWISKA

Sfinansowano ze środków Narodowego Funduszu Ochrony Środowiska i Gospodarki Wodnej

PROJEKT PRAC GEOLOGICZNYCH NA WYKONANIE OTWORÓW WIERTNICZYCH DZIWIE 1 I DZIWIE 2I DLA ZBADANIA CHŁONNOŚCI UTWORÓW JURY

Wykonano na zamówienie Ministra Środowiska za środki finansowe wypłacone przez narodowy Fundusz ochrony Środowiska i gospodarki Wodnej w ramach przedsięwzięcia „Rozpoznanie formacji i struktur do bezpiecznego geologicznego składowania CO2 wraz z ich programem monitorowania", Zadanie 1.1.18.

Autorzy części technologicznej projektu zatłaczania i monitoringu	Autorzy części geologicznej i geofizycznej
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Egz. 5 Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy
Egz. 6 Akademia Górniczo-Hutnicza

Warszawa-Kraków, grudzień 2010 r.

1

MINISTER ŚRODOWISKA

Warszawa, dnia 10.05. 2011 r.

DGiKGhg-4730-12/23075/11/MK

DECYZJA

Działając na podstawie art. 33 ust. 1 oraz art. 103 ust. 2 pkt 2 lit. c ustawy z dnia 4 lutego 1994 r. *Prawo geologiczne i górnicze* (Dz. U. z 2005 Nr 228, poz. 1947, z późn. zm.) oraz art. 104 K.p.a., na wniosek Państwowego Instytutu Geologicznego – Państwowego Instytutu Badawczego w Warszawie oraz po rozważeniu możliwości oddziaływania projektowanych prac geologicznych na obszary Natura 2000, zgodnie z art. 96 ust. 1 ustawy z dnia 3 października 2008 r. *o udostępnianiu informacji o środowisku i jego ochronie, udziale społeczeństwa w ochronie środowiska oraz o ocenach oddziaływania na środowisko* (Dz. U. z 2008 r. Nr 199, poz. 1227, z późn. zm.)

zatwierdzam

„Projekt prac geologicznych na wykonanie otworów wiertniczych Dziwie 1 i Dziwie 2I dla zbadania chłonności utworów jury", zlokalizowanych na terenie miejscowości Dziwie, gmina Przedecz, powiat kolski, województwo wielkopolskie, opracowany przez Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy w Warszawie oraz Akademię Górniczo – Hutniczą w Krakowie, obejmujący wykonanie:

1) otworu wiertniczego „Dziwie 1" do głębokości 1430 m ± 10%;
2) otworu wiertniczego „Dziwie 2 I" do głębokości 1390 m ± 10%;
3) badań laboratoryjnych w zakresie:
   a) powierzchniowych zdjęć gazowych i monitoringu środowiska naturalnego w strefie otworów „Dziwie 1" i „Dziwie 2I" przez rozpoczęciem wiercenia i po jego zakończeniu;
   b) własności fizycznych (porowatość i przepuszczalność) i chemicznych próbek rdzeni pobranych z otworu „Dziwie 1";
   c) analiz mikrofaunistycznych i petrograficznych w otworze „Dziwie 1";
   d) analiz wód złożowych, płuczki oraz płynów porównawczych w otworach „Dziwie 1" i „Dziwie 2I";
   e) parametrów zaczynu i kamienia cementowego w otworach „Dziwie 1" i „Dziwie 2I";
4) profilowania geofizycznego w otworach „Dziwie 1" i „Dziwie 2 I";
5) pomiarów i analiz wód podziemnych;
6) pilotażowego zatłaczania dwutlenku węgla otworem „Dziwie 2 I" w łącznej ilości do 27 072 ton;
7) monitoringu powierzchniowego i międzyotworowego procesu zatłaczania dwutlenku węgla;
8) likwidacji otworów „Dziwie 1" i „Dziwie 2I";
9) dokumentacji wynikowej.

Lokalizację otworów wymienionych w pkt 1 i 2 niniejszej decyzji opisują następujące współrzędne prostokątne w układzie 1992:

Nazwa otworu wiertniczego	x	y
Dziwie 1	495 112	494 806
Dziwie 2I	495 184	494 789

Szczegółowy zakres i harmonogram prac został ustalony w projekcie prac geologicznych, stanowiącym integralną część niniejszej decyzji.

Projekt prac geologicznych składa się z 116 stron i 3 załączników.

Wszystkie próbki geologiczne, w tym rdzenie wiertnicze uzyskane w wyniku przeprowadzenia prac geologicznych zalicza się do próbek geologicznych trwałego przechowywania.

1

9. Project risk assessment (permitting, construction, policy, HSE etc…)

In latter part of this chapter a historical review of original assumptions on risks for the planned project (abandoned in 2012, after the key industrial partner – PGE Bełchatów – refused to sign the consortium agreement) is be presented (Table 3.1).

A short update summarizes the current permitting and legal issues.

In Poland the CCS law implementing the CCS directive (Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide) entered into force in November 2013 (Shogenova et al., 2014; The law of September 27, 2013 on amending the geological and mining law and some other laws). The law prohibits CO_2 storage until 2024, except for demonstration projects. It is unclear, whether any pilot injection up to 100 kt CO_2 in total is covered by this prohibition. For example, at Borzęcin site (depleted gas field) the injection of acidic gas (60% CO_2, 15% H_2S, residual hydrocarbons) is ongoing since 1995 (Lubaś, 2010) and was not stopped after the Polish CCS law entered into force. The Polish CCS law is supplemented with regulations issued by Ministry of Environment (the permitting authority in case of CO_2 storage) on implementation of technical provisions included in Annexes I and II to the CCS Directive (e.g. the regulation of October 30, 2015 on requirements pertaining to operating the CO_2 storage site, CO_2 stream composition and carrying out the storage complex monitoring). One of these regulations, of September 3, 2014 on areas where CO_2 geological storage is allowed, points out an offshore area in Cambrian reservoir/aquifer in eastern part of Polish sector of Baltic Sea.

Putting all together there is a solid possibility of launching a pilot project in the frames of a newly announced demo project, most likely offshore, though one can try to convince Ministry of Environment to amend the relevant regulation in order to allow CO_2 storage onshore. Whether a pilot injection (up to 100 kt) in the frames of R&D activities aimed at testing new technologies and processes is possible in Poland, might be an open question. In case of the original pilot injection project planned at Dziwie the former path was utilized and a geological workplan was the sole document permitting the pilot project activities: drilling new wells, CO_2 injection and monitoring (no environmental impact assessment was required because the site was not within or close to any protected area and the environmental impact of such small scale R&D experiment was deemed negligible). The provisions allowing that path still exist in Polish geological in mining law but it is unclear, whether provisions introduced by the Polish CCS law superseded them.

Below the original assumptions on risks for the planned (and then abandoned) CO_2 pilot project at Dziwie site are characterized (using a simplified template based on these utilized in NER300 applications). The project used to be supported both by government and industry (see Chapter 1), so the prospects seemed to be rather bright at that moment – the table refers to the period 2009-2012 from the moment the consortium was established till the moment the biggest funding contributor refused to sign the consortium contractual agreement and then any further risk analyses became irrelevant.

Table 9.1 Risk assessment for the original pilot project (as in the beginning of 2012)

No.	**Project stage**	**Risk description**	**Risk category**	**Consequence/Impact**	**Estimated likelihood value**	**Estimated impact value**	**Pre-mitigation value**	**Mitigation actions**	**Estimated likelihood value**	**Estimated impact value**	**Post-mitigation value**
1	Site selection	Possible conflicts of interest/lack of public acceptance	Political/societal	No agreement on site utilization with landowners	medium	medium	high	Public awareness campaign, another site selected, a piece of land bought by consortium partner	low	low	low
2	Injection permit	Evidence of storage safety insufficient	Technical (geology, reservoir engineering), environmental	The permit is not granted or postponed – project schedule not met	low	low	high	Reworking the geological workplan or selecting another site	low	low	low
3	Injection permit	The lack of political support	Political/societal	The project is blocked	low	low	high	Lobbing the project in the government and local authorities	low	low	low
4	Site development	Funding insufficient	Financial/funding	The project is blocked or postponed	low	low	medium	Securing funding from other sources, reworking the consortium agreement	low	low	low
5	Site development	Accidents at the site, well blowouts	Technical (drilling)	HSE consequences, cost contingencies	low	low	medium	Working out a plan of actions in emergency situations (emergency plan).	low	low	low

6	Site operation and closure	CO_2 leakage into groundwater and/or soil	Environment, Societal	(A very unlikely) impact on local drinking water supply or environment; flora and fauna – project delays or abandonment	low	low	high	The geological workplan examines any possible natural leakage paths, surface and subsurface monitoring	low	low	low
7	Site operation and closure	CO_2 leakage through new wells (injection monitoring)	Environment	As in item 6	low	low	high	Selection of proper cements, monitoring of technical status of wells	low	low	low

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Appendix VI

South Brădești Storage Pilot

Case study for the ENOS project

Authors:

Alexandra – Constanta Dudu
Constantin Stefan Sava

Bucharest, March 2020

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1. CONCEPT AND AIMS OF THE PILOT

The proposed storage project is located in Oltenia development region, Cotofenii din Dos commune, Dolj County, SW Romania.

The overall project is designed to capture CO_2 from the Isalnita power plant (owned by CE Oltenia), transport it by trucks and inject partly in the Brădești oil field for EOR and associated storage and in a smaller part in a deep aquifer structure (1,640 m depth) located south of the oil structure. Location of the project is illustrated in the map in Figure 1.

The main objectives of the storage pilot in the South Brădești structure are to accompany a planned EOR project in the Brădești hydrocarbon structure, to test the effects of impurities from the CO2 stream captured from the Isalnita power plant on the reservoir and to investigate the potential implications for oil operations in the area.

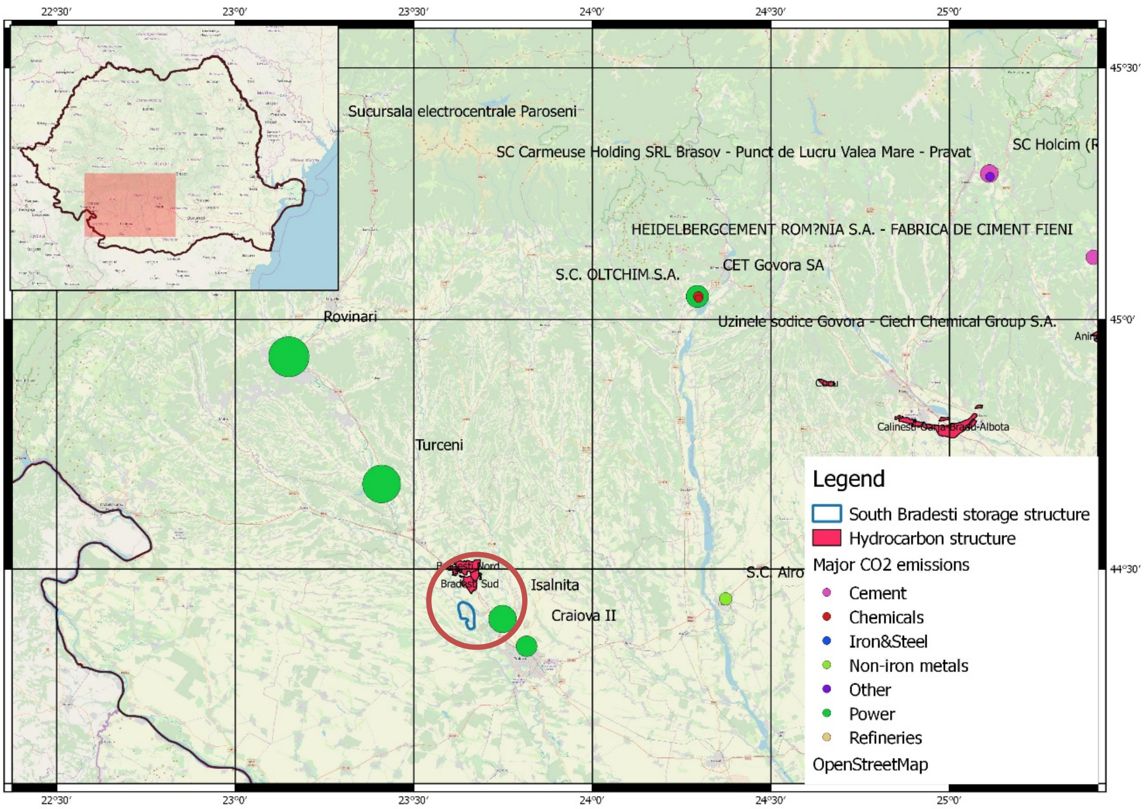

Figure 1. Location of the project

2. REVIEW OF GEOLOGY

2.1 Regional geological framework

Brădești oil structure and South Brădești deep saline aquifer are located in the western zone of Romania and west side of the Moesian Platform, one of the most important oil and gas provinces from Romania, which extends in the southern part of the country and continues even in Bulgaria, beyond the Danube. The area of interest is as well limited by Amaradia River to the east and Jiu River to the west.

The western sector of the Moesian Platform shows major E-W trending fractures (Figure 2), affecting both the basement, and the sedimentary cover up to the Jurassic-Lower Cretaceous level. These fractures create areas of basement uplifts, showing a thin sedimentary cover, as well as depressions, representing areas with thick sedimentary cover (Paraschiv, 1975, 1979). In the studied region there are two areas of basement uplift (N Craiova - Balş - Optaşi and Strehaia - Vidin) and a depression (Lom – Craiova). Figure 2 presents the location of major structural elements from Moesian Platform, including the western sector.

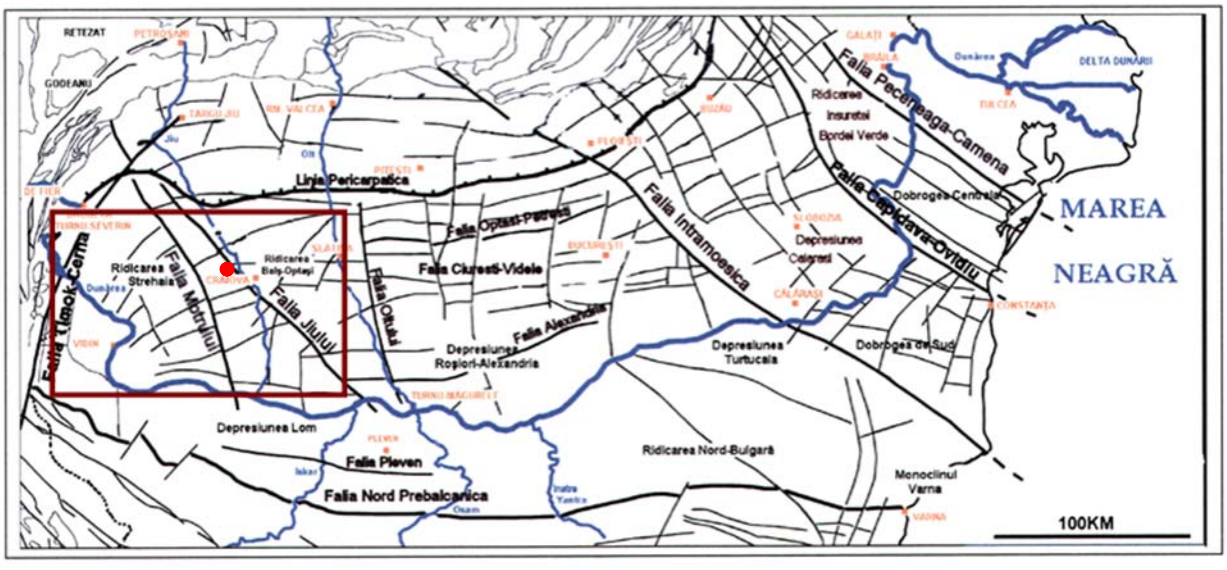

Figure 2. The main tectonic elements from Moesian Platform, with emphasis (red rectangle) on the west of Olt river sector (modified after Matreşu, 2004). The location of the pilot is marked with red.

The Balş - Optaşi high (location in Figure 2) represents a true massif, where the metamorphic rocks (intercepted by Budesti, Străjeşti, Oporelu, Balş, Cucueţi, Optaşi wells) and the Paleozoic deposits lie at depths between 1,940 m (Priseaca well) and 3,715 m (Străjeşti well) (Ionesi, 1994). The study of wells and geophysical logs from Balş area indicates a significant thinning of the sedimentary cover, the limit between the basement and Paleozoic formations being intercepted at the depths of 2,468 m (Diaconescu et al, 1999). West of Craiova, deep seismic measurements have shown a thickness of the sedimentary cover of 5,000 m (Răileanu et al, 1994). Within the Balş - Optaşi uplift, several anticlinal and hemi-anticlinal arching have been revealed, the most relevant being Iancu Jianu, Oporelu, Ciureşti N şi Ciureşti S (Paraschiv, 1975, 1979).

The Strehaia uplift (location in Figure 2) is the most elevated high in the western sector of the Moesian Platform; seismic and borehole data indicate that the Paleozoic was intercepted at the 1,000 m isobath and the basement at 4,500 - 5,000 m. This uplift appears like a brachianticlinal arch, oriented NE - SV (Paraschiv, 1975, 1979). North of Strehaia, seismic measurements identified a thickness of the sedimentary cover up to 7,000 - 9,000 m (Răileanu et al, 1994).

The Lom Depression is oriented N - S and limited westward by Strehaia uplift, and eastward by Slatina - Ghighen – Totleben uplift. Its structure and geological constitution are known from boreholes (Brădeşti, Argetoaia, Branişte – Carboniferous deposits) and from geophysical data, suggesting that it deepens even more in front of the Balkans (Paraschiv, 1979).

Beside these first order structural elements, the Moesian Platform is affected by major fractures with various structural directions. The studied region includes some of these major fractures, some N-S (NW - SE) oriented (Dârvari and Pleniţa, Radovanu, Jiu, Motru, Olt Faults), while others are oriented E-W (the swarm of faults associated to Balş – Optaşi uplift).

The sediments of the Moesian Platform cover are grouped into four major sedimentation cycles (Paraschiv, 1975; Ionesi, 1989). The Upper Cambrian - Westphalian cycle, with a maximum thickness of 6,500 m, consists of clastic deposits in its lower part and carbonate successions in its upper part. The deposits of this cycle are covered by a dominantly clastic Permo-Triassic succession (clays and sandstones), up to 5,000 m thick. The Permian shows layers of tuffs and evaporites, while the Middle Triassic shows limestones and evaporites. The younger deposits, up to 3,000 m thick, are represented by the detrital Lower Jurassic succession (sandstones and clays), the carbonate-dominated Upper Jurassic – Upper Cretaceous and by detrital Cenozoic sediments (Paleogene - Pliocene). The Cenozoic deposits show variable thickness, from 2 to 7 km close to the Carpathians and get thinner away from the Carpathian belt.

Figure 3 shows a synthetic lithological column of the Moesian cover in the western part of the Platform.

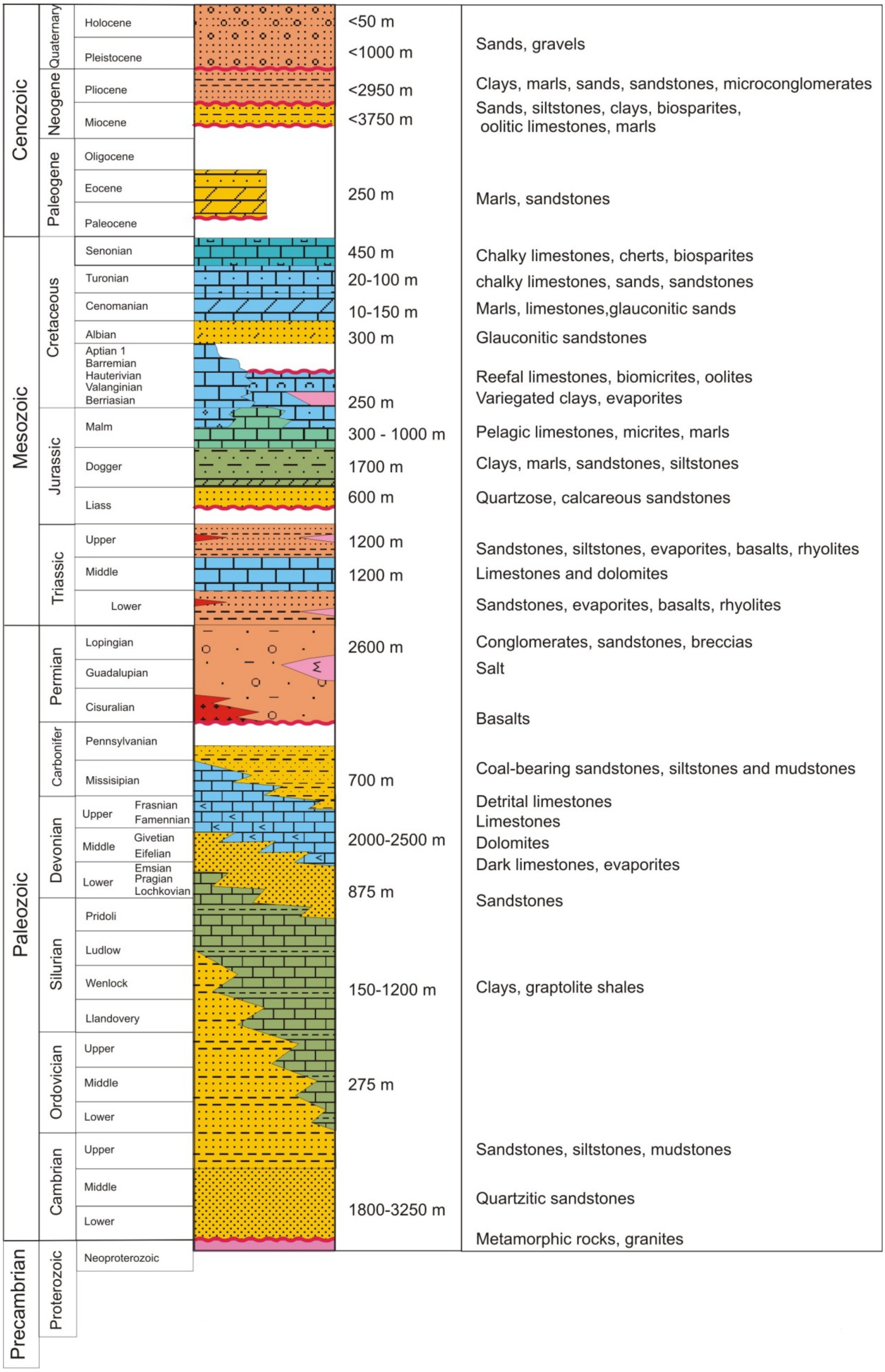

Figure 3. Synthetic lithological column in the western part of the Moesian Platform

The Cambrian-Westphalian cycle starts with a clastic succession ("lower detrital cycle") that accumulated from Cambrian to the lower part of the Middle Devonian (Paraschiv, 1974). This first sedimentary cycle starts with Cambrian quarzitic sandstones and continues with a dominantly pelitic succession, its main lithologies being dark clays and graptolitic shales of the Upper Ordovician and Silurian (Iordan et al., 1985; Iordan, 1994). The succession continues with Devonian deposits that overlay the Silurian in the western part of the platform without any gap in sedimentation. The Devonian deposits show clayey basal facies, continuing with dominantly gritty facies (quarzitic sandstones, quarzitic conglomerates, red arkosic sandstones) grading upward to a carbonate-lagoonal facies (Iordan, 1994).

The carbonate succession of the first sedimentary cycle starts in the Givetian and terminates in the Middle Carboniferous-Visean (Paraschiv, 1974). This succession has variable thickness, completely missing in the uplift areas and thickness up to 2,000 - 2,500 m in the depressions. The Givetian presents a large variety of carbonate facies, including dolomites, dolomitic limestones, organogenic limestones, bituminous limestones, together with sandstones, shales and evaporites (Paraschiv, 1975). The Upper Devonian continues with a dolomitic complex up to 1,000 m thick and terminates with limestone dominated deposits of the Lower Carboniferous- Tournaisian, up to 1,200 m thick (Paraschiv, 1975). Starting with the Visean, the carbonate deposition reduces in favour of clastic sedimentation (Paraschiv, 1975).

The Upper Carboniferous ("upper detrital complex") is represented by coal-bearing clastics, with a maximum thickness of 565 m. Dominant lithologies are marls and shales, subordinately sandstones, conglomerates and limestones. The rocks contain Namurian and Westphalian plant remains.

The Permian - Triassic cycle differs from the lowermost cycle by its content of red continental clastics, evaporite and carbonate layers, as well as magmatic rocks. Above the basement uplifts, like Leu - Balş – Optaşi high, this succession may be totally or partly missing, mainly due to post-depositional erosion (Tari et al, 1997).

Three main lithostratigraphic units, developed in German facies, have been deposited in the Permian - Triassic cycle (Ionesi, 1989): "the lower red series, the carbonate series and the upper red series" (Paraschiv, 1975).

"The lower red series" (Roşiori Formation), belonging to the Permian – Lower Triassic interval, presents continental facies, consisting of conglomerates, microconglomerates, sandstones, clays, magmatic rocks (basic and acid lava flows). Locally gypsum and anhydrite nests occur, as well as salt lenses. Being discordant on various Palaeozoic terms and mouldings a pre-existing relief, the thickness of this formation is variable, from several meters to 2,600 m (Paraschiv, 1975).

"The Alexandria Formation" of Middle Triassic age is a carbonate-dominated sequence with a total thickness of over 1,200 m. The succession includes neritic limestones and dolomites with anhydrite interbeds and salt lenses.

"The upper red series" (Segarcea Formation) of the Upper Triassic, with a maximum thickness of 1,200 m, is only locally developed (Tari et al, 1997). This unit consists of red continental clastics (clays, marls, sandstones, sands and microconglomerates) with carbonate and evaporite intercalations (anhydrite, gypsum and seldom salt) (Paraschiv, 1975).

Typical for the Middle and Upper Triassic is the presence of effusive, dominantly acid and intermediate rocks, with calk-alkaline geochemistry, indicating an intense magmatic activity (Săndulescu, 1984; Savu, Paraschiv, 1985).

The Jurassic-Cretaceous cycle (Lower Jurassic-Senonian, locally continuing till the Eocene, Ionesi, 1989), with a maximum thickness of 3,500 m (Tari et al, 1997), represents a resumption of sedimentation after its interruption at the end of the Triassic. The sedimentary succession starts with continental clastics up to 600 m thick. Starting with the Callovian, the clastic sediments have been replaced with carbonate deposits, with a medium thickness of 1,700 m. In the basin depocenter, pelagic limestones have been deposited, and reefal, shallow marine limestones in the marginal areas. Sedimentation continues with the same characteristics until the platform uplift in the Lower Aptian, when carbonate sediments are still accumulated in the south-east of the platform (pelites, policolore sandstones and evaporites). In the Albian - Senonian interval, there are various rocks accumulated: sandstones, marls, micritic limestones, glauconite-bearing sands and sandstones glauconite sandstones, chalky limestones, sandy limestones, cherty limestones. The Senonian is unequally developed in the Moesian Platform, almost completely missing in the western sector.

On a small area (south of Craiova), sedimentation continued after the platform uplift in the Late Senonian – Upper Badenian interval. Here, in the Upper Paleocene, the waters came again from the Lom basin, the sediments deposited up to the Upper Eocene (max. 250 m thick) being formed of marls and sandstones.

The Upper Badenian – Pleistocene cycle includes a very thick Neogene succession at the northern margin of the platform (up to 5,500 m). The thin unit (20-200 m) of the Middle Miocene, dominated by shallow marine carbonates, supports deep-water clastic sediments, the marls and sandstones of the Upper Miocene.

The Badenian, discontinuously developed on the northern and western platform margin and thicknesses up to 200 m, includes clays, marls, biosparites, limestones, sandstones and local anhydrites.

The Sarmatian in the Moesian Platform belongs to the Dacian Basin and includes, based on the molluscs' faunas identified in boreholes, the Volhinian, Basarabian and Kersonian (Ionesi, 1989). A synthetic litofacies column of the Sarmatian deposits in the Dacian basin is presented in Figure 4. The lithological constitution includes clays, siltstones and sands, with sandstone, biosparites and oolitic limestone interbeds. The Sarmatian transgression from the north took place after the uplift during the Buglovian. It is difficult to accomplish a Sarmatian succession at the scale of the entire platform, both due to lateral facies changes, and to the transgressive character of the Lower Sarmatian, regressive character of the Lower Basarabian, as well as to the interruption of sedimentation at the Basarabian-Chersonian limit (Ionesi, 1989). The Volhynian is predominantly clastic on the largest part of the platform (sands, siltstones, clays, sandstones and seldom conglomerates), while in the highest areas carbonate lithologies also occur. The Basarabian consists of clays and siltstones in the deeper areas and limestones, sandstones and sands in the shallower areas. The Kersonian occurs only in the western part of the platform and consists of sands, siltstones, marls and biosparites.

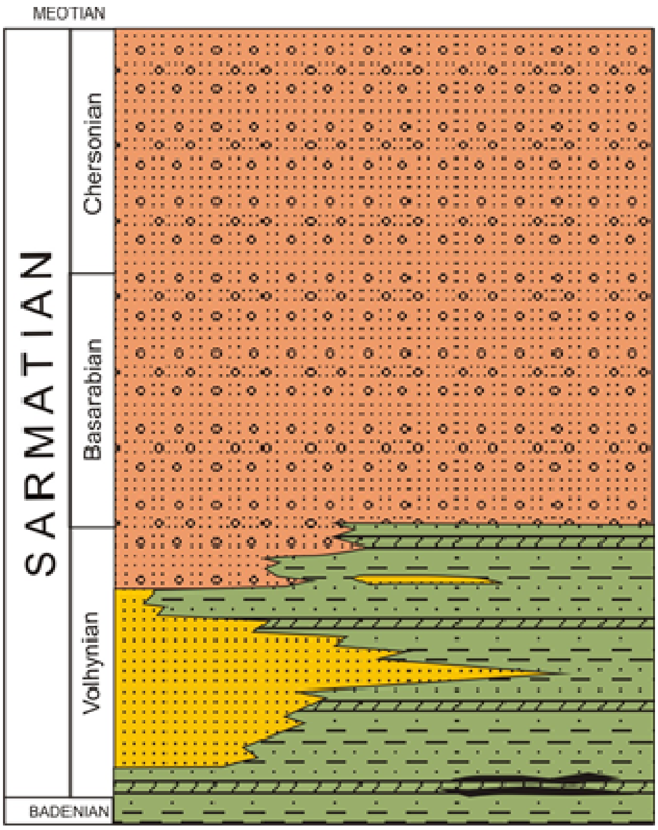

Figure 4. Synthetic litofacies column of the Sarmatian deposits (s.l.) from the western part of the Dacian Basin (simplified after Marinescu, 1978)

The Meotian is only a few meters thick in the south, attaining 1,400 m northward and westward. It includes clays, siltstones, marls and sands with interbeds of sandstones in various proportions, without having a uniform distribution. North of Craiova two lithologic units dominated by pelites could be distinguished, separated through an arenitic unit (Paraschiv, 1979).

The Pontian, transgressive, with thicknesses between 20 and 800 m, includes clays, siltstones and marls, with sand and sandstone interbeds. Maximum thickness of deposits is in the Ghergheasa – Balta Alba area, where several layers of sands and sandstones exist.

The Dacian, up to 500 m thick, represents an upward fining type of succession, dominated by sands, sandstones and micro-conglomerates in the lower part and clays, siltstones and marls at the upper part. The Upper Dacian includes lignite beds with thickness of up to 3 m (Papaianopol et al., 1987).

The Romanian consists of a lower, pelite-dominated unit and an upper unit, dominated by sands and gravels (the Cândeşti Formation). In the eastern part of the platform, the Romanian includes thin, submetric, discontinuous intercalations of lignite (Papaianopol et al., 1987). The Cândeşti formation, exposed in the western part of the platform, with highly variable thickness (from a few meters to almost 1,000 m in the Focşani Depression), represents continental, fluvio-lacustrine deposits continental, dominated by coarse sands associated with fine-grained sand and associated with fine-grained sandstones, siltstones and clays.

The Quaternary formations have various thicknesses (0 - 200 m) and develop mainly at the platform margin, where starting with the Pliocene a significant neotectonic uplift has started. These deposits consist of clastic continental sediments, conglomerates, sands, clays, loess (Bandrabur, 1971; Feru et al., 1983; Ionesi, 1989; Tari et al, 1997).

The thick sedimentary record, proper lithologies, as well as the displacement of the platform blocks, created favourable conditions for genesis and storage of hydrocarbon at various levels, starting with the Paleozoic and ending with the Pliocene. The western sector of the platform is considered the richest in oil and gas fields.

2.2 Brădești hydrocarbon structure

One of the oil and gas fields from the western sector of Moesian Platform, which is also the subject of the proposed pilot CO_2-EOR project, is the Brădești commercial deposit, located near the city of Craiova. Its exploitation license is currently owned by OMV Petrom. The field was discovered in 1970 and began oil production in 1971.

The deposit comprises 3 productive layers saturated with non-paraffinic crude oil (type A3-oily) and dissolved gases namely Triassic, Dogger, and Sarmatian. The dissolved gases contain 83-91% methane and 4-17% ethane. The associated waters are of chloro-calcic type with mineralization of 50-70g/l. The main properties of these productive layers are presented in Table 1.

Table 1. Main properties of productive layers from Brădești structure

Productive layer	Triassic	Dogger	Sarmatian
Depth of the top of formation (m)	2,580	2,400	2,200
Effective thickness (m)	10-30	20-40	10-20
Lithology	Limestones and silicious sandstones	Limestones and silicious sandstones	Limestones and silicious sandstones
Porosity (%)	15	15	16
Absolute permeability (mD)	150-350	150-350	150-350
Fluid content	Oil and gases	Oil and gases	Oil and gases
Oil density (kg/mc)	830	840	850
Oil viscosity in standard conditions (cP)	2.5	3.5	3.5
Initial/actual pressure (atm)	240/180	220	210
Temperature of the reservoir (^0C)	85	82	80
Drilled wells	58		

The Brădești geological structure has the shape of an arched monocline with variable inclinations (5-20 degrees). It is affected by a system of longitudinal and transversal faults with 10-15 degrees inclination, faults that divide the structure into 25 tectonic blocks. The traps in which the Brădești oil deposits were formed are complex, structural, stratigraphic and lithological.

The main objective of exploitation of the Brădești commercial deposit is the Triassic (Figure 5), which has 3 saturated oil layers in dolomites with siliceous sandstones intercalations of 15-25 m thickness. The current recovery factor is estimated at 30%, STOIIP is 46.6 ST Mm3. The main parameters of Triassic oil bearing deposits are presented in Table 2.

Table 2. Main parameters of Triassic oil bearing deposits from Brădești structure

Depth (m)	2,210 – 2,580 m
Total thickness (m)	15-130 m
Effective thickness (saturated with oil)	10-30 m
Initial pressure (bars)	210-245
Present pressure (bars)	179-180
Reservoir temperature (°C)	80 – 83
Effective porosity (%)	14-15
Absolute permeability (mD)	150-350
Effective permeability (horizontal, mD)	100-165
Effective permeability (vertical, mD)	50-110
Rsi (Smc/mc)	33-130
Boi	1.193 – 1.424
Oil density (kg/mc)	830
Oil viscosity (cP)	2.5
Oil viscosity in standard conditions (cP)	0.9 – 2.5
Number of drilled wells	58

The gasses dissolved in the oil contain 63-91% methane and 4-17% ethane.

The scenarios of CO2-EOR operations are under analysis within ECOBASE project.

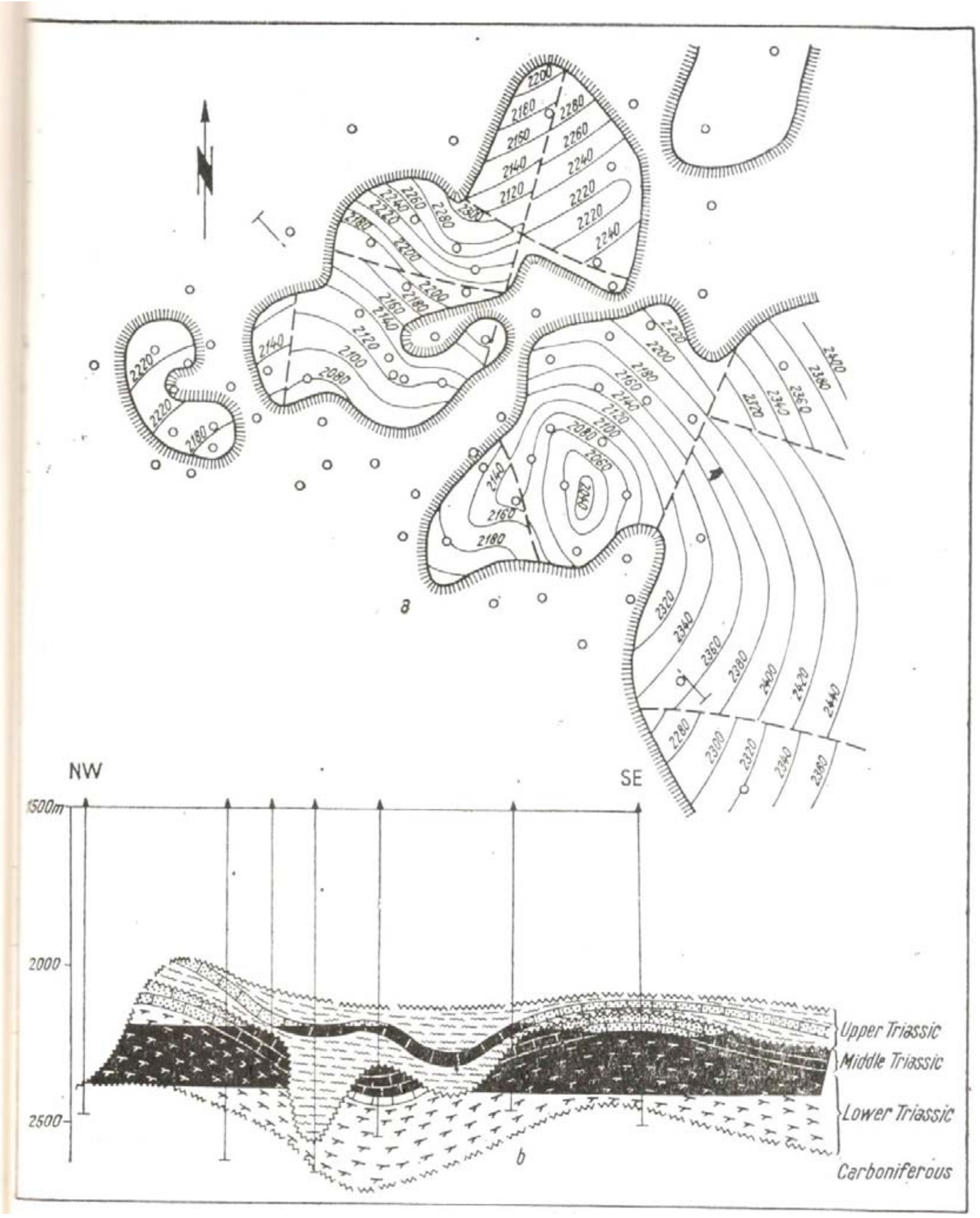

Figure 5. Brădești structure. Structural map at the level of Middle Triassic. Geological cross section.

2.3 South Brădești storage complex

The storage part of the pilot project is planned south of the Brădești hydrocarbon structure, in a Sarmatian sandstone reservoir, part of a regional aquifer selected as potential storage site in the framework of the currently stalled GETICA CCS demonstration project. At regional level, the accumulation of Sarmatian siliciclastic sequences composed from coarse sediments occurs in a large canyon of the Tertiary Base. The Sarmatian sequences (including reservoir sequences and cap rock sequences) pinch-out on Pre-Tertiary paleo-relief, creating a structural-stratigraphic trap.

Caprock of the proposed storage structure is composed of shales and represents the sequences from top of the Sarmatian to the top of the reservoir. Top of the Sarmatian sequences varies from 1,150 m to 1,200 m depth as can be seen on the map in Figure 6.

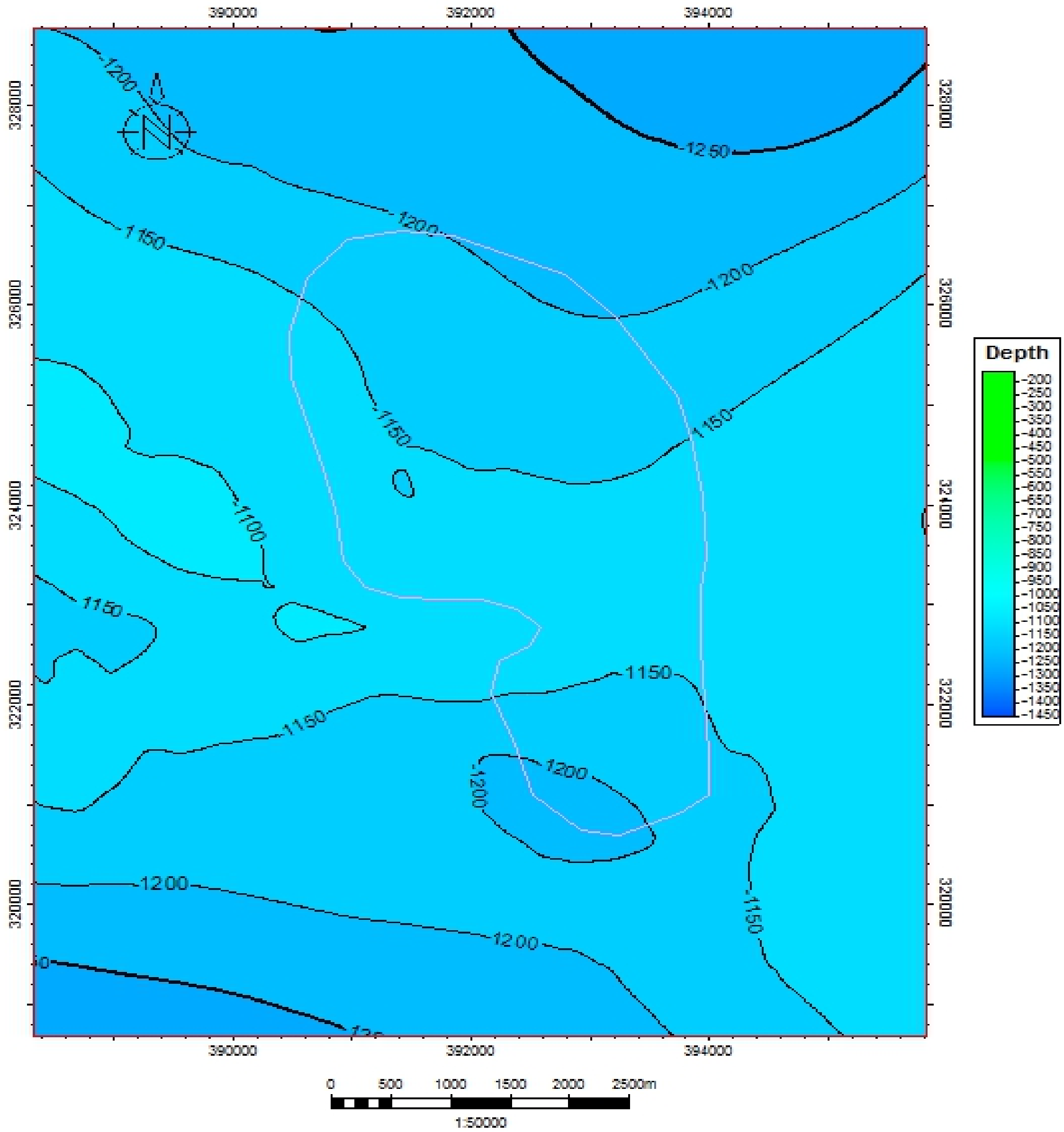

Figure 6. Depth contour map of top of Sarmatian sequences

The reservoir is composed of siliciclastic sequences situated between two horizons, Sa7 (Figure 7) and Sa5 (Figure 8), delimited by seismic interpretation. The extent of the reservoir is given by the contour line of -1,640 in the Sa7 map (Figure 7).

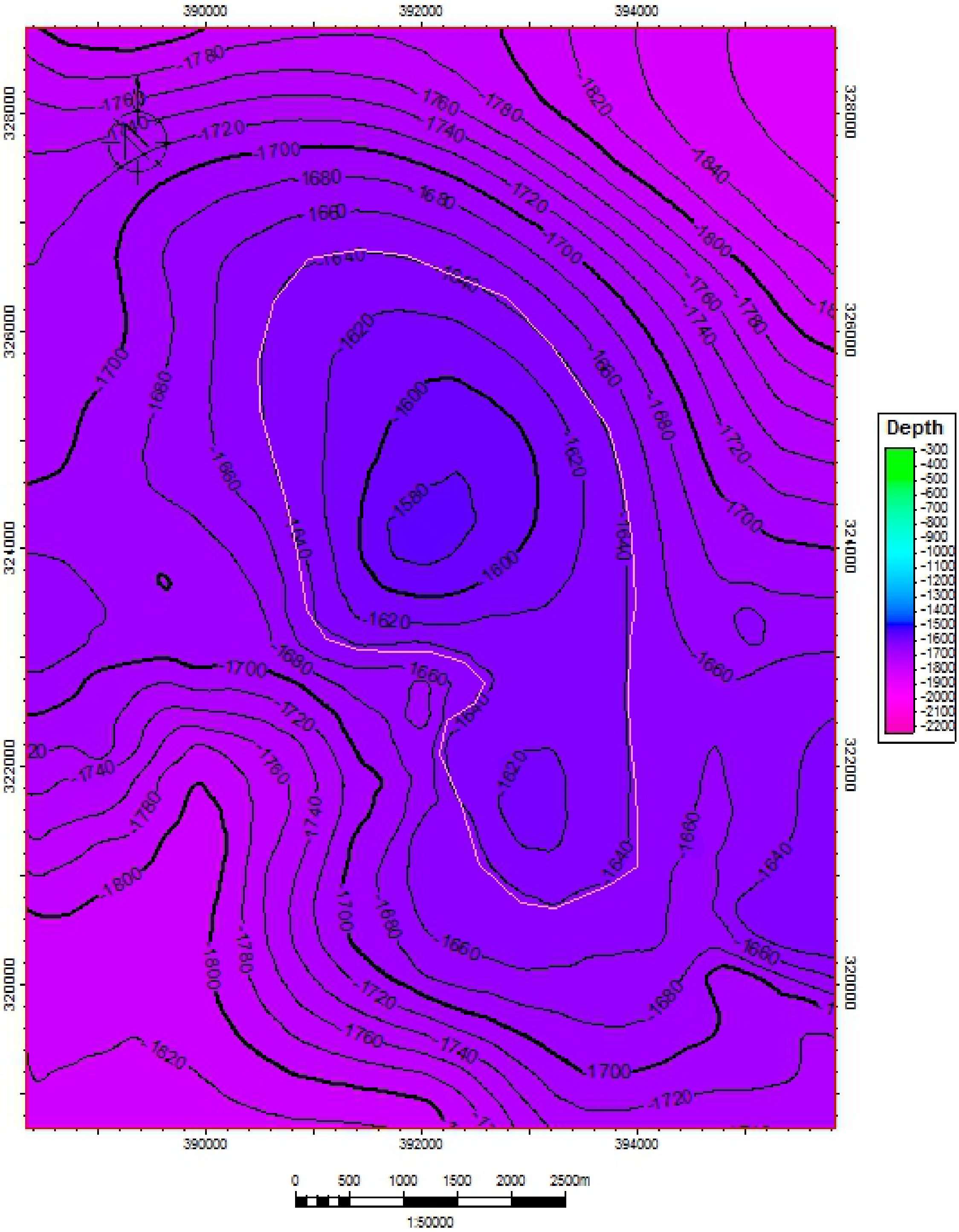

Figure 7. Depth contour map of top Sa7 (top of the reservoir)

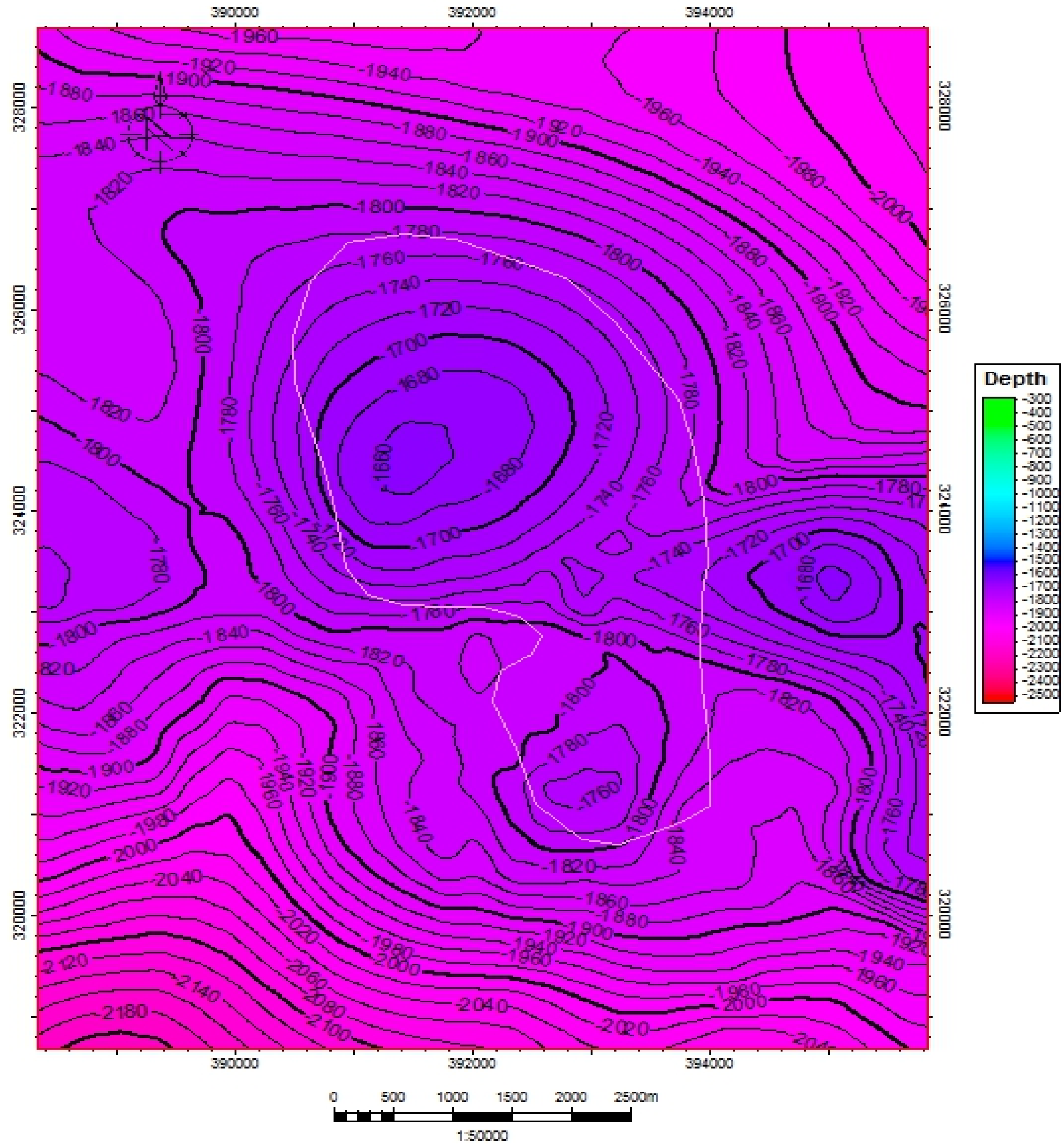

Figure 8. Depth contour map of top Sa5 (reservoir bottom)

At the top of the structure, above the 1,640 m contour line, there is a structural trap - saline aquifer, with an average porosity of 15%. The total trap volume is ca. 266 million m^3. Taking the 15% porosity considered for the reservoir into account, the volume available for supercritical CO_2 storage is around 40 million m^3. Considering the supercritical CO_2 density of 0.594 t/m3, we obtain a storage capacity of the South Brădești structure at a level of 23.8 mil. tonnes of CO_2 in a supercritical state.

The reservoir underburden is composed of shale sequences also belonging to Tertiary, ranging from the Sa5 horizon to the Tertiary Base (Figure 9).

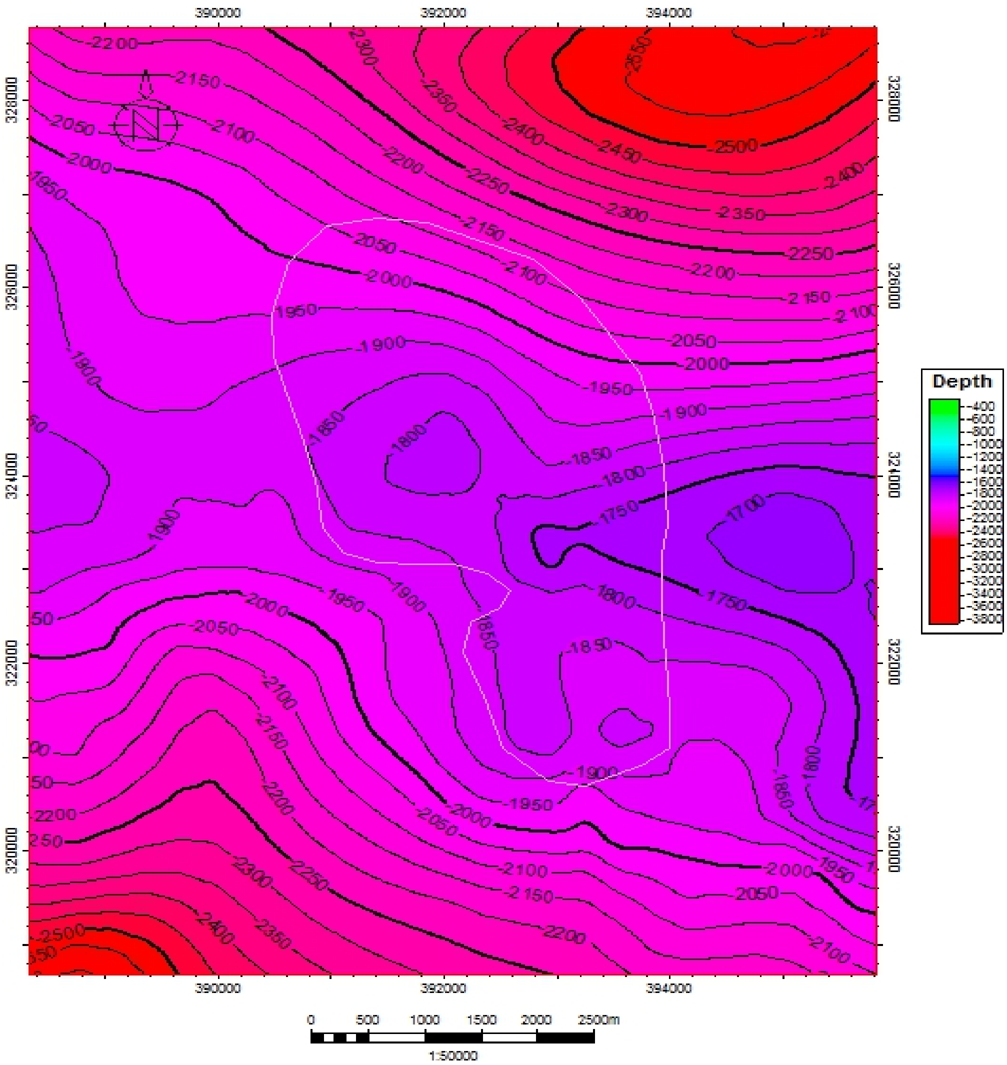

Figure 9. Depth contour map of Tertiary base

3 APPRAISAL AND INJECTION CONCEPT

The site exploration (appraisal) is designed to respond to important questions regarding the closure of the structure and the properties of the reservoir and, therefore, to select the location of the injection well and injection strategy. The appraisal strategy consists of one exploration well drilling and testing (to become monitoring well in the next phase of the project), 2D seismic on two lines (direction chosen to intersect legacy wells) and 3D seismic on the entire surface of the structure (25.46 km^2).

The injection will be done through a single injection well (newly built) located on the isobath of 1580 m of Sa7. For monitoring, one well will be used, redesigned from the exploration well drilled during the appraisal phase of the project. The planned appraisal and injection works are represented in Figure 10.

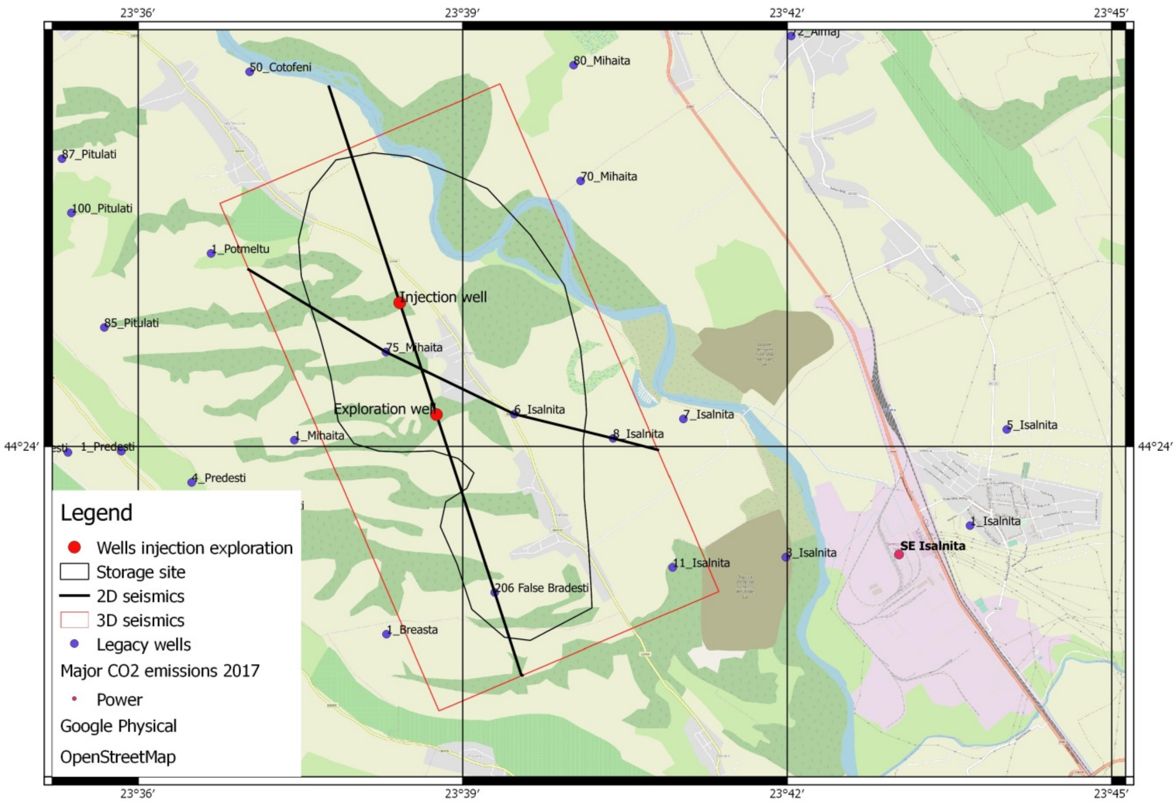

Figure 10. Site map showing appraisal and injection strategy

4 SOURCES OF CO_2

In the region of the pilot, there are 6 major CO_2 sources (Figure 11), 4 coal-fired power plants and 2 sources from chemical industry (Ciech Soda Romania and SC Oltchim S.A.). Power plants Rovinari, Turceni, Isalnita and Craiova II are operated by the Oltenia Energy Complex. Oltenia Energy Complex can annually supply up to 18 TWh of electric power and can cover up to 33 % of the electricity demand of Romania.

The nearest CO_2 source from the pilot is the Isalnita power plant. The power plant, located in Dolj county, was built in 1964-1968 and has two lignite-fired condensation power units. From these two power units, one has been modernized and one unit is currently undergoing rehabilitation. Importantly, as of the year 2017, the Isalnita power plant was the fourth largest CO_2 emitter in Romania (after Rovinari, Turceni- and, ArcelorMittal Galati), with total verified annual emissions of approximately 2 Mt CO_2. Of this amount, for the purpose of the pilot, only 30 kt will be injected for storage.

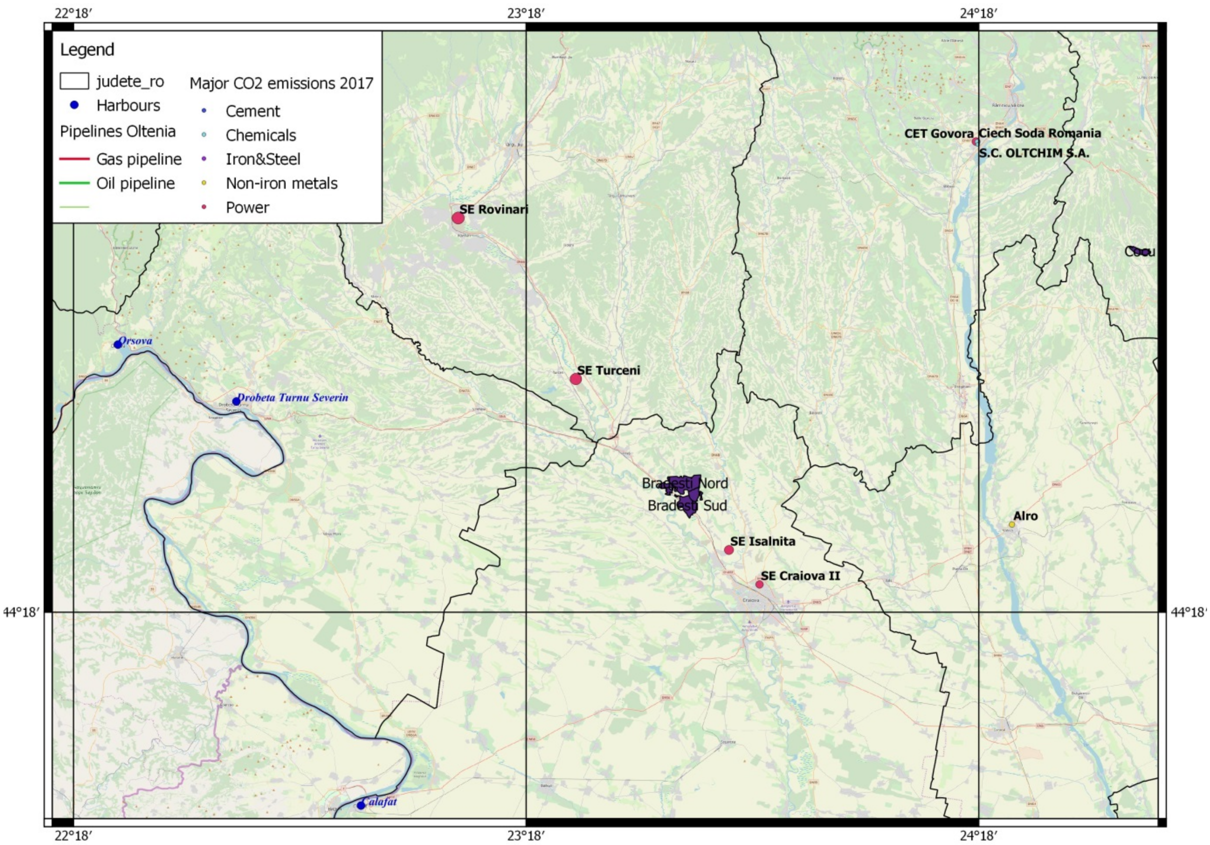

Figure 11. Map of major CO_2 sources in the area of interest

5 BUDGET

(SITE INVESTIGATION COSTS – INITIAL AND DETAILED, DRILLING AND WORKOVER COST ESTIMATES –INVESTMENT COSTS AND OPERATIONAL COSTS WHEN APPLICABLE)

The budget estimation is presented in Table 3. The budget figures are based on the work done within the GETICA CCS project.

Table 3. Cost details

COST ANALYSIS (k €)

Brădeşti pilot project

Feasibility | Appraisal | Development

Injection | Closure | Post-closure

Monitoring

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DURATION:									3 years			3 years			20 years											
								COMM.	1	2	3															
YEAR:			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
CAPEX	**Capex sub category**	**Total (k€)**																								
DATA COLLECTION & ACQUISITION		**4,437**																								
Surveys - data acquisition costs	Existing Data Collection and Quality Check	50	50																							
	Cores & Sampling acquisition	100			100																					
	Seismic 3D or 2D and other geophysical	1,212			132	1,080																				
	Seismic VSP	75			50			25																		
	Well testing	900			200	200		500																		
	Downhole logging (incl. Minifrac)	2,000			667	333		1,000																		
	DTS	100						100																		
STUDIES & MODELLING		**3,455**																								
Well integrity studies		240	20	20	100	100																				
Geological studies		200	100	0	100																					
Hydrogeological studies		100			50		50																			
Geomechanical studies		310	10		200	100																				
Core & sampling analysis		150			150																					
Impact study (environement, population...)		90	30		30		30																			

Risk Assesment / Prevention and Mitigation Plans (incl monitoring)		270	50	20	50	100	50																			
Static modelisation		415	65	100	150		100																			
Dynamic modelisation		530	80	100	150	100	100																			
FEED & Detail design	Well Construction design	150		50			100																			
	Seismic	150		150																						
FEED & Detail design	Surface infrastructure design	50					50																			
	FID	70		20		50																				
	Others						0																			
Project management costs	Feasibility study	130	80	50																						
	Appraisal	600		300	300																					
	Development	600				300	300																			
Others intangible assets	permitting (all types)	30	0	10		20																				
ASSETS & infrastructure		**8,790**																								
Surface infrastructure	flow lines (incl. Civil work)	0						0																		
	access roads	200		50	50			100																		
	other civil work	20		5	5			10																		
appraisal wells - drilling costs and completions		4,000		2,667	1,333																					
Injection well - drilling costs (including Completion)		3,500						3,500																		
Monitoring capex	Monitoring wells (excl. Completion) deep and shallow wells	0						0																		
	Microseismicity capex	300						300																		
	DTS	300						300																		
	Downhole P&T gauges	100						100																		
	Surface sensors (metering, soil, air)	50				25	25																			
	Data mgt infrastructure - reporting system	100						100																		
Old wells repair & work over		0						0																		
Surface utilties (incl. Compression and power generation capex)		100						100																		
Land Purchase		120		20	20			80																		
Contingency on CAPEX for site construction		0		0	0	0	0	0																		
TOTALCAPEX		**17,312**	**485**	**3,562**	**3,837**	**2,408**	**805**	**6,215**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

OPEX + commissioning		Total	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
TRANSVERS HUMAN RESSOURCE		**1,875**																								
Project Manager		150						150	0	0	0	0	0	0												
Assistant Project Manager		150						150																		
Legal (JV internal + external)		200						200																		
Geologist		540						200	100	100	50	30	30	30												
Geomechanist		220						100	30	30	30	10	10	10												
RE		470						100	100	100	50	40	40	40												
WI engineer		145						100	10	10	10	5	5	5												
Others staffs		310						100	50	50	50	20	20	20												
Overheads		109							29	29	19	11	11	11												
DIRECT OPERATING COSTS		**2,361**																								
Energy		11						1	10	0	0	0	0	0												
Maintenance technicians		200						200	0	0	0	0	0	0												
Workover		200							0	200	0	0	0	0												
Monitoring opex	Microseismicity opex	0							0	0	0	0	0	0												
	Seismic 3D or 2D and other geophysical surveys	100							0	0	0	100	0	0												
	Seismic VSP	600							300	300	0	0	0	0												
	Downhole logging	1,200							300	300	300	100	100	100												
	Insar / gravity surveys	50												50												
	DTS opex	0							0	0	0	0	0	0												
	Others (env. monitoring) opex							200	0	0	0	0	0	0												
G&A and OTHERS		**1,000**																								
Communication & Knowledge sharing		750			100			400	50	50	50	50	25	25												
Administration - office, etc		250		50	50	50	50	50	0	0	0	0	0	0												
TOTAL OPEX		**5,854**	**0**	**50**	**150**	**50**	**50**	**1,951**	**979**	**1,169**	**559**	**366**	**241**	**291**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
TOTAL		**23,166**	**485**	**3,612**	**3,987**	**2,458**	**855**	**8,166**	**979**	**1,169**	**559**	**366**	**241**	**291**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

6 POTENTIAL IMPACTS OF THE PILOT

The implementation of this pilot would mean a small step towards reducing emissions from Oltenia, which produces about 25% of the country's emissions. At the same time, it opens the way to promoting a wider installation (see chapter 1) by upscaling of the pilot, based on the GETICA study.

One of the important benefits of the pilot is opening the door to the maintenance of the industrial installations in the area (maintenance of jobs, social impact) and the development of local economy (e.g. new jobs, new incomes for the local budget).

The implementation of the pilot is also a good opportunity to familiarize the public with the concept of CCUS and to promote the technology in Romania.

7 STAKEHOLDER MAPPING IN THE REGION

The main stakeholders identified for the implementation of the proposed pilot are: local administration of the Cotofenii din Dos commune and the Dolj County, the agency for regional development and industry.

7.1 Local and regional administration

7.1.1 Cotofenii din Dos local administration

Cotofenii din Dos is a commune localised in the central northern part of the Dolj County, Romania, 22 km from Craiova city. Under this administration, 3 villages are reunited: Coțofenii din Dos, Potmelțu, Mihăița. The surface area of the commune is of 4,552 ha; it has a population of 2,337 residents.

Cotofenii din Dos is led by a Mayor and a Local Council. The Local Council is composed of 11 counsellors divided in 3 specialized commissions: 1. Commission for economic-financial activities, agriculture, land-use planning and urban planning; 2. Commission for education, socio-cultural activities, health, family, environmental protection, child protection, tourism, cults, social protection and 3. Legal Commission.

The competences of the Mayor are established according to art. 63 of Law no. 215/2001 republished, on the local public administration, and refer mainly to:

a) Coordination of activities in position of the main authorized officer, representative of the state. The mayor cooperates with the deconcentrated public services of the ministries and other specialized bodies of the central public administration in the administrative-territorial units, as well as with the County Council, in order to exercise his / her competences.

b) Issuing of the draft of the local budget and the account at the end of the budget period and submitting them for approval to the Local Council.

c) Tasks related to public services provided to citizens.

d) Elaboration of the drafts of strategies regarding the economic, social and environmental status of the administrative-territorial unit and their submission for the approval of the Local Council.

e) Coordination of the public services of local interest rendered by specialized apparatus or by the bodies providing public services and public utilities of local interest;

f) Elaboration of urban plans required by the law, submitting them for approval to the Local Council and acting to comply with their provisions.

g) Issuing the opinions, agreements and authorizations within his/her competence given by law and other normative acts.

h) Ensuring accomplishment of works and taking necessary measures in conformity with the provisions of the commitments assumed in the process of European integration in the field of environmental protection and water management with regard to services provided to the citizens.

7.1.2 Dolj County Council

The Dolj County is, from the perspective of the area and the stable population, the largest in the South-West Oltenia region and one of the economically most important counties in Romania (8th place). It also presents the following features:

a) Density of the population exceeds the regional and national average;

b) The Dolj is part of the South-West Oltenia Development Region, and the Regional Development Agency is located in Craiova;

c) It is a border county with Bulgaria and has about 150 km direct access , to the Danube River;

d) Dolj County has the highest contribution to the GDP of the South-West region and is ranked among the top 10 most important Romanian counties in terms of economic development;

e) Dolj County has one of the highest agricultural employment rates at national level (around 50%), with the lowest labour productivity, especially in rural areas, where subsistence agriculture is widely practiced, with rudimentary means, mainly for self-consumption;

f) At county level there are industrial agglomerations with local specialization potential and competitive advantages on domestic and foreign markets in areas such as car and automotive production (concentrated around Ford Romania, the most important company in the county), energy, textile articles and clothing, agri-food products, railway transport equipment and electrical and electrotechnical equipment;

g) The county is administered by a County Council. Its competences are regulated by Law 215 of 2001. The County Council has the role to coordinate the activities of communes, cities and municipalities under subordination.

7.1.3 Regional Development Council of South-West Oltenia

Regional Development Council is a deliberative regional body established by free association of five counties, Dolj, Gorj, Mehedinti, Olt and Valcea, under Law 151/1998, forming the South-West Oltenia Development Region. According to Law 315/2004 on regional development in Romania, which replaced Law 151/1998, the Regional Development Council of SW Oltenia has the following attributions:

a) analyses and approves the regional development strategy and programs;

b) supports the development of the National Development Plan in partnership;

c) approves the regional development projects, selected at regional level, in accordance with the criteria, priorities and methodology developed by the national institution with competences in the field of regional development, together with the specialized regional bodies;

d) submits, the proposed portfolio of projects, for which a selection procedure is applied at national level, to the National Regional Development Council for approval of financing

e) approves the criteria, priorities, allocation and destination of resources of the Regional Development Fund;

f) presents proposals for allocation of resources to the Regional Development Fund to the National Council for Regional Development;

g) supervises proper use of the funds allocated from the National Fund for Regional Development;

h) proposes to the National Council for Regional Development the amount of the annual contributions, within the limits of the approved sums by the budgets of the districts, respectively of the Bucharest Municipality, allocated to the Regional Development Fund, for financing of regional policy objectives and their destination and payment schedules;

i) attract other financial, local and regional financial contributions to achieve the regional objectives; attracted sources are revenue for the Regional Development Fund;

j) approves the half-year activity reports drawn up by the regional development agencies;

k) coordinates and supports the development of regional partnerships;

l) elaborates and approves its own functioning regulation, according to the framework regulation for the organization and functioning of the regional development councils;

m) endorses the agreements, conventions, protocols and other similar documents concluded by the regional development agency with third parties in the specific field of activity, including similar institutions within the European Union, and informs accordingly the National Council for Regional Development;

n) approves the organization and functioning status of the regional development agency, as well as its organizational chart;

o) coordinates the regional media coverage of regional development policies and objectives, regional programs funded by the European Union, as well as the regional use of funds, ensuring transparency and accurate, timely and timely information of citizens, especially entrepreneurs.

7.2 Non-profit organizations

The Regional Development Agency of South-West Oltenia is the most important non-profit organisation in the region. It was founded on February 28, 1999, based on Law 315/2004 (amending Law 151/1998) on development regional level in Romania and in accordance with the statute of organization and functioning, approved by the Regional Development Council of South-West Oltenia. ADR SV Oltenia is part of the set of financial, regional and national bodies and instruments set up to enable Romania to absorb Community funds during the pre- and post-accession period.

The Agency currently operates in Craiova (the headquarters), and in the county offices in Targu-Jiu, Drobeta Turnu-Severin, Slatina and Ramnicu Valcea. Its mission is to facilitate and promote the development of Oltenia through the implementation of the Regional Development Plan endorsed by the Regional Development Council and the regional partners. The main goal is to attract resources from outside the region, in conjunction with increasing the use of local resources, in order to achieve the social cohesion of local communities in Oltenia, to improve the quality of life, and to increase the competitiveness of the regional economy.

7.3 Industry

Complexul Energetic Oltenia (Oltenia Energy Complex) is a major Romanian energy company. Its main business areas are lignite-based electricity and heat generation and extraction and preparation of lignite. CE Oltenia generates electricity and heat (especially for Craiova City) and sells coal to third parties (mainly to the electricity producers). The main raw material used to generate power is the lignite extracted from its own open pits in Oltenia Mining Basin. The company has a 40-year old history and significantly contributes to the safety of the National Power System. The coal of CE Oltenia can provide electricity for Romania for the next 40 years and this is possible based only on the reserves discovered so far. The shareholders are:

– Romanian State represented by the Ministry of Economy (77.15 %)
– Fondul Proprietatea SA (21.56 %)
– Electrocentrale Grup SA (0.84 %)
– Inchidere si Conservare Mine (0.44 %)

CE Oltenia produces electricity in 11 power units with an installed capacity of 3,240 MW, structured in four power plants:

- SE Rovinari – 3 x 330 MW lignite-fired condensation power units ;
- SE Turceni – 4 x 330 MW lignite-fired condensation power units;
- SE Isalnita – 2 x 315 MW lignite-fired condensation power units;
- SE Craiova II – 2 x 150 MW/160 Gcal lignite-fired cogeneration power units.

CE Oltenia also produces thermal energy in the Craiova II Thermal Power Plant Branch and hydropower in a the plant built on Jiu River, 3.5 km upstream of Turceni Thermal Power Plant, with an installed capacity of 10 MW (1 x 1 MW and 3 x 3 MW hydro-power units).

OMV Petrom is the owner of the hydrocarbon exploration and exploitation block which includes the Brădești structure and the proposed CO2 storage structure. OMV Petrom is the largest energy company in Southern and Eastern Europe. The company is active in every aspect of the energy value chain: from wells and oil and gas production through refining and fuels distribution, gas supply to power generation & supply. The company is a follower of Petrom, the National Romanian Petroleum Company. At the end of 2004, the company was privatized, with the Austrian oil company OMV AG becoming the new majority shareholder.

Another important stakeholder from hydrocarbon industry is ***Romgaz,*** which owns exploration and exploitation blocks for natural gas for the fields near Craiova city. Romgaz is the largest natural gas producer and the main gas supplier in Romania. It is a joint stock company, whose majority shareholder is the Romanian State owning a 70% stake. The company has a vast experience in the field of gas exploration and production and a history that began in 1909 with the discovery of the first commercial gas reservoir in the Transylvanian Basin by drilling the Sarmasel well. Starting from 2013, Romgaz extended its scope of work by taking over the Iernut thermoelectric power station, becaming thus also an electric power supplier.

8 PROVISIONAL TIMELINE AND FUNDING OPPORTUNITIES

The project consists of 5 stages: feasibility study (1.5 years), appraisal/exploration (33 months), development/construction (36 months), injection / operation (3 years), closure (3 years), post- closure (20 years).

Part of the feasibility study and appraisal studies (except seismic survey or well drilling) can be possibly financed through Horizon 2020 calls. Till now two calls have been identified as possible to apply for financing of the project: Low carbon industrial production using CCUS LC-SC3-NZE-5-2020 (Opening date: 05 May 2020) and Geological Storage Pilots LC-SC3-NZE-6-2020 (Opening date: 05 May 2020).

The drilling and seismic campaigns can be financed by national funds and sponsorships (from the energy complex and oil company) and through the Norway – Romania financing mechanism, if the project is declared a national priority project in the decade after 2020.

The construction works can be financed through the EU Modernisation Fund, to be accessed by the owner of Isalnita power plant (CE Oltenia).

If upscaled, the project can also apply for the EU Innovation Fund resources.

9 PROJECT RISK ASSESSMENT (PERMITTING, CONSTRUCTION, POLICY, HSE, ETC.)

At the level of the CO_2 storage pilot, several categories of risk have been identified: technical, economical/financial, legal and environmental. These risks are detailed in the Risk register presented in Table 4.

Table 4. Risk register

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
1	FEED	Legal	Project	The legislator has questions/is opposing to the CCS project	Difficulties to obtain legal permits (e.g. Environment agreements, permits (Fire drilling, building)	- No legislation in place on time - Lack of experience of Authorities on CCS projects (new project) - Legislation changes (e.g. environmental laws, construction norms, legislation regarding the construction permits) - Misunderstanding of the authorities	Delaying the project	Schedule	Project company (manage-ment)	Medium	Medium	4	- Explanations / persuasion of the regulators - Proposing interventions to impulse the process - Ensuring early communication and liaison with authorities	Low	Low	1
2	FEED	Financial	Project	Not obtaining the budget to implement the project in the expected time		- Financial uncertainties (non-observance of the specific points from the financial planning) - Project is not in line with EU expectations - Technical requirements are not well defined (not reached) - Drop in political support	Delaying the project	Schedule	Project company (manage-ment)	Low	High	3	Establishing strong contractual obligations, backed by the Government.	Low	Low	1
3	FEED / EPC	Public	Project	Public groups challenge the project		-Miscommunication -Lack of communication -Lack of technical knowledge of the public	Delaying the project	Schedule	Project company (manage-ment)	Low	High	3	Establishing CCS acceptance through smart communication	Low	Medium	2

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probabilit y level	Severity level	risk level		Probabilit y level	Severity level	Risk level
4	FEED / EPC	Political	Project	Governmental instability (e.g.: Government change)		- Different governments could have different policies	Delaying the project	Schedule	Project company (manage-ment)	Medium	Medium	4	- Establishing direct relation with the EU to have their support - Establishing strong contacts with technical representatives within Romanian Government	Low	Medium	2
5	FEED / EPC	Financial	Project	CAPEX / OPEX is higher than expected		- New taxation (e.g. for land buying) - Extra cost during the construction - Impact of the changes in the technical solutions	Delaying the project - Increasing the costs	Schedule, Financial	Project company (manage-ment)	Low	Medium	2	- Establishing strong EPC contracts - Supervising contracts	Low	Low	1
6	FEED / EPC	Contractual	Project	Difficulties related to all contract issues		- New market, lack of strong contractual procedures, poor commercial terms (referring to prices and deadlines), poor contract - Unprepared legal counsellors	-Delaying the project -Increasing the costs	Schedule, Financial	Project company (manage-ment)	Medium	Medium	4	- Establishing strong contractual procedures - Building clear scheme for price augmentation - Having strong legal counsellors	Low	Low	1
7	FEED / EPC	Legal	Project	Difficulties related to the legal issues during the creation of a new company		- Project company internal procedures legally inappropriate - Unprepared legal counsellors - Project company constitutive documents inappropriate	-Delaying the project Increasing the costs	Schedule, Financial	Project company (manage-ment)	Medium	Medium	4	- Establishing appropriate project company constitutive documents - Drafting legally appropriate project company internal procedures - Having strong legal counsellors	Low	Low	1
8	FEED / EPC	Communica-tion	Project	Data/inputs coming from other activities (transport, storage, capture plant) are erroneous		Lack of communication control	-Delaying the project -Increasing costs -Bad design for the other technical subsystems	Schedule, Financial, Technical performance	Project company (manage-ment)	Low	Low	1	- Implementing periodical meetings between the different teams - Ensuring high level quality documentation	Low	Low	1

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
9	FEED / EPC	Technical	Project	A change occurs within one of the other activities (transport, storage, capture plant).		Bad coordination between the project activities (technical part)	-Delaying the project -Increasing costs -Bad design for the other subsystems	Schedule, Financial, Technical performance	Project company (manage-ment)	Medium	Medium	4	- Ensuring an early communication and liaison between sub-systems - Implementing internal communication procedures within the project - Organizing regular meetings	Low	Low	1
10	FEED / EPC	Financial	Project	Uncertainties on costs		- New project, no referential projects, lack of experience - Inflation - Exchange rate fluctuations - Prices of the materials	Funding gap	Financial	Project company (manage-ment)	Medium	High	6	- Obtaining a very strong governmental support - Considering the prognoses for inflation and exchange rates - Providing a margin in the budget	Low	Low	1
11	FEED / EPC	Manage-ment	Project	Difficulties to find experienced companies for construction		- Labour market instability - Lack of skilled workers	Delaying the project	Schedule	Project company (manage-ment)	High	Medium	6	- Establishing strong EPC contractual obligations - Selecting relevant companies with experience	Low	Low	1
12	Operation	Technical	Project	No proper CO_2 detection systems in place		- Failure of the metering system - Conditions are out of permitted range	No control of the CO_2 conditions (human exposure to elevated CO_2 concentrations causing asphyxiation/ hypercapnia, pollution, CO_2 conditions are not as required)	Legal, Monitoring	Project company (manage-ment)	Low	High	3	- Using the best available detection systems. - Updating and maintaining the system over the operation period - Establishing standard H&S procedures	Low	Low	1

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
13	FEED / EPC	Manage-ment	Project	Project company technical management issues		-Lack of experience in CCS -Complexity of the project -A lot of systems and actors	Delaying the project	Schedule	Project company (manage-ment)	Medium	Medium	4	- Defining clearly missions, organization and responsibilities within PC - Implementing risk management processes and procedures in compliance with the ISO 31000 standard - Ensuring required technical management procedures - Developing systematic knowledge transfer and handover procedures - Developing lessons learnt database	Low	Medium	2
14	FEED / EPC	Legal	Project	Requirements from regulations are too restrictive for the environmental issues		-Lack of experience -Lack of knowledge about CCS and impact on environment	-Delaying the project -Increasing the costs	Schedule, Financial	Project company (manage-ment)	Low	High	3	Ensuring early communication and liaison with environmental agency	Low	Medium	2
15	Operation	Financial	Project	Long term price of CO_2 emission allowances decreasing		- Changes of EU policy regarding CO_2 emissions price - An alternative technology turns out to be more cost-effective, negatively impacting the price of CO_2 emissions	Reducing the benefits of the project company	Financial	Project company (manage-ment)	Low	Medium	2	*			
16	Operation	Technical	Project	Inadequate operation and maintenance procedures (incomplete or inappropriate)		Lack of experience with CCS	-Accidents may occur -Stop of the operations -Cost increase	Technical perfor-mance, HSE, Financial	Project company (manage-ment)	Low	High	3	- Implementing detailed operating procedures - Proposing HAZOP studies - Establishing a relevant maintenance budget for the operation for the full chain	Low	Medium	2

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
17	FEED / EPC	All	Project	Hazard is not identified or fully recognized (scaling up from the pilot scale to large industrial scale, the hazard could not be effectively managed)				All	Project company (manage-ment)	Low	High	3	Performing dedicated risk analyses regularly over project lifecycle	Low	Medium	2
18	Operation	Legal	Storage	Reports does not satisfy the requirements of the concession (for the authorities)	Project company must annually report to the regulator (present its work, the progress of the project, what are they doing now)	-New project -No clear requirements from the authorities	Delaying the project	Schedule, Legal	Project company (manage-ment)	Low	High	3	Early communication and liaison with the authorities	Low	Low	1
19	EPC	Technical	Storage	Incomplete injection test during the testing phase due to lack of CO_2			Delaying project	Schedule	Project company (storage leader)	Low	Low	1	Requiring plans to buy food-grade CO_2 to perform the first tests	Low	Low	1
20	FEED / EPC	Technical	Storage	Delay of permit required for CO_2 injection test during exploration		- Incomplete and non-satisfactory tests - Incomplete understanding by the authorities	Delaying project	Schedule	Project company (storage leader)	Medium	Medium	4	Ensuring early communication and liaison with authorities	Low	Medium	2

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
21	FEED / EPC	Technical	Storage	Inadequate storage site	Shown by seismic investigation and drilling operation	-Uncertainties due to lack of data on the site -Non-satisfactory injection tests (wrong storage information, wrong test assumptions)	-Increasing delay -Increasing costs	Schedule, financial	Project company (storage leader)	Medium	High	6	- Including an alternative site in the planning (backup storage) - 2D seismic studies for the backup storage zone	Medium	Medium	4
22	FEED / EPC	Contractual	Storage	Land owners refuse exploration / operation on their land		Lack of communication	-Delaying the project -Costs increase	Schedule, Financial	Project company (storage leader)	Low	High	3	- Ensuring early communication and liaison with landowners - Providing financial compensation - Performing lobbying for land access	Low	Low	1
23	Operation	Technical	Storage	System integrity failures (equipment, piping, valves, instruments) for storage		-Poor material -Poor reliability of the material -Bad control procedures	-CO_2 release -Decrease of the CO_2 flow rate	Technical perfor-mance, HSE, Financial	Project company (storage leader)	Low	High	3	-Appropriate design/ equipment/ materials/ operation/ monitoring/ maintenance	Low	Low	1
24	Operation	Technical	Storage	Failure of equipment for storage		Not selecting relevant suppliers for equipment/ devices/ pipes/materials	-CO_2 release -Decrease of the CO_2 flow rate	Technical perfor-mance, HSE, Financial	Project company (storage leader)	Low	High	3	- Establishing a careful vendor qualification process before selection - Establishing strong EPC contracts	Low	Low	1
25	Operation	Technical	Storage	Failure of equipment for storage		Indirect human interaction: external impact, technical culture or civilization degree causes, as well as the tension of the population in the area	-CO_2 release -Decrease of the CO_2 flow rate	Technical perfor-mance, HSE, financial	Project company (storage leader)	High	High	9	- Ensuring safe areas (and monitoring them) - Provision of automatic systems that could successfully intervene in case of human errors	Medium	Medium	4

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
26	Operation	Technical	Storage	Failure of equipment for storage		Direct human interaction (perpetration or skippping of errors): design failures, construction failures, operation failures	-CO_2 release -Decrease of the CO_2 flow rate	Technical perfor-mance, HSE, financial	Project company (storage leader)	Low	High	3	- Having a liable designing staff - Team training - Provision of automatic systems that could successfully intervene in case of human errors	Low	Medium	2
27	Operation	Technical	Storage	Release of CO_2 in closed space on storage site		Failure of equipment	Increase CO_2 concentration in a confined area	HSE	Project company (storage leader)	Medium	High	6	- Choosing pipes & equipment with high reliability rates + quality operation (from strong EPC contracts) - Implementing detection and warning systems - Implementing ventilation system	Low	Low	1
28	Operation / Post operation	Technical	Storage	Unable to effectively monitor the integrity of the storage site		- Destruction of monitoring devices (vandalism) - Monitoring system works insufficiently (power cut, ageing)	No control of the CO_2	Monitoring, Legal	Project company (storage leader)	Low	High	3	Performing a detailed study involving an experienced company	Low	Low	1
29	Operation / Post operation	Technical	Storage	Brine displacement into sensitive targets (freshwater) through induced fracture		-Overpressure -Physical-chemical reactions between injected gas & the rocks -Decrease in fracture pressure of the formations -Presence of heterogeneities -Unidentified conductive faults (or fracture corridors) crossing the caprock	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Low	Low	1	- Developing a baseline survey - Chemical analyses of downhole fluids in monitoring wells - Geomechanical tests and modelling	Low	Low	1

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				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
30	Operation / Post operation	Technical	Storage	Brine displacement into sensitive targets (freshwater) through fault reactivation		-Overpressure -Physical-chemical reactions between injected gas & the rocks -Decrease in fracture pressure of the formations -Presence of heterogeneities	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Low	Low	1	- Developing a baseline survey - Performing chemical analyses of downhole fluids in monitoring wells -Performing detailed fault analysis in appraisal phase	Low	Low	1
31	Operation / Post operation	Technical	Storage	Brine displacement into sensitive targets (freshwater) through old plugged and abandoned wells		-Well components ageing (degradations due to injected gas and formation fluids) - Mechanical issue at an old legacy well -Well components initial integrity failure	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Low	Low	1	- Performing chemical analysis of downhole fluids in monitoring wells - Assessing well integrity performance for the old plugged and abandoned wells	Low	Low	1
32	Operation / Post operation	Technical	Storage	CO_2 gas migration into sensitive targets (freshwater, surface) through induced fracture		-Overpressure -Physical-chemical reactions	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Medium	High	6	- Developing a baseline survey - Performing high resolution 3D seismic during appraisal - Geomechanical tests and modelling	Medium	Low	2
33	Operation / Post operation	Technical	Storage	CO_2 gas migration into sensitive targets (freshwater, surface) through conductive fault		-Overpressure -Physical-chemical reactions	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Medium	High	6	- Acquiring geo-mechanical data - Developing a baseline survey - Performing high resolution 3D seismic during appraisal -Performing detailed fault analysis in appraisal phase	Medium	Low	2

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
34	Operation / Post operation	Technical	Storage	CO_2 gas migration into sensitive targets (freshwater, surface) through old plugged and abandoned wells		-Well components ageing (degradations due to injected gas and formation fluids) -Mechanical issue at an old legacy well -Well components initial integrity failure	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Medium	High	6	- Detailed analysis and assessment of long-term well integrity - Assessing well integrity performance for the old plugged and abandoned wells (re-entry & workover if applicable before injection starts, Mmonitoring wells for salinity and CO_2 appearance)	Medium	Low	2
35	Operation / Post operation	Technical	Storage	CO_2 gas migration into sensitive targets (freshwater, surface) through monitoring/ injection wells		-Well components ageing (degradations due to injected gas and formation fluids) -Mechanical issue at an old legacy well -Well components initial integrity failure	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Low	High	3	- Assessing well integrity performance for the new monitoring / injection wells (completion design and material, quality control of cementing, monitoring of annular space)	Low	Low	1
36	Operation / Post operation	Technical	Storage	CO_2 gas migration into sensitive targets (freshwater, surface) through caprock	Possible CO_2 migration through the caprock via permeation	-Physical-chemical reactions -Permeability of caprock could be non-negligible due to currently uncertain lithology	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Medium	High	6	- Developing baseline survey - Performing high resolution 3D seismic during appraisal - Performing extensive caprock logging, coring and laboratory testing during appraisal	Medium	Low	2
37	Operation / Post operation	Technical	Storage	CO_2 gas migration into sensitive targets (freshwater, surface) due to an inadvertent drilling into the storage complex		Poor record keeping	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Low	High	3	Informing periodically the authorities about any CO_2 plume evolution	Medium	Low	2

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
38	Operation / Post operation	Technical	Storage	Loss of containment (lateral plume extension)		Structural closure of site currently uncertain. Some pinchouts are currently assumed and have to be verified during the appraisal.	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Medium	High	6	- Performing proper appraisal characterization and high-resolution 3D seismic - Acquiring data and performing reservoir modelling and simulations	Low	Medium	2
39	Operation / Post operation	Technical	Storage	Loss of containment (lateral plume extension)		Unidentified faults within the reservoir not laterally transmissive	Pollution, consequence for permit to operate, bad reputation	Technical perfor-mance, HSE, Legal, Public	Project company (storage leader)	Medium	Medium	4	- Performing appraisal characterization and high-resolution 3D seismic - Acquiring data and performing reservoir modeliing and simulations -Changing injection strategy	Low	Medium	2
40	Operation	Technical	Storage	Loss of well control		-Drop in pressure -Influx of liquid/solid impurities in well	Shutdown of the operation	Financial	Project company (storage leader)	Low	Medium	2	- Using foam substances, lifting etc. - Using special filters, gravel packing etc.	Low	Low	1
41	Post operation	Technical	Storage	Accidental CO_2 eruption after well abandonment.		-Overpressure -Well equipment failure	Pollution, bad reputation	HSE, Public	Project company (storage leader)	Low	Medium	2	- Safety area around the plugged and abandoned wells - Eruption prevention systems to be installed	Low	Low	1
42	Operation	Technical	Storage	Well blow-out		-Overpressure -Well equipment failure	Pollution, bad reputation, costs increasing	HSE, Financial, Public	Project company (storage leader)	Low	High	3	- Implementing emergency plan - Implementing monitoring system - Installing valve system in the well design	Low	Low	1
43	Operation	Technical	Storage	Surface deflection	Injection and regional pressure increase leads to geo-mechanical reactions of the reservoir and the overburden.	-Overpressure -Pressure redistribution	Consequence for permit operation, bad image of CCS	Legal, Public	Project company (storage leader)	Medium	Low	2	- Performing geo-mechanical studies - Monitoring surface deflection and pressure in the reservoir	Low	Low	1

Risk ID	Project Phase	Risk categories	System	Risk Description				Objectives impacted	Risk owner	Risk rating (before mitigation)			Mitigation actions	Risk rating (after mitigation)		
				Risk	Comments	Causes	Effects / Consequences			Probability level	Severity level	risk level		Probability level	Severity level	Risk level
44	Operation	Technical	Storage	Loss of injectivity	Location of injection wells, number of injection wells, injection conditions: Position of injectors and choice of storage site is assessed using a sparse dataset and analogy estimation.	-Loss of permeability (reservoir clogging, pressure increase, cooling effect of the injection into the aquifer) -Physical reactions between reservoir (rock and fluid in place) and injected gas: dry-out effect around the well, salt precipitation -Chemical reactions between the rock and injected gas: CO_2 hydrates formation, carbonate precipitation -Local compartmentaliza-tion of the aquifer -Well interference	Impact on injectivity index	Technical performance	Project company (storage leader)	Low	Medium	2	- Collecting additional data to improve reservoir characterization - Performing reservoir modelling, reservoir tests and physical testing on cores - Ensuring chemical compatibility of drilling and CO_2 with formation brine - Stimulating or fracturing reservoir - Fitting well injection strategy (number of wells, location of injection wells)	Low	Low	1

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