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Estonian-Latvian Transboundary Carbon Dioxide Capture, Transport and Storage (CCS) Scenario for the Cement Industry

Master thesis

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Eesti-Läti piiriülene süsinikdioksiidi kinnipüüdmise, transpordi ja ladustamise (CCS) stsenaarium tsemenditööstusele

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Autorideklaratsioon

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CONTENT

ABSTRACT

The climate target of Estonia for 2050 is to decrease greenhouse gas emissions by 80% compared to 1990, including 67% from industry and the energy sector. By 2016, 61% of this target has been reached, but an additional 10.2 Mt of annual emissions must be reduced from the industry and the energy sector by 2050. To achieve this goal, two CO_2 capture and storage (CCS) scenarios were presented, and for the first time in the Baltic Region, both of the scenarios involve the cement industry (AS Kunda Nordic Tsement). North Blidene and Blidene structures in Latvia were selected for these scenarios, their structure maps, geological sections and 3D geological models were constructed, and CO_2 storage capacities were calculated using improved estimation of all the parameters. Minimum, maximum and average capacities were calculated for optimistic and conservative cases for two structures. Their total optimistic capacity (min-max/mean) is 186-380/297 Mt, while the conservative is 33.6-68.0/53.4 Mt. The average optimistic capacity is more than two times higher than the capacities reported previously (132 Mt, Vangkilde-Pedersen, et al., 2009a), explained by estimated larger area and higher CO_2 density in the reservoir. The average conservative capacity is lower by 2.5 times, explained by the higher conservative storage efficiency applied before.

The first CCS scenario is composed for CO_2 emissions produced by AS Kunda Nordic Tsement Plant (KNC), captured using Ca-looping technology and transported to the Blidene structure. According to the EU Emissions Trading System, KNC produced 0.56 Mt/CO_2 in 2017 and will produce about 16.8 Mt/CO_2 emissions during the next 30 years. For this scenario even the average conservative estimate of the Blidene structure (17.8 Mt) will be sufficient for more than 30 years. Only one borehole at the dome of the Blidene and 750 km of pipelines of 300 mm diameter are planned. However, the costs for this scenario could be relatively high considering high capital costs for the capture, the compression station and the transport pipelines. According to (EPRI, 2015) the costs per one ton of CO_2 avoided for transport and storage of small volumes of CO_2 over long distances could be from several to ten times higher than transport of large quantities to smaller distances. Also, this scenario does not enable Estonia to reach its 2050 strategical climate targets.

The second CCS scenario is proposed for CO_2 emissions produced and captured by KNC, Eesti Elektrijaam and Balti Elektrijaam, two of the largest industrial CO_2 emission sources in Estonia, and the largest industrial CO_2 emitter in Latvia - Latvenergo, TEC-2, all of them collaborating in one joint CO_2 transport and storage scenario into North-Blidene and the Blidene structures together. Sharing estimated expenses among project partners will make CCS project more attractive to all parties involved. The share of Estonian CO_2 emissions in this scenario will be about 93.4%, including 5% by KNC, and the Latvian emissions will compose 6.6%. Three sources from Estonia and one source from Latvia produce 11.26 Mt/CO_2 every year. Seven boreholes at the dome of the North Blidene structure and one borehole at the dome of Blidene structure are planned, considering 1.5 Mt injection rate per one borehole, per year. The construction of about 800 km of pipelines of 800 mm diameter are planned. Considering the Latvian's 50 years of experience with Inčukalns underground natural gas storage, the optimistic estimated mean value of CO_2 storage capacity was applied, supporting CO_2 storage for the duration of 26 years for the Estonian-Latvian transboundary project in the second scenario.

Compared to the previously modelled Estonian-Latvian CCS scenario for the Balti Elektrijaam and Eesti Elektrijaam, with their estimated eight years storage duration into South-Kandava and Luku-Duku structures (Shogenova, et al., 2011a), this scenario has the advantage of Latvian-Estonian cooperation of four of the largest CO_2 producers in the Baltics, including cement industry, it has a longer project duration (26 years), and it will help to both countries to reach their strategical climate targets.

Keywords: CO_2 capture, transport and storage, North Blidene and Blidene structures, AS Kunda Nordic Tsement, Eesti Elektrijaam, Balti Elektrijaam, Latvenergo TEC-2.

ANNOTATSIOON

Eesti kliimapoliitika eesmärk on aastaks 2050 vähendada kasvuhoonegaaside emissioonide hulka 80% võrreldes aastaga 1990, sh. 67% energia- ja tööstussektoris. 2016. aastaks oli kasvuhoonegaaside heidete hulka vähendatud 61%. Lõppeesmärgi saavutamiseks on vajalik energia- ja tööstussektoris vähendada iga-aastast emissioonide kogust 10,2 miljoni tonni võrra. Seatud eesmärgi saavutamiseks on käesolevas töös käsitletud kahte süsinikdioksiidi kinnipüüdmise stsenaariumit, mis hõlmavad CO2 kinni püüdmist, transportimist ja ladustamist ning esimest korda Baltikumis on kaasatud mõlema stsenaariumi jaoks tsemenditööstus (AS Kunda Nordic Tsement). Stsenaariumi loomiseks on käesolevas töös arvutatud Lätis asuvate Põhja-Blidene ja Blidene struktuuride CO_2 mahutavus. Mõlema struktuuri puhul arvutati miinimum, maksimum ja keskmine väärtus nii optimistlikul kui ka konservatiivsel lähenemisel. Mõlema struktuuri mahutavus (min-maks/keskm) optimistlikul lähenemisel on kokku 186-380/296 miljonit tonni ja konservatiivsel kokku 33,6-68,0/53,4 miljonit tonni. Optimistliku lähenemise keskmine tulemus on kaks korda suurem kui varasemalt hinnatud mahutavus 132 miljonit tonni (Vangkilde-Pedersen, et al., 2009a), mida võib seletada selles töös suurema maa-ala käsitlemisega ning suurema CO_2 tihedusega reservuaaris. Konservatiivse lähenemise keskmine tulemus on kaks ja pool korda väiksem, mida võib seletada madalama efektiivsuskoefitsiendi kasutamisega käesolevas töös.

Esimene CCS stsenaarium on koostatud ainult CO_2 emissioonidele, mis on toodetud AS-is Kunda Nordic Tsement (KNC) poolt. CO2 püütakse kinni kaltsiumtsükli tehnoloogiaga ja CO2 transporditakse Blidene struktuuri. Euroopa Liidu heitmekaubanduse süsteemi andmetel tootis KNC 2017. aastal 0,56 miljonit tonni CO_2 ning sellest lähtuvalt võib eeldada, et järgmise 30 aasta jooksul toodab KNC kokku 16,8 miljonit tonni CO_2. Selleks stsenaariumi puhul, et mahutada KNC toodetud CO_2 vähemalt 30 aasta jooksul, piisab isegi konservatiivsel lähenemisel arvutatud keskmisest tulemusest (17,8 miljonit tonni) ainuüksi Blidene struktuuris. Selleks stsenaariumiks on vaja ühte puurauku Blidene struktuuri ning lisaks rajada 750 km pikkuse ja 300 mm läbimõõduga torujuhe. Sellise stsenaariumi hind võib aga kujuneda võrdlemisi kõrgeks kuluka tehnoloogia tõttu. Lähtuvalt (EPRI, 2015) artiklile võib transpordi ja ladustamise hind kujuneda ühe kinnipüütud CO_2 ühiku kohta kuni kümme korda kallimaks kui suurte CO_2 koguste transportimine lühikesel vahemaal. Samuti ei piisa sellest stsenaariumist üksinda, et saavutada Eesti kliimapoliitika eesmärke.

Teine CCS stsenaarium pakub välja, et KNC koos kahe Eesti suurima tööstusliku CO_2 tootjaga (Eesti ja Balti elektrijaamad) ning suurima tööstusliku CO_2 tootjaga Lätis (Latvenergo, TEC-2) moodustavad ühise CO_2 transpordi ja ladustamise süsteemi. Kulude jagamine projekti partnerite vahel teeb võimaliku CCS projekti kättesaadavamaks kõikide osapoolte jaoks. Lähtudes CO_2 emissioonidest moodustub Eesti osa selles stsenaariumis 93,4% (5% KNC) ning Läti osa 6,6%. KNC, Eesti ja Balti Elektrijaamad ning TEC-2 toodavad aastas kokku 11,26 miljonit tonni CO_2. Arvestades, et ühe puurauguga on võimalik aastas reservuaari pumbata 1,5 miljonit tonni CO_2, siis on vaja rajada seitse puurauku Põhja-Blidene struktuuri ja üks puurauk Blidene struktuuri. Vaja on rajada 800 km torujuhet diameetriga 800 mm. Arvestades kogemusi Lätis, võib projekti pikkuseks eeldada 26 aastat, mis lähtub optimistliku lähenemise keskmise väärtusega mahutuvusest.

Varasema Eesti ja Läti vahelise CCS stsenaariumi kestvuseks oli hinnatud kaheksa aastat ja see käsitles Eesti ja Balti Elektrijaamade CO_2 transportimist ja ladustamist Lõuna-Kandava ja Luku-Duku struktuurides (Shogenova, et al., 2011a). Käesolev stsenaarium käsitleb suuri CO_2 tootjaid Eestis, sh. tsemenditööstust ning kaasab ka Läti suurt CO_2 tootjat. Projekti kestuseks on hinnatud 26 aastat ning projekt aitab nii Eestil kui Lätil jõuda kliimapoliitika eesmärkide täitmiseni.

Märksõnad: CO_2 kinnipüüdmine, transport ja ladustamine, Põhja-Blidene ja Blidene struktuurid, AS Kunda Nordic Tsement, Eesti Elektrijaam, Balti Elektrijaam, Latvenergo TEC-2.

ABBREVIATIONS, TERMS AND UNITS

Abbreviations

Al_2O_3 - aluminium oxide
CaL - calcium looping
CCS - CO_2 capture and storage
CGS - CO_2 geological storage
CO_2 - carbon dioxide
CO - carbon monoxide
CaO - calcium oxide
$CaCO_3$ - calcium carbonate
COP21 - Conference of the Parties 21
EOR - enhanced oil recovery,
EU ETS - EU Emissions Trading System
GHGE - greenhouse gas emissions
KNC - AS Kunda Nordic Tsement
LEGMC - Latvian Environmental, Geological and Meteorological Centre
Min-max (mean) - minimum-maximum (average)
NA - not available
NG - net to gross ratio of the aquifer in the trap (%)
ROZ - residual oil zone
S_{ef} - storage efficiency factor (for the trap volume, %)
SiO_2 - silicon dioxide
ϕ - porosity (%)
3D - 3-dimensional
T, ºC
S_{eff}Opt./Cons.

Terms

Baltic Region - Baltic States (Estonia, Latvia and Lithuania)
Baltic Sea Region - Denmark, Estonia, Latvia, Finland, Germany, Lithuania, Poland, Russia, Sweden, Norway and Belarus
Cambrian Series 3 - earlier Middle Cambrian
Eesti Elektrijaam, Balti Elektrjaam, Auvere Elektrijaam - Eesti, Balti and Auvere power plants
U.S. - United States

Units

atm - unit of pressure (1 atm = 101 325 Pa)
g - grams
MPa – mega Pascal (unit of pressure)
g/l - grams per litre
Gt – gigatonne
m - metre
km - kilometre
km^2 - squire kilometre
mD – millidarcy, unit of permeability (1 Darcy $\approx 10^{-12}$ m^2)
Mt - million tonnes
MW - megawatts
t - tonnes
T, ˚C - temperature by Celsius

1. INTRODUCTION

A global climate agreement was reached in December 2015 in Paris at the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change. In Paris, the countries agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels by 2100. This will significantly reduce the risks and impacts of climate change. The agreement entered into force on 4 November 2016, and 176 Parties (10.05.2018) have already ratified of 197 Parties to the Convention, including Estonia (United Nations, 2018).

In 2016 more than 36 Gt of CO_2 (Figure 1) were produced globally by fossil fuels and industry (European Comission, 2018). European countries produced about 3.6 Gt of CO_2 in 2016 (EU-28 countries produced about 3.4 Gt of CO_2). Global CO_2 emissions per capita in 2016 were 4.8 t, while Estonia produced 17.1 t per capita (2nd place in Europe and 12th place in the world (European Commission, 2018). Estonia is the largest CO_2 emitter among the Baltic States due to use of its local oil shale for energy production. Total CO_2 emissions produced in Estonia have increased from 18.6 Mt in 2010 up to 22.4 Mt in 2016 (Latvia produced 8.2 Mt and Lithuania 13.7 Mt in 2016) (European Commission, 2018a; Olivier, et al., 2016). In 2017 Estonian total industrial CO_2 emissions registered in EU Emission Trading System (14.7 Mt) have increased for 9.2%, compared to 2016 (EU Emission Trading System, 2018).

By 2050, Estonia is aiming to decrease greenhouse gas emissions (GHGE) by nearly 80% compared to the level of 1990. To reach these targets, by 2030 about 70% of GHGE and by 2040 about 72% of GHGE should be reduced. If the policies are implemented, then by 2050, GHGE will have decreased the most in the energy sector and industry (by 67%) (Keskkonnaministeerium, 2017).

The cement industry is one of the key-sectors for the reduction of CO_2 emissions after the energy sector (around 5.5% of the global emissions are from the cement production). Cement production is responsible for about 27% of global anthropogenic CO_2 emissions from industrial sources around the world (IEA, 2009). It is the second largest industrial contributor to CO_2 emissions worldwide, responsible for the emissions of about 2 Gt CO_2/year and according to the ETP (Energy Technology Perspective) Baseline scenario, it is expected to rise to about 2.5 Gt CO_2/year by 2050 (IEA, 2011). According to IEA and ZEP studies, cement industry should contribute to the largest CO_2 emission reduction with carbon capture and storage in Europe (ZEP, 2013).

Carbon Capture and Storage (CCS) technology is an efficient tool to mitigate climate change and to allow continue the use of fossil fuels in energy sector and industry. CCS is a technology that can capture up to 90% of the carbon dioxide (CO_2) emissions produced from the use of fossil fuels in electricity generation and industrial processes, preventing the carbon dioxide from entering to the atmosphere (CCSA, 2018). CCS has been proposed as a critical technology for the avoidance for future CO_2 emissions (Paul, et al., 2017). CCS could account for about 19% of the necessary emission mitigation (International Energy Agency, 2010).

CCS includes CO_2 capture, transport and CO_2 Geological Storage (CGS). Geological conditions in Estonia are unsuitable for CGS because of the shallow sedimentary basin and potable water availabe in all known aquifers. The most suitable conditions for CGS in the Baltic Region (Estonia, Latvia and Lithuania) are available in Latvia (Šliaupa, et al. 2008; Shogenova, et al. 2009a; Shogenova, et al. 2011a).

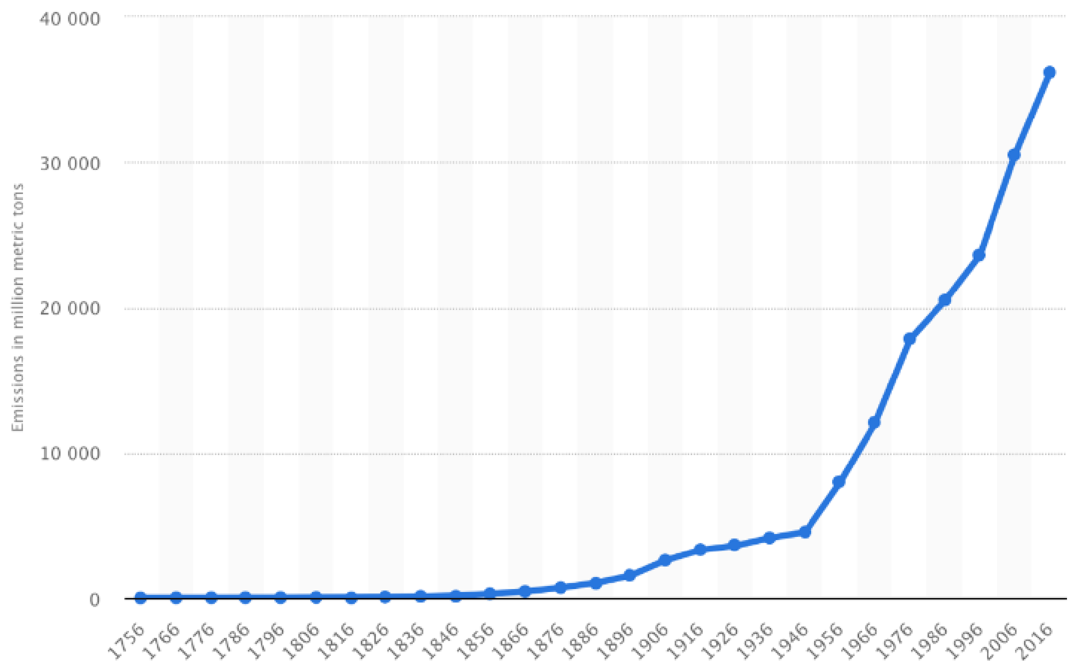

Figure 1. Historical carbon dioxide emissions from global fossil fuel combustion and industrial processes from 1756 to 2016 (in Mt, (Statista, 2018)

The main and only one cement producer in Estonia, Kunda Nordic Cement Plant (KNC), is one of the eight Estonian largest CO_2 emitters. The main goal of this study is to compose CCS scenario for the cement industry in Estonia, represented by KNC, to analyse its feasibility, permitting to Estonia to reach its strategic climate targets. Until now cement industry was not involved in any of the CCS scenarios or projects studied in the Baltic States. But in Europe the first CCS project for the Brevik Cement Plant is developing now in Norway (Brevik, 2017).

2. CARBON CAPTURE AND STORAGE

The CCS chain consists of three parts: capture of carbon dioxide, transport of the carbon dioxide and storing the CO_2 emissions underground in depleted oil and gas fields or deep saline aquifers (CCSA, 2018). Simplified picture of capture, transport and storage of CO_2 is shown in Figure 2.

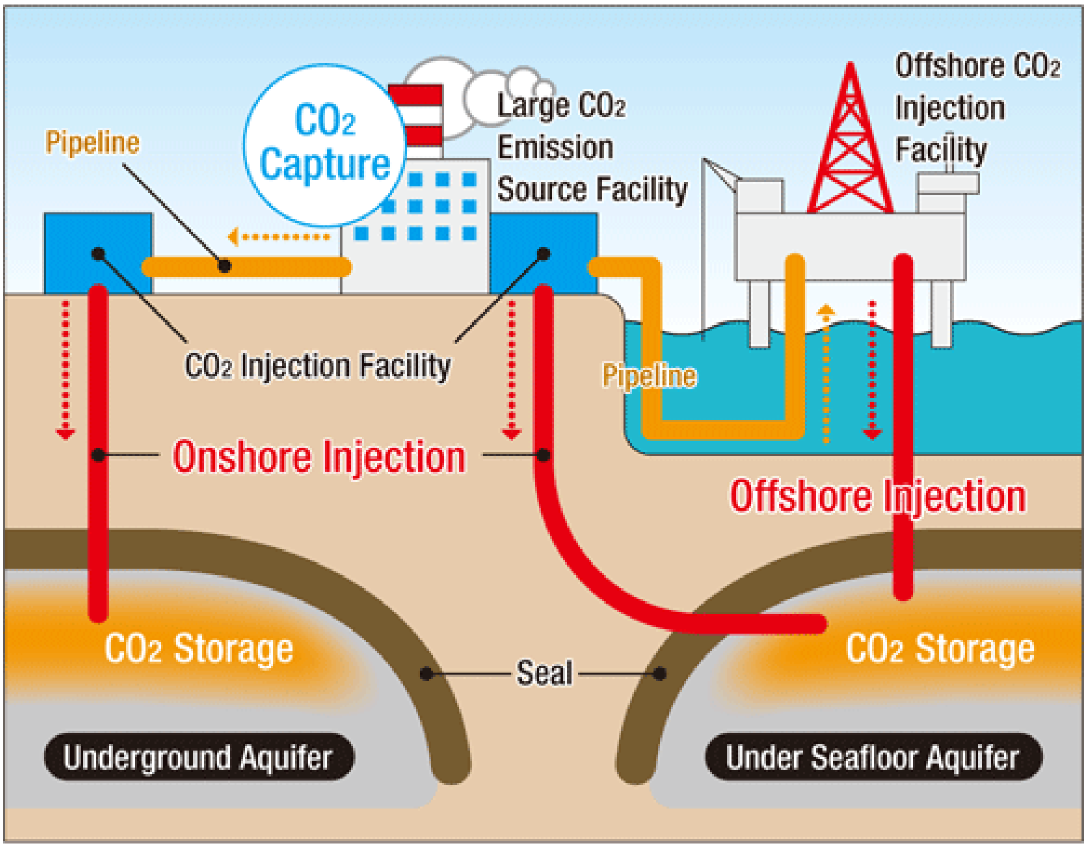

Figure 2. Carbon Capture and Storage (Alternative Energy Tutorials, 2018)

The first stage in the CCS process is the capture of CO_2 released during the burning of fossil fuels, or as a result of industrial processes such as production of cement, steel or in the chemical industry (CCSA, 2018). Three main distinctive technologies of carbon capture for the power sector can be summarized as post-combustion, pre-combustion and oxyfuel capture (Paul, et al., 2017).

In post-combustion capture, CO_2 is removed from the flue gas of a power plant or other industry activity after the ordinary combustion. This is done using a chemical process. After that the CO_2 can then be released from the solvent by increasing the temperature (Gibbins & Chalmers, 2010). In pre-combustion capture the fossil fuel is not combusted in its original form, it will be undergoing high temperature gasification and oxidation with oxygen and steam to produce a syngas mixture of carbon monoxide, hydrogen, water and carbon dioxide. CO will be converted to hydrogen and CO_2. Separation of the hydrogen from the CO_2 can use a physical solvent, membrane or pressure swing process. The remaining hydrogen can be used to generate electricity or other purposes (Paul, et al., 2017). Oxyfuel capture is a post-combustion capture process, however it differs from standard post-combustion capture in that the combustion of the primary fuel takes place in pure oxygen rather than air (Paul, et al., 2017). This involves the process of burning the fuel with pure oxygen, in order to control the temperature of the flame, some of the flue gas is recycled back into the furnace.

Oxyfuel combustion is one of the leading technologies considered for capturing CO_2 from the power plants (Stanger, et al., 2015). Calcium looping (or CaL) is recognized as one of the promising technologies for CO_2 capture in cement plants (IEA, 2011; Vatopoulos & Tzimas, 2012; European Cement Research Academy, 2012). It is considered as one of the most efficient CO_2 capture technologies (Perejón, et al., 2016). With calcium looping technology CO_2 will be separated using carbonation reaction of CaO, after the CaO has reached its ultimate conversion to $CaCO_3$ by reaction with CO_2, it could be regenerated thermally by heating at its calcination temperature after which pure CO_2 is released (Sivalingam, 2012). Today, Horizon 2020 project CLEANKER is focusing to demonstrate the feasibility of the intergrated Calcium looping concept at industrial picture in a demo system by the Buzzi Unicem cement plant in Vernasca, Italy (CLEANKER, 2018).

Transportation and storage infrastructure is required to remove captured CO_2 from power plants and other industrial installations and to inject CO_2 into deep saline aquifers, depleted oil and gas fields (Banks, et al., 2017). The technologies involved in pipeline transportation are similar to those used extensively for transporting natural gas, oil and many other fluids around the world (CCSA, 2018). CO_2 is transported through pipelines, ships and tanker trucks. Pipeline transport is considered to be the cheapest and reliable method of tansporting CO_2 for onshore capture sites (Svensson, et al., 2004). In some cases it may be possible to re-use existing but redundant pipelines (CCSA, 2018). For example, U.S. has a vast network of CO_2 pipelines (estimately 3 900 miles of CO_2 pipelines (Forbes, et al., 2008) that has been developed over more than four decades for use in oil production in enhanced oil recovery process (Banks, et al., 2017).

There are over hundred sites all around the world where CO_2 is being injected underground as part of normal oilfield operations (Blunt, 2010). Suitable storage formations can occur in both onshore and offshore settings and each type of geological formation presents variety of oppurtunities. CO_2 could be stored into saline formations, oil and natural gas reservoirs, unmineable coal areas, organic-rich shales and basalt formations (NETL, 2015). Depleted oil and gas reservoirs are most likely to be used for early projects, as extensive information from geological and hydrodynamic assessments is already available (CCSA, 2018). The main challenge is how to design a storage site which can hold the CO_2 underground for thousands of years and how to handle the large volumes to make an impact on global CO_2 emissions (Blunt, 2010). CO_2 can be stored underground as a supercritical fluid. The CO_2 has some properties like a gas and some properties like a liquid as a supercritical state (NETL, 2015). CO_2 will be pumped underground through a well into porous geological formations. The CO_2 will be injected into sedimentary rocks, which is composed of sand, crushed sea shells or precipitated calcium carbonate. They are good for storage because they contain pores, which connect allowing fluids to flow through (Blunt, 2010). There are many barriers in between the surface and the reservoir (Global CCS Institute, 2018). Once injected, the CO_2 moves up through the storage site until it reaches the impermeable layer, which cannot be penetrated by CO_2. The layer is knows as cap rock which traps the CO_2. This storage mechanism is called “structural storage”. Some of the CO_2 gets trapped into the pore spaces of the rock, this mechanism is called “residual storage” (CCSA, 2018). Also, injecting CO_2 into depleted oil and gas fields for enhanced oil recovery (EOR), which results also in hydrocarbon recovery, generates income to pay off the costs of capture and storage (Lake, 1989). Over time the carbon dioxide stored in a geological formation will begin to dissolve into the surrounding salty water. This makes the salty water denser and it begins to sink down to the bottom of the storage site. This is known as “dissolution storage”. Finally “mineral storage” occurs when the carbon dioxide held within the storage site binds chemically and irreversibly to the surrounding rock (CCSA, 2018).

There are now over 17 large-scale carbon capture and storage facilities operating globally. Current CO_2 capture is 37 Mt per year, which is equivalent to removing 8 million cars from the road. More than 220 Mt of anthropogenic CO_2 has already been safely and permanently injected deep underground (Global CSS Institute, 2017).

There are two facilities operating in Norway today, both operated by the Norwegian oil company Statoil. The Sleipner CO_2 Storage facility was the first in the world to inject CO_2 into a dedicated geological storage (Global CCS Institute, 2018). The CO_2 is captured from natural gas production on the Norwegian shelf and it is reinjected into sub-seabed formations (Cornerstone, 2017). Approx. 0.85 Mt of CO_2 is injected every year and 17 Mt has been injected since the beginning (Global CCS Institute, 2017). The Snøhvit CO2 Storage facility is part of the development of gas fields in the Barents Sea, offshore Norway (Global CCS Institute, 2018). 5-6% of CO_2 from the well stream is separated before the gas is chilled to produce liquefied natural gas (LNG). This CO_2 is transported back to the Snøhvit field by pipeline and injected into a sub-seabed formation (Cornerstone, 2017). More than 4 Mt of CO_2 has been stored since 2008 (Global CCS Institute, 2018).

On behalf of the cement industry in Europe a small case test was held in test centre at Norcem Brevik. Four post-combustion CO_2 capture technologies were tested. The test kicked off in May 2013 and was scheduled for 3,5 years. Partners are Norcem, HeidelbergCement and ECRA (European Cement Research Academy, 2012). CO_2 from capture plant in Eastern Norway will be transported by ship to an intermediate storage site in Western Norway. After that the CO_2 will be transported by pipeline to a storage site in the North Sea. Statoil with partners Shell and Total are developing the storage concept. The Smeaheia area has been selected for CO_2 storage, which is 50 km from the coast. CO_2 will be stored in sandstone formation which is overlain by the shale formation (Faramarzi & Brigtsen, 2018).

3. GEOLOGICAL BACKGROUND OF THE REGION

Within the East European Craton the Precambrian crystalline crust is exposed only in Baltic and Ukrainian shields and in small areas of Belarus and south western Russia. Everywhere else, the East European Craton is covered by the Late Proterozoic and Phanerozoic sedimentary deposits of the Russian Platform (Bogdanova, et al., 2005).

The Baltic Basin (Figure 3) is a large marginal synclinal structure in the southwestern part of the East European Craton. The structure is 700 km long and 500 km wide (Paškevičius, 1997). Most of its bottoms are built made up of low- and unmetamorphosed sedimentary rocks beneath a cover of Quaternary deposits (Beckholmen & Tirén, 2008). Cambrian sandstones are prospective gas reservoir rocks in the Baltic region. The depth of the sandstones, that are over 800 m, are located in the Baltic Depression. Most favourable conditions of CO_2 storage are in central and western Latvia (Shogenova, et al., 2011a)

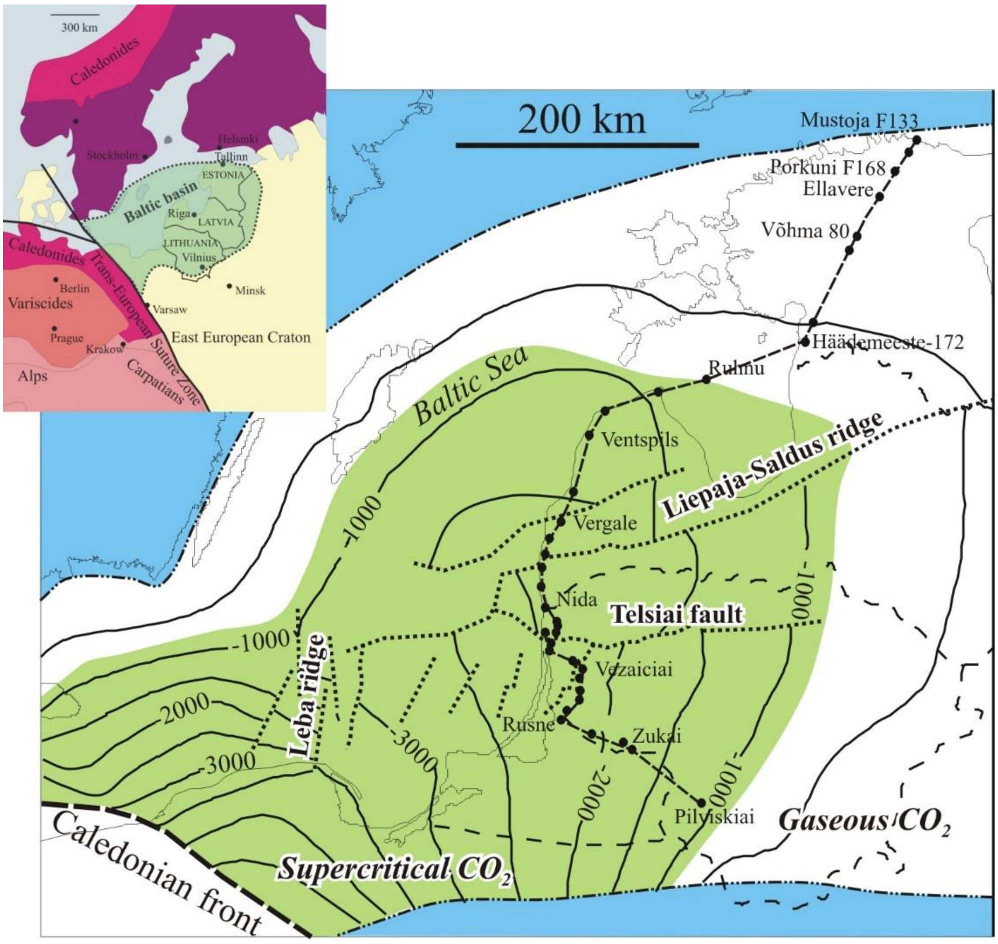

Figure 3. Structure map of the Baltic Basin (modified after Šliaupa et al. 2008). The contour lines indicate the depth of the top of the Cambrian. The dotted lines denote major faults. The pressure and temperature fields of gaseous (white) and supercritical (hatched) state of CO_2 are shown. The line of the geological cross section shown in Fig. 4 is indicated. (Figure 1, Shogenova, et al., 2009a)

Geological conditions in Estonia are not suited for carbon capture and storage because of relatively shallow sedimentary basin (thickness is less than 800 m) and the water in all known aquifers is potable (Shogenov, 2015). The thickness of sediments in Lithuania is up to 2 300 m, although the estimated CO_2 storage capacity of 116 local structures in Lithuania is too small and therefore not suitable for gas storage. Although, two structures have the capacity of CO_2 over 1 Mt (Shogenova, et al., 2011b). In Poland the best formations for storage are found in Polish Lowlands, where Lower Cretaceous, Lower Jurassic and Lower Triassic sedimentary rocks are thick enough with good reservoir properties (Shogenova, et al., 2011b). In Sweden sector of the Baltic Basin the thickness of sedimentary cover ranges from 0 m up to 1 500 m. The most suitable reservoirs have been identified as the Cambrian Faluden, När and Viklau sandstone units (Sopher, et al., 2014). The bedrock in Finland is composed mainly by crystalline and low porosity rock types, which lack a potential for CO_2 storage in deep saline aquifers. The nearest identified and demonstrated storage sites for Finland could be in the North Sea, Polish-German basin or Baltic basin (CCSP, 2016). Norway has suitable geological formations on the Norwegian Continental Shelf. Saline aquifers has been identified and many dry-drilled structures proven. CO_2 can be stored in producing oil fields, depleted oil and gas fields (Halland, et al., 2013). The Danish Basin is characterized by an up to 9 km thick sedimentary rocks of Late Paleozoic to Cenozoic age. The succession is deeply truncated and with faults. 1 000 - 1 900 m deep structures are in the top of Early Jurassic and Lower Triassic reservoir sandstone Gassum, Bunter and Skagerrak formations (Shogenova, et al., 2011b). Russia's geological structure in the Kaliningrad region is located on the East European Craton. The neighboring regions with Estonia are part of the Moscow Syneclise/Basin. The thickness of the Middle Cambrian loosely cemented sandstones is 40 - 140 m and are situated at the depth of 800 - 1 200 m (Shogenova, et al., 2011b).

Since the present work concentrates on the geological structures that are situated in Latvia, then the geological situation of Latvia is described in details as follows. Latvia is situated in the area where the Baltic Syneclise, the Latvian Saddle and the southern slope of the Baltic Shield are singled out on top of the crystalline basement and under the sedimentary cover. It forms interregional structures. The sedimentary basin that is overlaying the block-type crystalline basement is 300 - 600 m thick in north-eastern Latvia and 1 900 m in south-western Latvia (LVĢMC, 2007). The Baltic Basin includes the Upper Proterozoic, Palaeozoic, Mesozoic and Cenozoic deposits. In this succession four structural complexes are distinguished, separated from each other by angular unconformity (Shogenova, et al., 2009a). The Latvian sedimentary cover is subdivided into the Baikalin, Caledonian, Hercynian and Alpine structural complexes (Figure 4). The structures are divided from each other by angular unconformity (LVĢMC, 2007).

The Timanian (Baikalin) structural complex, that occurs only in the eastern Latvia and in a small area in the north-western Latvia (LVĢMC, 2007), is composed of up to 200 m thick Ediacaran and up to 120 m thick lowermost Cambrian terrigenous rocks (Shogenova, et al., 2009a). The Caledonian structural complex includes the rest of the Cambrian and the Ordovician, Silurian and Devonian successions (Shogenova, et al., 2009a). The thickness of the rocks vary from 60 m in north-eastern Latvia and up to 1 000 m in the south-western areas (LVĢMC, 2007). Cambrian rocks are represented by up to 170 m thick terrigenous rocks, Ordovician rocks are represented by 40 - 250 m thick clayey carbonate rocks (Shogenova, et al., 2009a). The complex is known by varying structures, with different components that include many faults, that make the complex favourable for geological trapping (LVĢMC, 2007). The Variscan (Hercynian) structural complex includes almost the entire Devonian (with exception of the oldest rocks) and the lowermost Carboniferous siliciclastic-carbonaceous rocks (LVĢMC, 2007). The Devonian sequence consists of up to 1 100 m thick marly-carbonaceous rocks with alternating sandstones (Shogenova, et al., 2009a).

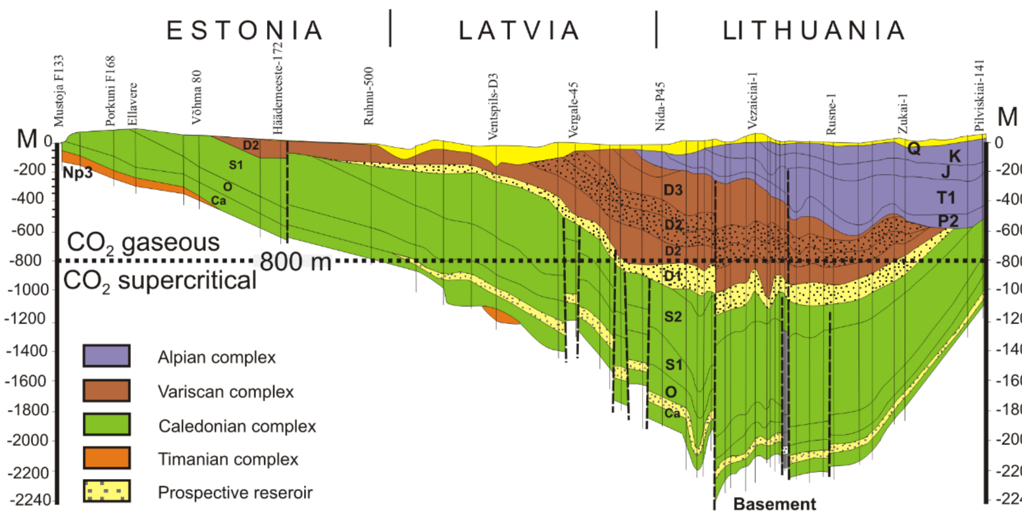

Figure 4. Geological cross section across Estonia, Latvia, and Lithuania (modified after Sliaupa et al. 2008). Major aquifers are indicated by dots. Np3, Ediacaran (Vendian); Ca, Cambrian; O, Ordovician; S1, Lower Silurian (Landovery and Wenlock series); S2, Upper Silurian (Ludlow and Pridoli series); D1, D2, and D3, Lower, Middle, and Upper Devonian; P2, Middle Permian; T1, Lower Triassic; J, Jurassic; K, Cretaceous; Q, Quaternary. (Figure 2, Shogenova, et al., 2009a)

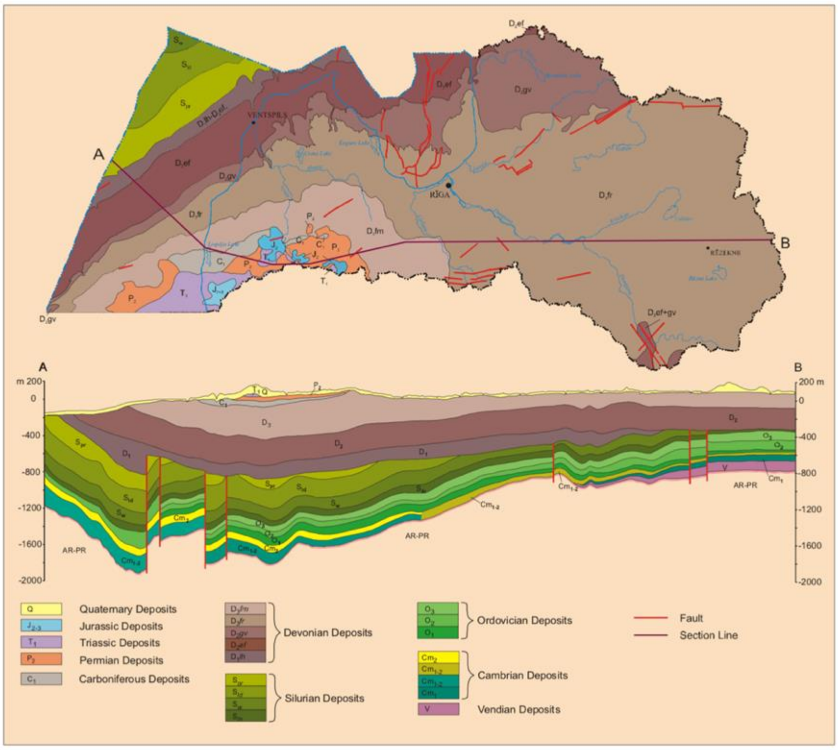

Figure 5. Simplified bedrock geological map and geological section of Latvia (Figure 2, (LVĢMC, 2007)

The Alpine structural complex includes Permian, Triassic and Jurassic deposits, which are up to 130 m thick. The structure occurs in south-western areas of Latvia (LVĢMC, 2007). Permian succession consists of carbonates and evaporates, Triassic consists of mudstones, Jurassic consists of sandstones, claystones, limestones, glauconites, marls and siliclastic rocks. The bedrock is covered by Quaternary sediments varying in thickness from a few centimetres to a few hundred meters (Shogenova, et al., 2009a).

More detailed cross-section of Latvia is shown in Figure 5.

4. CO_2 STORAGE CAPACITY OF THE BALTIC SEA REGION

It is estimated that the global potential amount for carbon capture and storage is from 220 to 2 200 Gt CO_2, which means that carbon capture and storage contributes 15 - 55% of the total mitigation effort worldwide until 2100, averaged over a range of baseline scenarios (Metz, et al., 2005). It is reported that total conservative capacity of CO_2 storage in Europe is around 117 Gt (approx. 25% is in offshore Norway), of which 96 Gt is estimated in deep saline aquifers, 20 Gt in hydrocarbon fields and 1 Gt in un-mineable coal fields (Vangkilde-Pedersen, et al., 2009a). The storage capacity of the Baltic Sea Region has been estimated as 16 Gt CO_2 (Vernor, et al., 2013). Storage capacity estimates for individual structures for the Baltic Sea regions include 760 Mt for the Latvian structures and the Dalders structure, 9.1 Mt for the structures in Poland, 31 Mt in Lithuania and 170 Mt CO_2 in Kaliningrad (CCSP, 2016).

In the Baltic Region the suitable structure that has the necessary depth (>800 m) is the Baltic Depression. The geological conditions that suits the best are located in central and western Latvia, where at least 16 anticline structures has been reported with CO_2 storage capacity of 2 - 74 Mt each (Figure 6, Shogenova, et al., 2011b). Structural trapping can be applied for CO_2 storage in the anticlinal structures in Latvia (LEGMC, 2007; Shogenova, et al., 2009a). In total the estimated capacity of onshore structures in Latvia is 400 Mt and for the offshore structures it was estimated as 300 Mt of CO_2 (Table 1, Šliaupa, et al., 2013). Two onshore geological structures (South-Kandava and Dobele) and two offshore structures (E6 and E7) in Latvia for CGS were estimated in detail in the research published in 2013 (Shogenov, et al., 2013). It was reported that average storage potential of the Latvian E6 and E7 offshore structures are respectively 377 Mt and 34 Mt (Shogenov, 2015), which is higher than previously reported capacity of all onshore Latvian structures (400 Mt, Šliaupa, et al. 2013).

The average estimated effective porosity of the largest 16 onshore structures (Table 2) of Latvian Cambrian sandstones is 20 - 25%, permeability is 300 - 700 mD, the depth of the reservoir is within the range of 900 - 1 100 m and thickness 25 - 70 m (Shogenova, et al., 2009a; Shogenova et al., 2011b). It is considered that geological structures that are suitable for underground gas storage are one of the most important resources in Latvia (LVĢMC, 2007). Latvia has a potential to accommodate for about 200 years of its CO_2 emissions (Šliaupa, et al., 2013).

Geological conditions in Estonia are unsuitable for carbon capture and storage because of the shallow sedimentary basin and all the water in aquifers is potable (Shogenov, 2015). Evaluation of the capacity of 116 Lithuanian local structures of the Cambrian aquifer (made before 2017) showed that the two largest structures have the storage capacity only 8 Mt and 21 Mt (Shogenova, et al., 2009a; Shogenova et al., 2011b; Šliaupa, et al., 2013). The EOR option is considered as a prospective CO_2 application technique for the region, since the Baltic Basin represents as a proven hydrocarbon province (Figure 7). In total, about 40 hydrocarbon accumulations have been discovered in offshore Poland (7 Mt oil-fields and 16 Mt gas-fields) and Polish sector of the Baltic Sea, Kaliningrad district (26 Mt onshore and 7 Mt offshore), Lithuania (5.7 Mt), Latvia and Gotland (Brangulis, et al., 1993; Šliaupa, et al., 2004; Pikulski, et al., 2010; Šliaupa, et al., 2013). In Lithuania CO_2 EOR action was taken by “Minijos Nafta” to investigate exploitation of the ROZ (residual oil zone; otherwise not exploitable) in the Cambrian sandstones in three oil exploitation wells using CO_2 in 2013 and 2015. Obtained results showed high oil recovery percentage using CO_2 and about 100 Mt CO_2 storage potential in the west Lithuanian Gargzdai zone. The recoverable additional oil resources can reach 100 million barrels of oil (CGS Baltic seed project (S81), 2017).

Figure 6. Prospective structures in the Cambrian aquifer (CO_2 storage potential exceeding 2 Mt) and Inčukalns underground natural gas storage (UGS) in Latvia. The dashed line shows gas pipelines (modified after Shogenova, et al., 2009a)

Table 1. CO_2 storage capacity reported for Latvian structures

Year	Onshore		Offshore		Reference
	No of structures	Capacity, Mt	No of structures	Capacity, Mt	
2008	15	300	-	-	Šliaupa, et al., 2008
2009	16	404	-	-	Shogenova, et al., 2009a; Shogenova, et al., 2009b
2013	16	400	16	300	Šliaupa, et al., 2013

The Russian Federation, which is not yet been systematically studied, is extremely rich in oil and gas deposits and is likely to hold a large potential for CO_2 storage (CCSP, 2016). The Russian Federation is accounting for 13% of the world oil reserves and more than 30% of world gas reserves. The north-western region has 10% of all Russian oil and gas reservoirs and about 50% of hydrocarbon fields in NW Russia has been depleted and could be an interest for enhanced oil and gas recovery. BASTOR project concluded that Kaliningrad sector of the Baltic Sea could have good capacity for storage in the Cambrian and Devonian sandstones (CCSP, 2016).

Table 2. Physical parameters of the Latvian structural traps (Shogenova, et al., 2009a)

Structure	Depth, m	Thickness, m	Area, km^2	CO_2 storage capacity, Mt
Aizpute	1096	65	51	14
Blidene	1050	66	43	58
Degole	1015	52	41	21
Dobele	950	52	67	56
Edole	945	71	19	7
Kalvene	1063	45	19	14
Liepaja	1072	62	40	6
Luku-Duku	937	45	50	40
N. Kuldiga	925	69	18	13
N. Ligatne	750	50	30	23
N.Blidene	920	40	95	74
S.Kandava	983	25-30	69	44
Snepele	970	30	26	17
Usma	975	50	20	2
Vergale	981	65	10	5
Viesatu	1020	50	19	10
Total				404

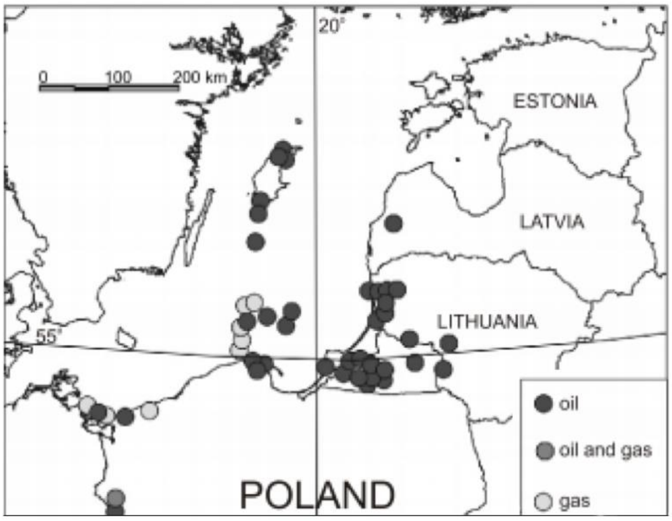

Figure 7. Hydrocarbon fields considered for CO_2 storage in the Baltic Basin in Poland and the Baltic States (updated from Fig. 3, (Šliaupa, et al., 2013)

Since the territory of Finland is not covered by sedimentary cover (Shogenova, et al., 2011b), then the possibility to find suitable CO_2 storage sites in Finland is highly unlikely (CCSP, 2016). In Sweden about 40 structures were identified for the Faludden, När and Viklau sandstone units, but only 12 structures are with storage capacity that is over 1 Mt. Storage potential within the Swedish sector of the Baltic Sea is limited in structural closures. The most suitable structural trap is the S41/Dalders structure with estimated low, mid and high storage capacities of 85 Mt, 145 Mt and

224 Mt, respectively (Sopher, Juhlin, & Erlström, 2014). The CO_2 storage capacity for the Baltic Sea Basin is shown in Table 3.

Table 3. CO_2 storage capacity reported for the Baltic Sea Basin

Country	CO_2 storage capacity reported (Mt)			Reference
	Onshore	Offshore	EOR	
Estonia	0	0	0	(Shogenova, et al., 2011b)
Latvia	400	300	-	Šliaupa, et al., 2013
Lithuania	29	0	5.7 /100	Šliaupa, et al., 2013; CGS Baltic seed project (S81), 2017
Finland	0	0	0	CCSP, 2016
Sweden	0	145	-	Sopher, et al., 2014
The Russian Federation (Kaliningrad)	-	-	33	Šliaupa, et al., 2013

Denmark's storage capacity is based on evaluation of 11 individual structural traps. The final GeoCapacity Public report gives the value of effective storage capacity of 2 756 Mt of CO_2 (Vangkilde-Pedersen, et al., 2009a; Vangkilde-Pedersen, et al., 2009b)

Total estimated storage capacity of the Jurassic sandstone formations in the Norwegian Sea is 5.5 Gt (Halland, et al., 2013). The storage capacity of the Utsira sandstone formation, a stratigraphic trap of the first in the world Slepiner storage site in the North Sea, is estimated approximately as 15 Gt (Halland, et al., 2011).

From the ranking of potential Swedish, Danish and Norwegian storage units and structures, 18 storage sites (10 Norwegian, 5 Danish and 3 Swedish) have been selected as the best potential CO_2 storage options in deep saline aquifers. The total estimated theoretical storage capacity for the top ranked sites is around 86 Gt, which should be sufficient to store the equivalent cumulative mass of the current annual CO_2 emissions from Nordic industry sources over more than 500 years (NORDICCS, 2016).

5. FEASIBILITY STUDY FOR CO_2 CAPTURE, TRANSPORT AND STORAGE SCENARIO

5.1 Data and methods

5.1.1 Industrial CO_2 emissions

The data for industrial CO_2 emissions were taken from the European Union Emissions Trading System (EU Emission Trading System, 2018). The reported data include 3 phases: Phase 1 (2005 - 2007), Phase 2 (2008 - 2012) and Phase 3 (2013 - 2020). For example, in phase 3 the CO_2 emissions reported in 2016 contains the summarized emissions of 2013 - 2016, year 2017 contains the summarized emissions of 2013 - 2017 etc. To calculate CO_2 emissions produced in 2017 only, the emissions reported in 2016 column (sum of 2013 - 2016) must be subtracted from the emissions shown in 2017 column (sum of 2013 - 2017). As a common rule of EU ETS, new data for the previous year (2017) were added at the end of April 2018.

The map of the large CO_2 emission sources in Estonia (Figure 8) was composed using Adobe Photoshop CS6 version 13.0.4. The base map data of the Southeastern Estonia was downloaded from the Google Maps 2018.

5.1.2 Kunda Nordic Tsement Plant

The sustainability report of AS Kunda Nordic Tsement is issued every year in the spring. The report is called Tsemendiwabrik (Tsemendiwabrik, 2014, 2015, 2016). The report issued in 2017 covers data for the year 2016. All the reports contain a table, describing the amounts of production, fuels used for production, produced emissions, waste materials, etc. (Kunda Nordic Tsement, 2018).

5.1.3 Blidene and North Blidene structures

There is limited boreholes drilled in the area of the North Blidene and the Blidene structures. There are four boreholes (Ciecere 10, Blīdene 5, Saldus RM-5 and Kuiļi 9) drilled in the area of the North Blidene structure and one borehole (Stūri 8) in the area of the Blidene structure (Карпицкий, 1963; Pomeranceva, 2003). The borehole data with the locations of geological fault lines were collected from the University of Latvia database used in (Popovs, 2015). Three another boreholes, drilled at the further distance, belong to Luku-Duku structure (Skrunda P-27, ~10 km east from the North Blidene structure), Dobele structure (Dobele 3, ~9 km southeast from the Blidene structure) and the third one is Remte 3 (~5 km north from the North Blidene structure).

Petrophysical data of rock samples were collected from the LEGMC report (Pomeranceva, 2003). There are two samples collected from the Deimena Formation, one from the borehole Saldus RM-5 (North Blidene) and one from the borehole Stūri 8 (Blidene). Five samples were collected from the Zebre Formation, one from the borehole Blīdene 5 (North Blidene) and four from the borehole Saldus RM-5 (North Blidene).

Horizontal and vertical permeabilities were measured and shown in the LEGMC report (Pomeranceva, 2003). Permeability used in this thesis was calculated as an average from the reported horizontal and vertical permeabilities (Table 8).

Only total porosity was available for the borehole Stūri 8. Effective porosity for this borehole was derived from the borehole Saldus RM-5. The difference between the total and effective porosity of the borehole Saldus RM-5 was calculated (eight samples) and the result was subtracted from the total porosity of the borehole Stūri 8.

Structural and tectonic maps based on geophysical and drilling data were used from (Брангулис, 1979). The logging and drill core data were used from (Карпицкий, 1963).

The data used for the modelling, were collected from the University of Latvia database (Popovs, 2015), the Blidene and the North Blidene structures map from (Vangkilde-Pedersen, et al., 2009a) and from the structural and tectonics maps (Брангулис, 1979). The data were collected into the table using the Microsoft Excel Version 15.13.3. From there, comma separated values (.CSV files) were generated for further modelling of the cross-sections and maps.

The cross-sections and the map of the structures were composed in Bentley PowerCivil for Baltics V8i (SELECTseries 2) version 08.11.07.494. Regional base surface of the top of the Cambrian Deimena Formation and its location within the studied structures (Figures 10 - 11) were considered for the modelling of the structure map of the North Blidene and Blidene. Regional base surface was composed based on the borehole data available in the region (boreholes Skrunda P-29, Ciecere 10, Saldus RM-5, Kuiļi 9, Kandava 27, Remte 3, Blīdene 5, Stūri 8, Irlava 87, Dobele 2, Dobele 3 and Īle 1) from Popovs, 2015. Surface of the top of the Cambrian Deimena Formation within the studied structures was composed based on the boreholes located within or near the structures (boreholes Skrunda P-29, Ciecere 10, Saldus RM-5, Blīdene 5, Kuiļi 9, Remte 3 and Stūri 8 from (Popovs, 2015). Contour lines and faults, constructed using seismic interpretation data, were gathered from Figure 2.3 from (Vangkilde-Pedersen, et al., 2009a) and the structural and tectonic maps published earlier (Брангулис, 1979). The areas of the structures were also calculated in the previously mentioned program.

The contour map and 3D structure map were composed in the Golden Software Surfer 15. The data files for Surfer 15 were interpreted in the Bentley PowerCivil for Baltics V8i (SELECTseries 2).

5.1.4 Calculation of storage capacity

The storage capacity of the structural trap was estimated by the formula (Vangkilde-Pedersen, et al., 2009b):

$$M_{CO2} = A \times h \times NG \times \varphi \times \rho_{CO2r} \times S_{eff},$$

Where
M_{CO2} is storage capacity (kg)
A is the area of an aquifer in the trap (m^2)
h is the average thickness of the aquifer in the trap
NG is an average net to gross ratio of the aquifer in the trap (percentage of effective thickness of the reservoir compared to its bulk thickness)
φ is the average porosity of the aquifer in the trap

ρ_{CO2r} is the in situ CO_2 density at reservoir conditions and
S_{eff} is the storage efficiency factor (for trap volume).

A different S_{eff} is considered for each structure based on its reservoir properties and different methods are employed to estimate these factors (Shogenov, 2015). According to (Vangkilde-Pedersen, et al., 2009b), S_{eff} of a high quality reservoir, that is an open reservoir without faults, is 40%. S_{eff} of a high quality reservoir with faults on two sides is 20%, with faults on three sides 10% and with faults on all sides 3 - 5%. The North Blidene structure has fault on one side, therefore the S_{eff} value is 30% for optimistic approach. The Blidene structure is closed with faults on all sides, therefore the S_{eff} value for optimistic approach is 5%.

The conservative approach for estimating the capacity was also considered. The S_{eff} value for conservative approach for the North Blidene structure is considered 4% and for the Blidene structure is considered 3% according to the approach by US Department of Energy report (US DOE, 2008) using Monte Carlo simulation. According to the approach, the S_{eff} values are between 1% and 4% for deep saline aquifers for a 15% and 85% confidence rate. Optimistic and conservative capacities were calculated with minimum, maximum and average values (min/max/mean) of porosity, determined using measured data that were available.

5.2 Large industrial CO_2 producers in Estonia

Industrial CO_2 emissions in 2017 were reported from 45 sources out of 66 registered in the European Union Emission Trading System (EU Emission Trading System, 2018). Eight sources (Table 4) had emissions larger than 100 000 tonnes, including three sources that had emissions larger than 1 Mt.

Table 4. Large industrial CO_2 emission sources in Estonia in 2016 - 2017 (EU ETS)

Source	Emissions in 2016 (Mt)	Percent of total emissions	Emissions in 2017 (Mt)	Percent of total emissions	Increase in emissions 2017-2016 (Mt/%)
Eesti Elektrijaam	7.94	62.22%	8.36	56.84%	0.42/5.3
Balti Elektrijaam	1.63	12.75%	1.60	10.90%	-0.03/-1.8
Auvere Elektrijaam	1.05	8.21%	1.36	9.25%	0.31/29.5
Enefit Õlitööstus	0.65	5.11%	0.81	5.54%	0.16/24.6
VKG Oil Petroter-3000 tehas	0.57	4.43%	0.59	4.04%	0.02/3.5
OÜ VKG Energia Põhja SEJ	0.45	3.54%	0.60	4.08%	0.15/33.3
AS Kunda Nordic Tsement	0.33	2.60%	0.56	3.81%	0.23/69.7
Kiviõli Keemiatööstuse OÜ	0.15	1.15%	0.15	0.99%	0/0
Total	12.76		14.03		1.27/10.0

Total verified industrial CO_2 emissions in Estonia registered in EU ETS in 2017 were 14 703 667 Mt. Eight sources (Figure 8) with emissions larger than 100 000 tonnes formed together 95.44%

(14.03 Mt) of total (14.7 Mt) emissions from all the 45 sources that presented their emissions to EU ETS. Eesti Elektrijaam, producing the highest emissions throughout the years, formed 56.8% of total industrial CO_2 emissions produced in Estonia. Industrial CO_2 emissions from all the sources in Estonia in 2017 increased for 9.2% compared to year 2016 (Table 5).

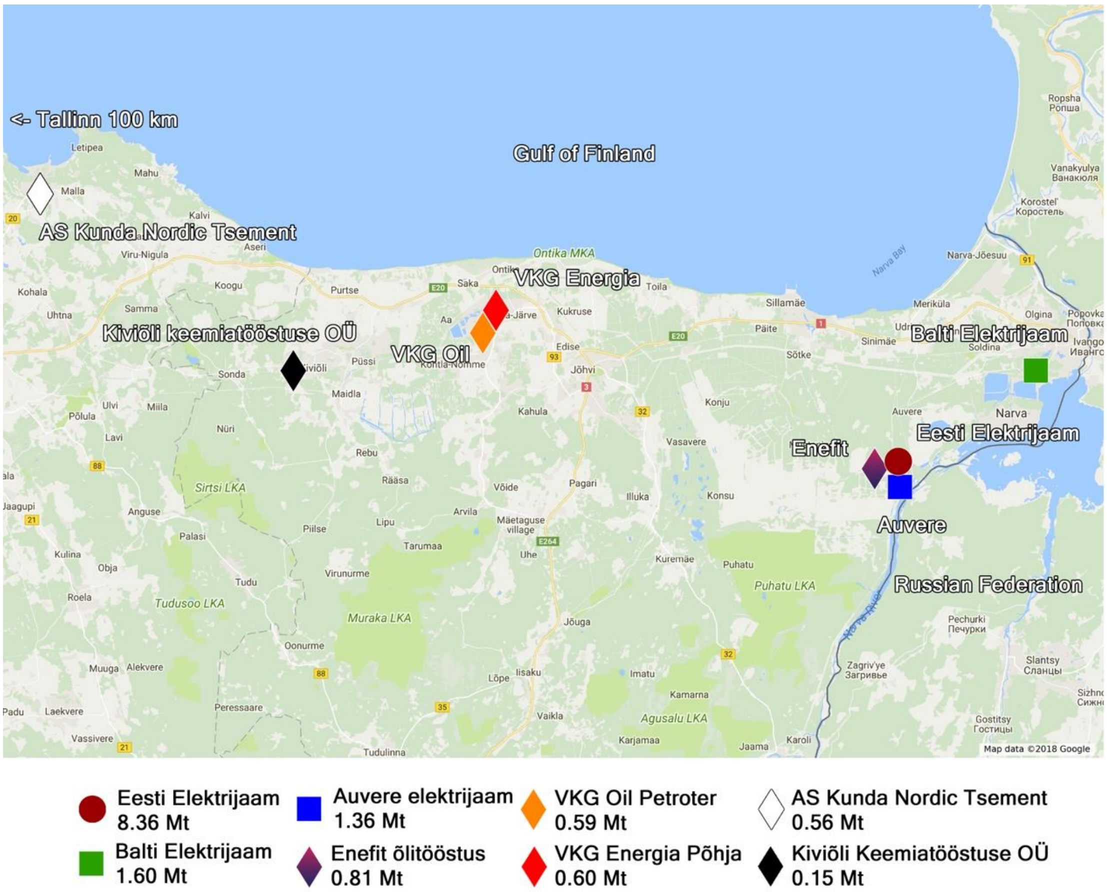

Figure 8. Map of large industrial CO_2 emissions (> 0.1 Mt CO_2) in Estonia in 2017. The map is composed using Adobe Photoshop CS6 software. The base map is from the Google Maps, 2018.

Table 5. Change in total emissions from all registered in ETS producers as a percentage of the previous year (EU ETS)

	2014	2015	2016	2017
Estonia	94.1%	79.5%	112.5%	109.2%

5.3 Kunda Cement Plant

AS Kunda Nordic Tsement (KNC) is located in the northern Estonia about 100 km east of Tallinn and about 80 km west of the Eesti Elektrijaam and about 90 km west of the Balti Elektrijaam. The Estonian cement factory is located in a small town of Kunda, established in the 1870s and state owned up to the recent system change, was privatised in 1992 as Kunda Nordic Tsement. Later the owners have been changed and currently Heidelberg Cement Group (Germany) has 75% and CRH (Ireland) 25% of the shares (Weiß & Bentlage, 2007). KNC produces constructional cements, crushed limestone and also provides port services (Kunda Nordic Tsement, 2018). Nearly all cement consumption in Estonia is covered by the KNC (HeidelbergCement Group, 2018). At the present time KNC is only one cement producer in Estonia and one of the largest cement producers in the Baltic States.

KNC operates a wet cement production process. Its main energy source is oil shale. The main raw materials that it uses, oil shale ash, clay and limestone are mined in nearby quarries. Cement, or Portland cement, is made when limestone, clay (or sand), and fuel is burnt in a rotating oven, so-called rotary kiln. During the burning process the material is forming a gravel-like, extremely hard-burned, clinker. The clinker is either used as such, or ground in cement mills together with small amounts of other material (plaster) to form the cement (Weiß & Bentlage, 2007).

About 60% of CO_2 emissions from cement production come from the calcining process, when the intermediate product clinker is produced. The remaining 40% of CO_2 emissions come from the combustion of fuels used to produce heat during the production process. KNC has formulated a zero vision for CO_2 emissions over the product's life cycle. Actions in five areas are required: energy efficiency, using biomass as energy, new cement types, carbon capture and storage, CO_2 mineral carbonation (Heidelberg Cement Group, 2016).

Key figures for KNC in 2014 - 2016 are shown in the Table 6 (Tsemendiwabrik 2014, Tsemendiwabrik 2015, Tsemendiwabrik 2016). KNC has exported most of the clinker to Cesla cement plant in Slantsy, which is also part of the Heidelberg Cement Group. Due to the loss of Russian market, because of the Russian financial crisis in 2014 – 2017, KNC had to reduce its clinker production by two times in 2015 compared to 2014. This also resulted the decrease of CO_2 emission by two times in 2015 compared to 2014. According to EU ETS the CO_2 emissions have increased for 69.7% in 2017, that is definitely a result of the increased production. This increase was the highest among the all Estonian large CO_2 emitters (Table 4).

Table 6. Key figures for KNC in 2013 - 2016

Production	2013	2014	2015	2016	2017
Clinker, t	691 443	720 480	356 287	318 500	NA
Cement, t	456 070	447 350	390 430	422 800	NA
Fuel					
Oil shale, t	155 750	150 120	70 201	48 313	NA
Coal, t	58 900	63 850	22 913	19 176	NA
Alternative fuels, t	71 600	78 740	51 640	51 558	NA
Emissions					
CO_2, t	748 123	785 695	379 310	331 299	559 629
Environmental investments, M €	0,98	0,49	0,91	1,89	NA

NA – not available

5.4 Blidene and North Blidene structures

5.4.1 Geological background

The North Blidene and Blidene structures are situated in the Western Latvia. The North Blidene is an anticlinal near-fault fold with three domes. The Blidene structure is located in a down-dip block. The Blidene structure is bounded by faults at the north-west and south-east. The structure is studied by five wells (Figure 9, Vangkilde-Pedersen, et al., 2009a)

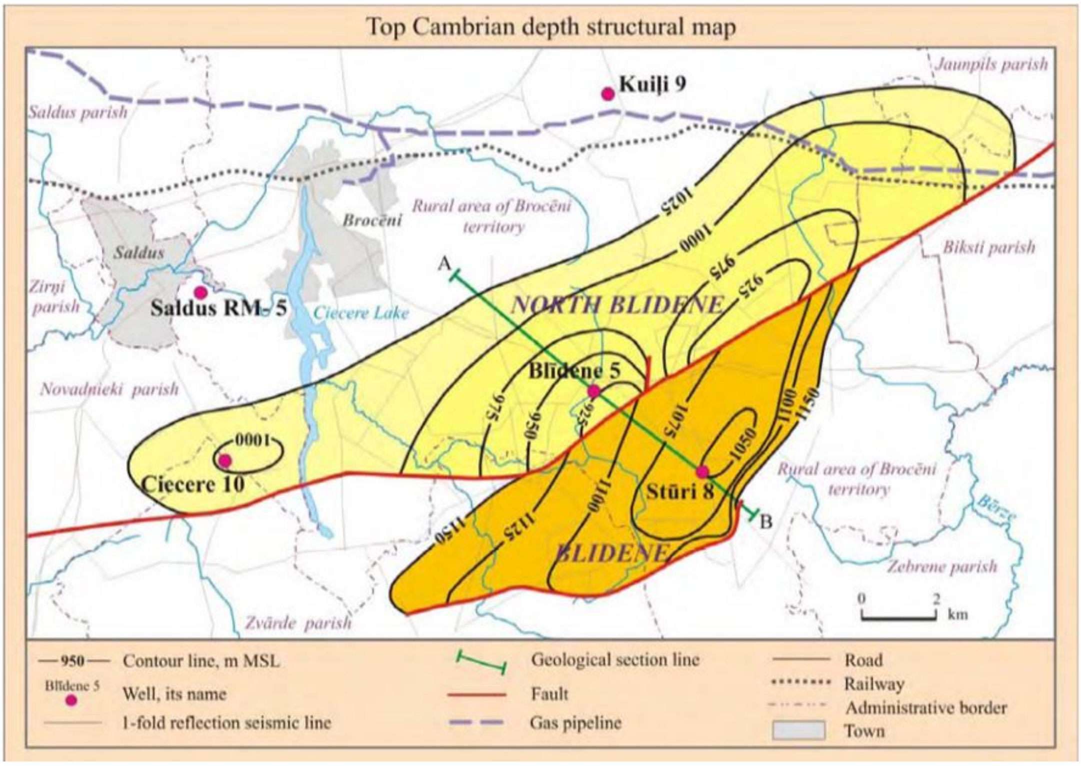

Figure 9. Blidene and North Blidene structures (modified after Figure 2.3, Vangkilde-Pedersen, et al., 2009a)

The top of the reservoir within the North Blidene structure occurs at the depth of 1 070 - 1 170 m. Its total thickness varies from 45 m at the dome of the high to 53 m in the periclinal zone, the effective thickness, from 37 to 41 m (Vangkilde-Pedersen, et al., 2009a). The area of the North Blidene structure is 95 km^2 (Shogenova, et al., 2009a). The average open porosity of the sandstone comprises 21%, based on the results of log interpretation; the permeability reaches 370 - 400 mD (Vangkilde-Pedersen, et al., 2009a).

The top reservoir of the Blidene structure occurs at the depth 1 170 - 1 270 m. The total thickness is equal to 66 m, the effective thickness 60 m (Vangkilde-Pedersen, et al., 2009a). The area of the Blidene structure is 43 km^2 (Shogenova, et al., 2009a). The average open porosity of the sandstone comprises 20%, based on the results of log interpretation; the permeability reaches 860 mD. The aquifer contains confined groundwater with the salinity 100 - 114 g/l. The well yield comprises about 100 m^3/day. The hydrostatic reservoir pressure is 100 - 115 atmospheres; the reservoir temperature is 18° - 20°C (Vangkilde-Pedersen, et al., 2009a).

The reservoir consists of quartz sandstone including interbeds of siltstone and shale (claystone). The average density of samples from depths of 800 - 1 800 m is 2 300 kg/m^3. The average chemical parameters of the Baltic Cambrian rocks are: SiO_2 – 89.3%, Al_2O_3 – 3,6%, CaO – 0,6% (Shogenova, et al., 2009a). For estimation of storage capacity, CO_2 density at reservoir conditions was considered up to 750 kg/m^3 and storage efficiency was assumed to be 35-40% (Šliaupa, et al., 2008; Shogenova, et al., 2009a).

The structures (North Blidene and Blidene) are considered a single object for the purpose of the establishment of a CO_2 storage. The conservative volume in the Cambrian aquifer at the North Blidene is 74 Mt and at the Blidene is 58 Mt (Vangkilde-Pedersen, et al., 2009a).

All the previously reported parameters of the North Blidene and Blidene structures are shown in Table 7.

Table 7. Studied parameters of the North Blidene and Blidene structures (Šliaupa, et al., 2008; Vangkilde-Pedersen, et al., 2009a; Shogenova, et al., 2009a)

Structure	North Blidene	Blidene
Reservoir parameters		
Trap area, km^2	95	43
Depth of the top, m	1 070 - 1 170	1 170 - 1 270
Thickness, m	45 - 53	66
Effective thickness, m	37 - 41	60
Porosity, %	21	20
Permeability, mD	370 - 400	860
Mineralization of groundwater, g/l	100 - 114	
Well yield, m^3/day	100	
Hydrostatic reservoir pressure, atm	100 - 115	
Water temperature, °C	18 - 20	
Density of the rocks, kg/m^3	2 300	
CO_2 density, kg/m^3	750	
Storage efficiency, %	35 - 40	
Chemical composition		
SiO_2, %	89.3	
Al_2O_3, %	3.6	
CaO, %	0.6	
CO_2 storage capacity		
Conservative estimates, Mt	74	58

5.4.2 Reservoir and cap rocks

All the boreholes and samples properties data collected by author for the North Blidene and Blidene structures are shown in the Table 8.

Table 8. Boreholes and samples data of the North Blidene and Blidene structures (Pomeranceva, 2003; Popovs, 2015)

Borehole	Kuiļi 9	Saldus RM-5	Ciecere 10	Blīdene 5	Stūri 8
Depths of the Deimena and Zebre formations from the surface					
Depth of the Deimena formation, m	1168.0	1199.9	1121.0	1040.5	1168.0
Thickness of the Deimena formation, m	53.0	48.0	46.0	44.5	66.0
Depth of the Zebre formation, m	1124.0	1153.9	1076.0	1000.0	1123.5
Thickness of the Zebre formation, m	39.0	46.0	45.0	32.0	44.5
Cambrian Deimena Formation					
Effective porosity, % (depth, m)		25.6 (1209)			26.6 (1233.6)
Average permeability, mD (depth, m)		367 (1209)			853 (1233.6)
Lithology	Quartz-sandstone				
Ordovician Zebre Formation					
Effective porosity, % (depth, m)		14.2 (1168.8), 14.1 (1172.5), 10.5 (1176.1), 7.89 (1177.1)		2.28 (1005)	
Average permeability, mD (depth, m)		0.2 (1168.8), 0.2 (1172.5), 0.1 (1176.1), 0.1 (1177.1)		0 (1005)	

5.4.2.1. Reservoir rocks

The prospective reservoir for CO_2 storage is the Cambrian Deimena Formation. According to the Latvian database used in (Popovs, 2015), the average depth of the Deimena formation in the North Blidene structure based on the four boreholes, that are within the calculated structure area (Ciecere 10 and Blīdene 5), or very close to the calculated structure area (Kuiļi 9 and Saldus RM-5), is 1128.6 m from the surface, the average thickness is 47.9 m, while the effective thickness is 36 m (Карпицкий, 1963). The depth of the Deimena formation in the Blidene structure based on one borehole (Stūri 8), that is within the calculated structure area, is 1 168 m from the surface, the thickness is 66 m (Popovs, 2015), while the effective thickness is 52 m (Карпицкий, 1963).

At the depth of 1 209 m in the borehole Saldus RM-5 (1 km north-west form the North Bldiene) the effective porosity is 25.58% and the average permeability is 366.92 mD. At the depth of 1 233.6 m in the borehole (Blīdene 5) the effective porosity is 26.61% and the average permeability is 853 mD (Pomeranceva, 2003).

5.4.2.2 Cap rocks

The primary cap rock of the structures is the Ordovician Zebre Formation. According to the Latvian database used in (Popovs, 2015), the average thickness of the Zebre formation in the North Blidene structure based on the four boreholes, that are within the calculated structure area (Ciecere 10 and Blīdene 5), or very close to the calculated structure area (Kuiļi 9 and Saldus RM-5), is 42.6 m. The thickness of the Zebre Formation in the Blidene structure based on one borehole (Stūri 8), that is within the calculated structure area, is 44.5 m (Popovs, 2015).

At the depth of 1 005 m (Zebre formation) in the borehole (Blīdene 5) the effective porosity is 2.28% and the average permeability is 0 mD. At the depths of 1168.8 - 1177.1 m (Zebre Formation) in the borehole (Saldus RM-5) the average effective porosity is 11.67% and the average permeability is 0.15 mD (Pomeranceva, 2003).

The average thickness of the secondary cap rock of the North Blidene and the Blidene structures according to (Popovs, 2015) based on the five boreholes, that are within the calculated structure area (Ciecere 10, Blīdene 5 and Stūri 8), or very close to the calculated structure area (Kuiļi 9 and Saldus RM-5), is 1 093.5 m. It composed of Ordovician clayey carbonate rocks, Silurian strongly clayey carbonate rocks and Devonian mixed carbonate-siliciclastic rocks additionally covered somewhere by Permian limestone and by Quaternary sediments.

5.4.3 Modelling of the structure maps and geological sections

According to the new composed models (Figures 10-12), total trap areas of the North Blidene and the Blidene structures are 141 km^2 and 62 km^2 with the perimeters of 64 km and 45 km. 3D structure maps of the North Blidene and Blidene structures are shown in Figure 12.

The depth of the Deimena Formation in the North Blidene structure varies from 1 035 - 1 150 m from the surface and 920 - 1 035 m from the sea level. The depth of the Deimena Formation in the Blidene structure varies from 1 168 - 1 357 m from the surface and 1 053 - 1 242 m from the sea level.

The total volume of the Deimena formation in the Norh Blidene structure is 6 737 142 288 m^3 and the total volume of the Deimena Formation in the Blidene structure is 4 094 946 931 m^3. The volumes are calculated by multiplying the average thickness of the Deimena formation (47.875 m for the North Blidene and 66 m for the Blidene structure) with the area of the structures.

The North Blidene is closed by the contour line of 1 150 m from the surface and the Blidene structure is closed by the faults from all sides (Figure 10).

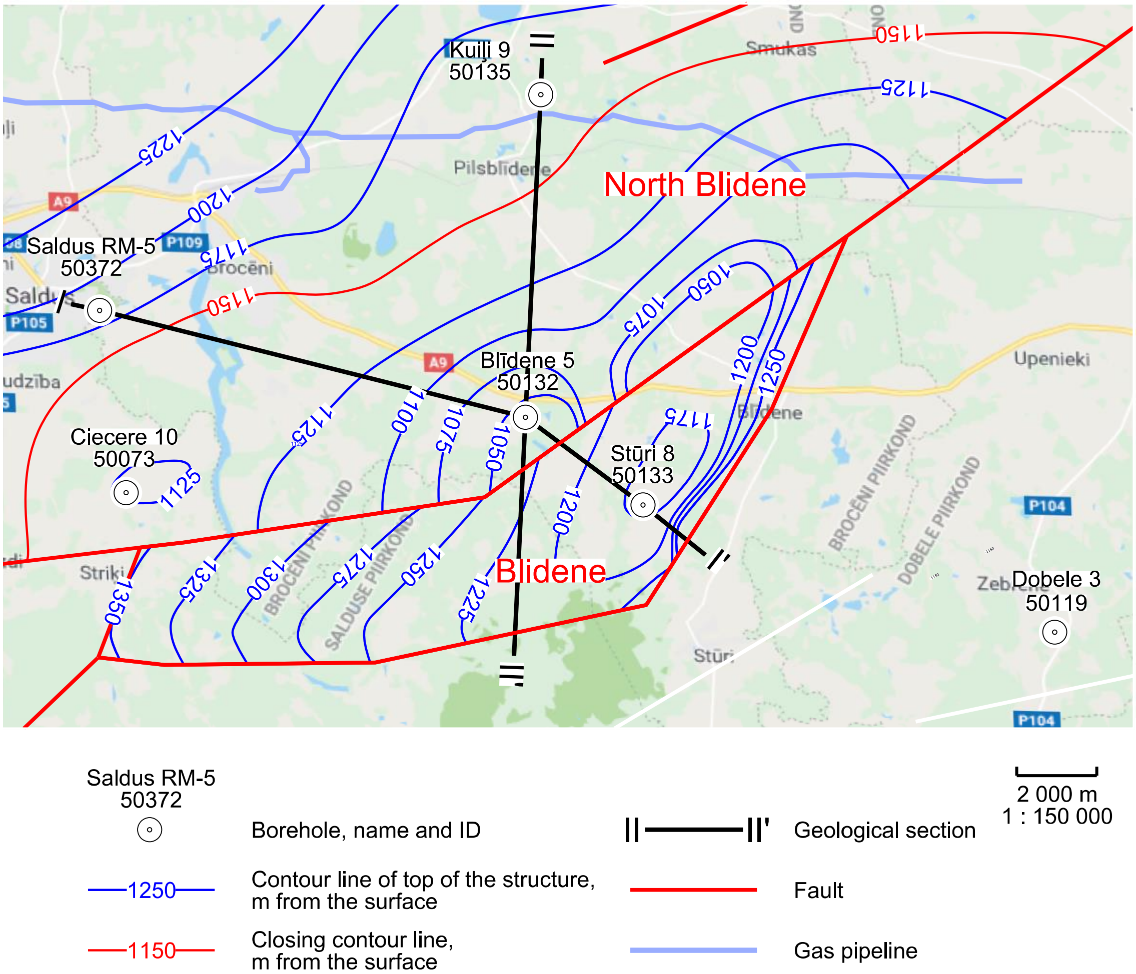

Figure 10. Structure map of the North Blidene and the Blidene structures. Lines of geological cross sections are shown (Fig. 15 and Fig. 16). The map is composed using Bentley PowerCivil for Baltics V8i (SELECTseries 2) software. Base map is from the Google Maps, 2018.

Two geological sections (sections lines are shown at the structure map, Figure 10) were composed using available borehole and seismic interpretation data (Figures 13 - 14). The borehole data from (Popovs, 2015) were used to compose nine layers of geological sections. The geological sections is only illustrative, since the data for modelling were very limited. The minimum distance between two boreholes is 3.7 km and the exact location of the layers surfaces is unknown. The location of the uplifts in the geological sections are also illustrative.

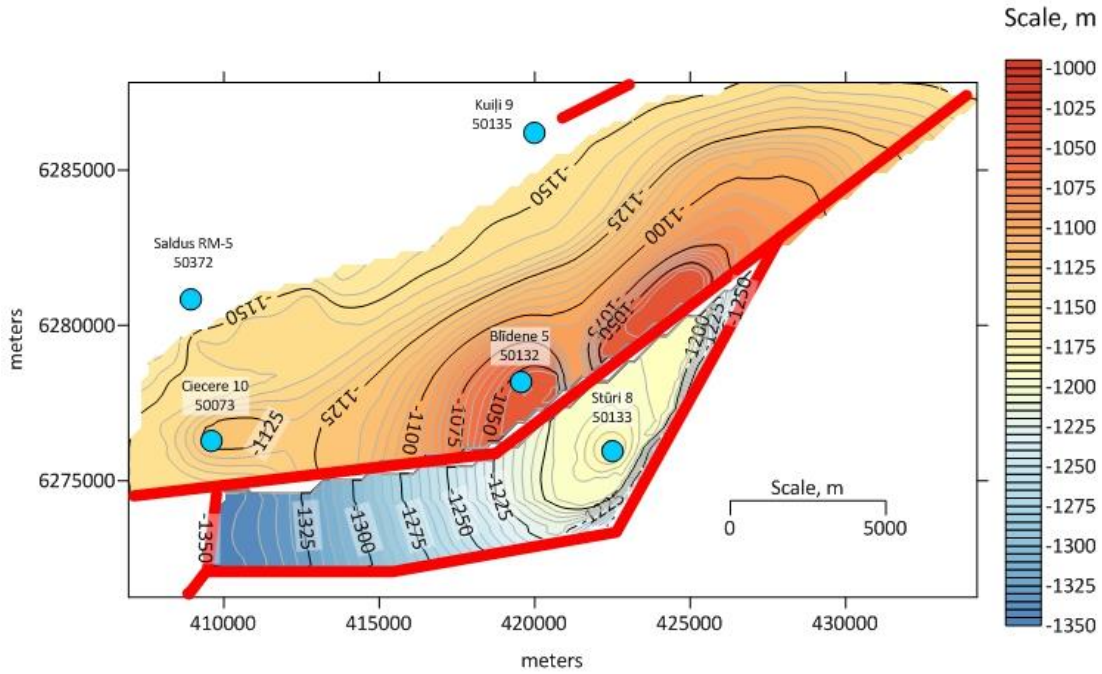

Figure 11. Contour maps of the Deimena Formation in the North Blidene (above) and the Blidene (below) structures composed using Golden Software Surfer 15 software. Fault line is indicated with red polyline.

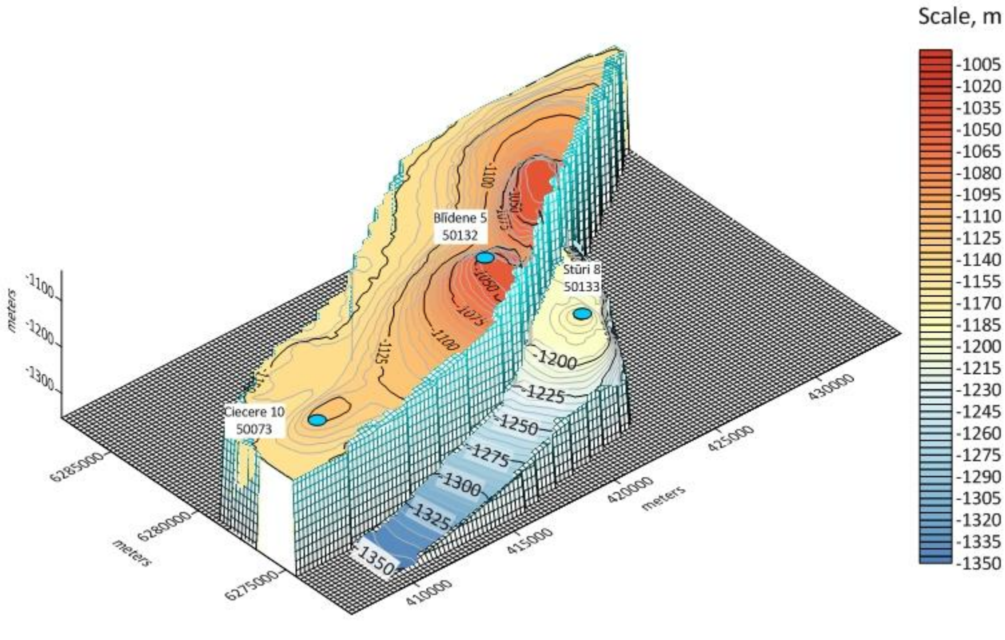

Figure 12. 3D structure maps of the North Blidene and Blidene structures. The map is composed using Golden Software Surfer 15 software.

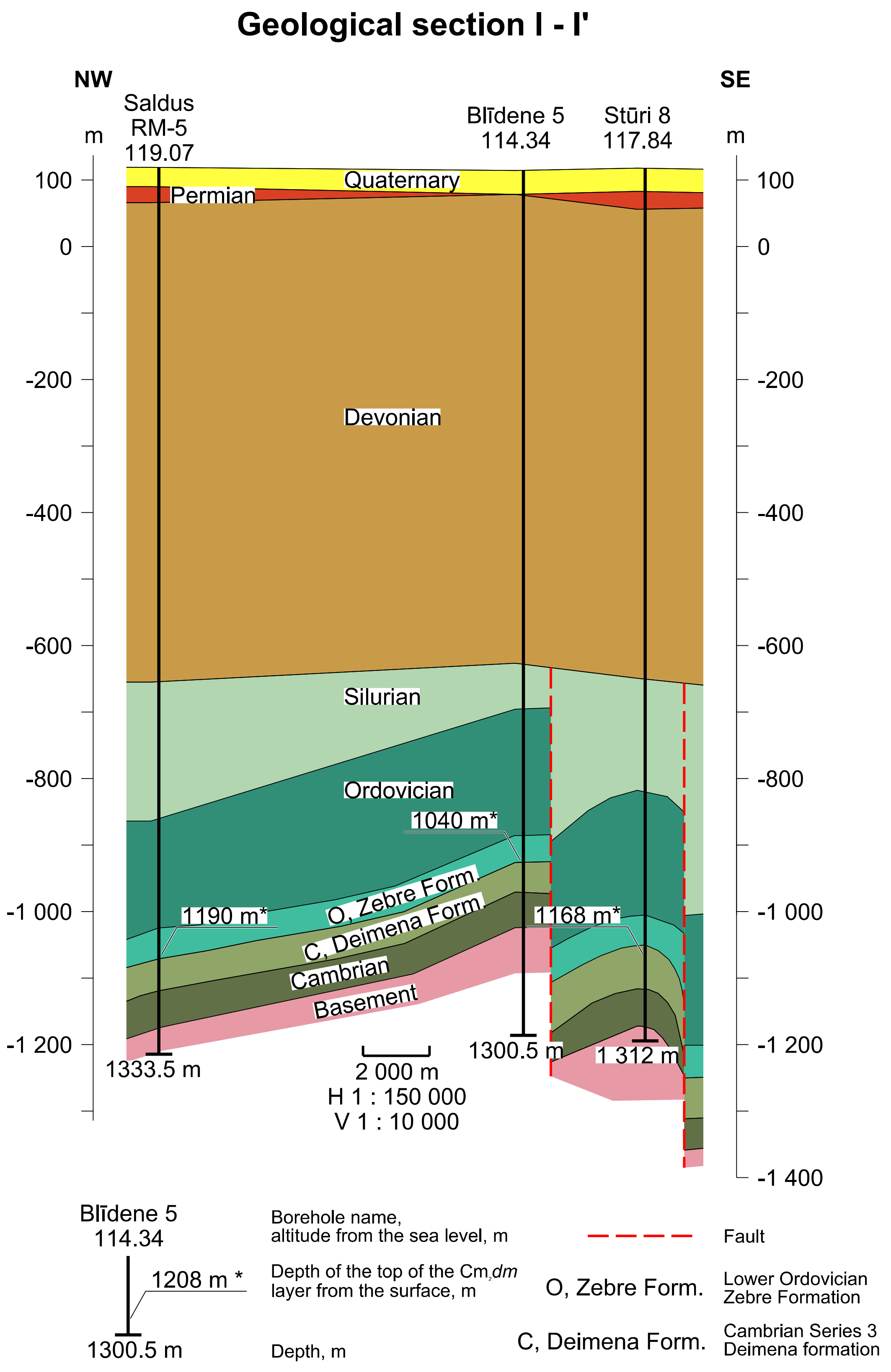

Figure 13. Geological section I-I'. The section is composed using Bentley PowerCivil for Baltics V8i (SELECTseries 2) software.

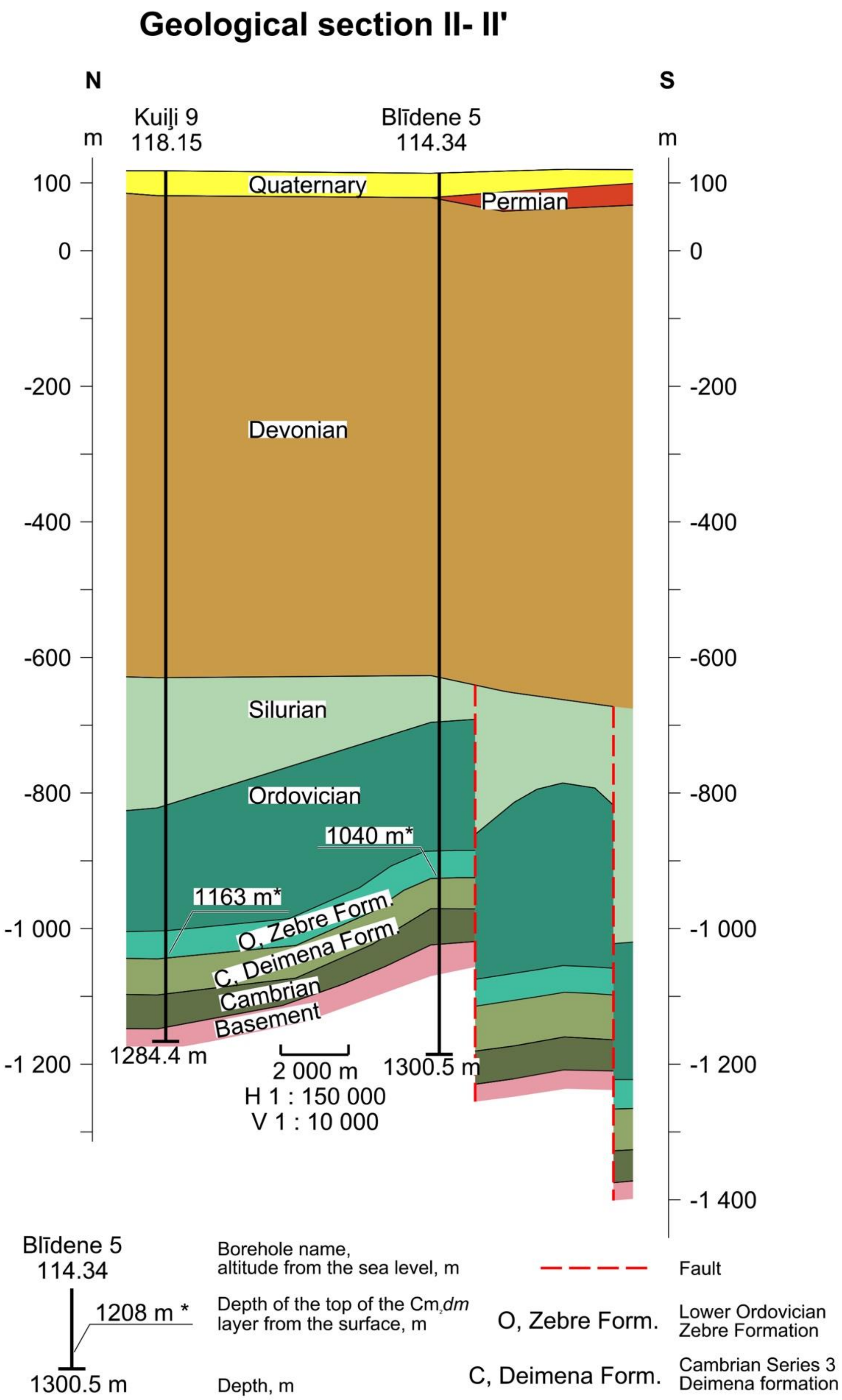

Figure 14. Geological section II-II'. The section is composed using Bentley PowerCivil for Baltics V8i (SELECTseries 2) software.

5.4.4 CO_2 storage capacity

The estimated CO_2 storage capacity of the North Blidene and Blidene structure according to optimistic and conservative approaches with different levels of reliability (min-max/mean) are shown in Table 9.

Table 9. Physical parameters of the studied structural traps

Structure	North Blidene			Blidene		
Reservoir parameters						
Depth of top, m	1035-1150			1168-1357		
Thickness, m	48			66		
Trap area, km^2	141			62		
CO_2 density, kg/m^3	881			866		
Net to gross ratio, %	75			80		
Salinity, g/l	100-114			100-114		
Pressure, MPa	11.0			12.65		
T, ºC	18			22.9		
S_{eff}Opt./Cons. (%)	30/4			5/3		
Porosity, %	Min	Max	Mean	Min	Max	Mean
	12.5	25.6	20	13.5	26.6	21.0
CO_2 storage capacity, Mt						
Optimistic estimates	Min	Max	Mean	Min	Max	Mean
	167	342	267	19.0	37.5	29.6
Conservative estimates	Min	Max	Mean	Min	Max	Mean
	22.2	45.5	35.6	11.4	22.5	17.8

Total CO_2 storage capacity, Mt					
Optimistic estimates			Conservative estimates		
Min	Max	Mean	Min	Max	Mean
186	380	297	33.6	68.0	53.4

The closing contour of the North Blidene structure was determined by the top depth contour of 1150 m from the surface (Figure 10). The average thickness of the formation is 48 m. The total area of the structure is 141 km^2. The CO_2 density is 881 kg/m^3 (calculated according to the (EMS Energy Institute, 2015), that is corresponding to the average pressure of 11.0 MPa and temperature of 18 ºC (LEGMC, 2013). The average net to gross ratio of aquifer for the North Blidene structure is 75%, according to the logging data (Карпицкий, 1963). The estimated minimum, maximum and mean porosities for calculations were 13, 26 and 20% correspondingly. The structure is considered as reservoir of good and high quality for CO2 storage (Shogenov et al, 2015). According to the "cartoon approach", that is described in Vangkilde-Pedersen, et al., 2009b, the storage efficiency factor for the North Blidene optimistic approach is 30% and for conservative approach is 4%. Based on the optimistic approach, the CO_2 storage capacity of the North Blidene structure is estimated 167 - 342 Mt (mean 267 Mt). Based on the conservative approach, the CO_2 storage capacity of the North Blidene structure is estimated 22 - 461 Mt (mean 36 Mt).

The Blidene structure is closed by faults from all sides, from west also by the contour of 1 350 m from the surface and from east by the contour of 1 250 m from the surface (Figure 10). The average thickness of the formation is 66 m. The total area of the structure is 62 km^2. The CO_2 density is 856 kg/m^3 (calculated according to the (EMS Energy Institute, 2015), that is corresponding to the average pressure of 12.65 MPa and temperature of 22.9 ºC (LEGMC, 2013). The average net to gross ratio of the aquifer for the Blidene structure is 80% calculated by logging data available in (Карпицкий, 1963). The estimated minimum, maximum and mean porosities for calculations were 14, 21 and 27% correspondingly. The structure is considered as good and high quality reservoir (Shogenov et al, 2015). According to the "cartoon approach", that is described in Vangkilde-Pedersen, et al., 2009b, the storage efficiency factor for the Blidene optimistc approach is 5% and for conservative approach is 3%. Based on the optimistic approach, the CO_2 storage capacity of the Blidene structure is estimated 19 - 37.5 Mt (mean 29.6 Mt). Based on the conservative approach, the CO_2 storage capacity of the Blidene structure is estimated 11.4 - 22.5 Mt (mean 17.8 Mt).

The total CO_2 storage capacity of the North Blidene and the Blidene structures based on the optimistic approach is 186 - 379 Mt (mean 296 Mt) and the total CO_2 storage capacity based on the conservative approach is 33.6 - 68 Mt (53.4 Mt).

5.5 CO_2 transport and storage scenarios

Estonia has the largest CO_2 emissions per capita in the region (2nd place in Europe, 12th place in the world in 2016 (European Comission, 2018). This is due to the combustion of oil shale for energy production. Due to the shallow sedimentary basin, that is containing mainly potable groundwater, the geological conditions are unfavourable for CO_2 storage in Estonia. Therefore the options for CO_2 storage is being searched in the neighbouring regions, like Latvia. The total distance from Eesti and Balti power plants to the Luku-Duku and South-Kandava structures (located from Blidene structures at the distance of about 15 - 20 km) along available pipelines route is about 800 km (Shogenova, et al., 2011a).

According to the European Union Emission Trading System (EU Emission Trading System, 2018), total verified industrial CO_2 emissions in Estonia in 2017 were 14.7 Mt. Eight sources with emissions larger than 100 000 tons formed together 95.44%, which is 14.03 Mt out of total 14.7 Mt. In 2017, industrial CO_2 emissions were higher by 9.2% compared to the year 2016.

AS Kunda Nordic Tsement (KNC) produced 0.56 Mt/CO_2 in 2017, this is 3.81% of total industrial CO_2 emissions. To store CO_2 emissions produced by KNC the following scenarios could be considered.

5.5.1 Kunda-Blidene CCS scenario

In this scenario, KNC will produce about 16.8 Mt/CO_2 emissions during 30 years, although it could be expected to be higher since the amount of emissions are expected to rise (emissions for KNC in 2017 rose 69.7% compared to the year 2016), but this was not taken into consideration for this scenario. For this scenario even average conservative capacity of the Blidene structure 17.8 Mt will be enough for the whole project duration (Figure 15).

It is assumed that Calcium looping oxyfuel CO_2 capture technology will be applied at the KNC. At the present time this technology is developed by the Horizon 2020 project CLEANKER and it will be demonstrated at the BUZZI Unicem cement plant in Vernasca (Piacenza, Italy). According to the CLEANKER project CO_2 capture efficiency will be more than 90%, and cost of CO_2 avoided will be <30 euro/t CO_2 (CLEANKER, 2018).

Only one injection borehole is planned at the central point of the dome of Blidene. Construction of 750 km of pipelines of relatively small diameter (300 mm diameter for up to 1 Mt emissions per year) could be planned according to (EPRI, 2015). However, the cost per one ton of CO_2 avoided could be relatively high considering high capital costs for capture, compression station and transport pipelines. According to (EPRI, 2015) the costs per one ton of CO_2 avoided for transport and storage of small volumes of CO_2 over long distances could be from several to ten times higher than transport of large quantities to smaller distances.

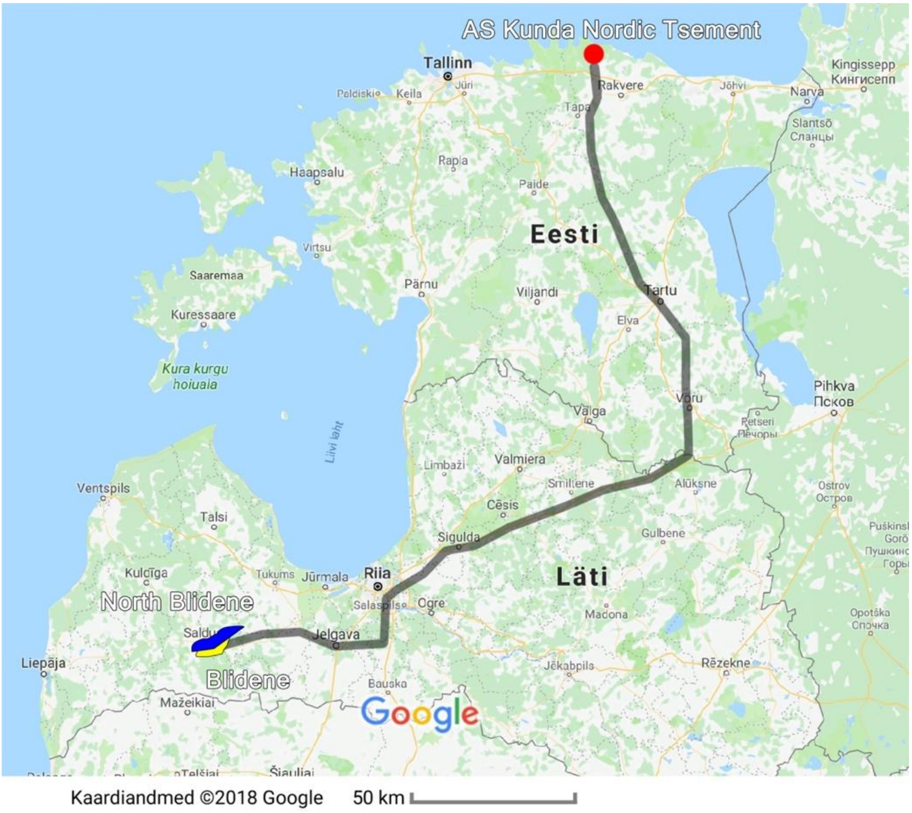

Figure 15. KNC-Blidene CCS scenario. Blue indicates the North Blidene structure, yellow indicated the Blidene structure and red indicated the KNC plant. Map is composed using Adobe Photoshop CS6 software. Base map is from the Google Maps, 2018.

5.5.2. Estonian-Latvian CCS scenario for large emission sources

In this scenario we propose that KNC together with the largest industrial CO_2 emission sources in Estonia and the highest industrial CO_2 emitter in Latvia (Latvenergo, TEC-2) will collaborate in one joint CO_2 transport and storage scenario (Figure 16). TEC-2 is one of the largest power plants in the Baltic States and according to the EU ETS, the plant produced 0.74 Mt/CO_2 in 2016.

According to EC JRC (2018) total CO_2 emissions produced in Estonia decreased in 2016 compared to 1990 for 39.4% (Table 10). However, the Estonian target by 2050 is to decrease GHGE for 80% including 67% from the energy sector and industry (Keskkonnaministeerium, 2017) compared to 1990. It means that in 2050 Estonian GHGE from these sectors should decrease additionally for 10.2 Mt. Emissions in Latvia are highest in the energy (42.90%), transport (26.74%) and agriculture sectors (19.22%), according to (VARAM, 2012).

Table 10. Total CO_2 emissions produced in Estonia

Year	1990	2000	2010	2015	2016
Total emissions, Mt	36970.60	15284.96	18560.48	22178.83	22402.41

According to the available data (EU ETS), Estonian largest Power Plants (Eesti and Balti) are producing 9.96 Mt/CO_2 in 2017. Together with KNC and Latvian TEC-2 they produce 11.26 Mt/CO_2 per year. Latvian CO_2 emissions will compose only 6.6% of all emissions in this scenario, while KNC emissions will compose about 5% of the emissions stored in this scenario.

The Narva power plants are the Eesti, Balti and Auvere power plants. Their combined maximum annual production capacity is 12 TW/h. As Estonia consumes about 8 TW/h of electricity per year, the Eesti Energia power plants play an important role in supplying the country with electricity. In 2017 Eesti Energia produced 11.1 Tw/h energy (Eesti Energia, 2018).

Eesti Elektrijaam and Balti Elektrijaam produce energy primarily based on oil shale. Eesti Elektrijaam is the biggest power plant in Estonia and since 2005, it can replace oil shale with up to 50% of biofuels. For the maximum use of oil shale and reduction of the environmental impact, one of the boilers is being reconstructed, so that up to 50% of oil shale gas can be burnt together with oil shale (Eesti Energia, 2018). The plant is located ~15 km south-west from Narva. Balti Elektrijaam, which is the second largest power plant in Estonia, can also use biofuel since the year 2004 and natural gas together with oil shale (Eesti Energia, 2018). The plant is located ~3 km south-west from Narva. Eesti Energia states that they will increase electricity production from alternative sources to up to 40% of its total output (Eesti Energia, 2018). TEC-2 is a gas type power plant that is located south-east from Riga. The plant uses primarily natural gas. The total power capacity is 832 MW (IndustryAbout, 2015).

According to the Table 11, the duration of the CCS scenario for the largest CO_2 emission sources in Estonia and the highest industrial CO_2 emitter in Latvia with optimistic estimates would be from 17 to 34 years (mean 26 years).

Considering Latvian about 50 years-experience of exploitation of Inčukalns underground natural gas storage, the mean value of optimistic capacity and 26 years duration of the project could be applied.

Oxyfuel CO_2 capture technology is planned to be applied at the Eesti, Balti and Latvian TEC-2 Power Plants in this scenario. This involves the combustion of the fuel with pure oxygen, resulting in a gas flow with a high concentration of CO_2. According to Shogenova, et al. (2011a) CO_2 capture cost for oxyfuel combustion process at the Eesti and Balti Power Plants was estimated as 25.5 euro/t CO_2 avoided. During last years experimental and research work ongoing in Tallinn University of Technology demonstrated feasibility of oxyfuel combustion technology applied to Estonian oil shales. Oxyfuel CO_2 capture technology has been demonstrated in Europe at pilot scale. High efficiency of this technology, permitting to capture up to 100% of CO_2 emissions, is its advantage compared to other capture technologies (Yörük, 2016).

Table 11. Duration of CO_2
storage project in two structures for Estonian and Latvian emissions

Approach	Optimistic estimates			Conservative estimates		
	Min	Max	Mean	Min	Max	Mean
Capacity, Mt	186	380	297	33.6	68.0	53.4
Duration of the project, years	17	34	26	3	6	5

Considering permeability of Latvian rocks, the maximum injection rate for one well would be 1.5 Mt_{CO2}/y (Shogenova, et al., 2011a). For this scenario in order to inject 11.26 Mt/CO_2 per year, eight boreholes are needed, one borehole for Blidene and seven for North Blidene structure. For injection of Latvian emissions one borehole will be drilled in the North-Blidene structure, while Estonian part of the project will drill one borehole in Blidene and six boreholes in the North-Blidene structure. Construction of 800 km of pipelines for Scenario 2 will be shared between Eesti and Balti Elektrijaam (800 km from the storage site), KNC (750 km from to storage site) and TEC-2 (70 km from the storage site). Pipelines of 800 mm diameter for up to 10 Mt emissions per year could be planned according to (EPRI, 2015). All the parameters of both Kunda-Blidene CCS Scenario 1 and Estonian-Latvian CCS Scenario 2 are shown in Table 12.

Sharing cost among project partners will make CCS project more attractive to all the parties. KNC will share transport costs with Eesti Elektrijaam and Balti Elektrijaam. Storage site monitoring should be included into the project according to (EU CCS Directive, 2009) and monitoring costs should be added to the storage costs (Shogenova et al, 2014), (EPRI, 2015). All partners will share exploration costs for base line seismic monitoring before storage, storage sites infrastructure and operational costs and monitoring costs during storage and in post-closure period. This way it will be easier to get exploration and storage permits in Latvia (EU CCS Directive, 2009). Estonia and Latvia will get additional working places and decreased emissions.

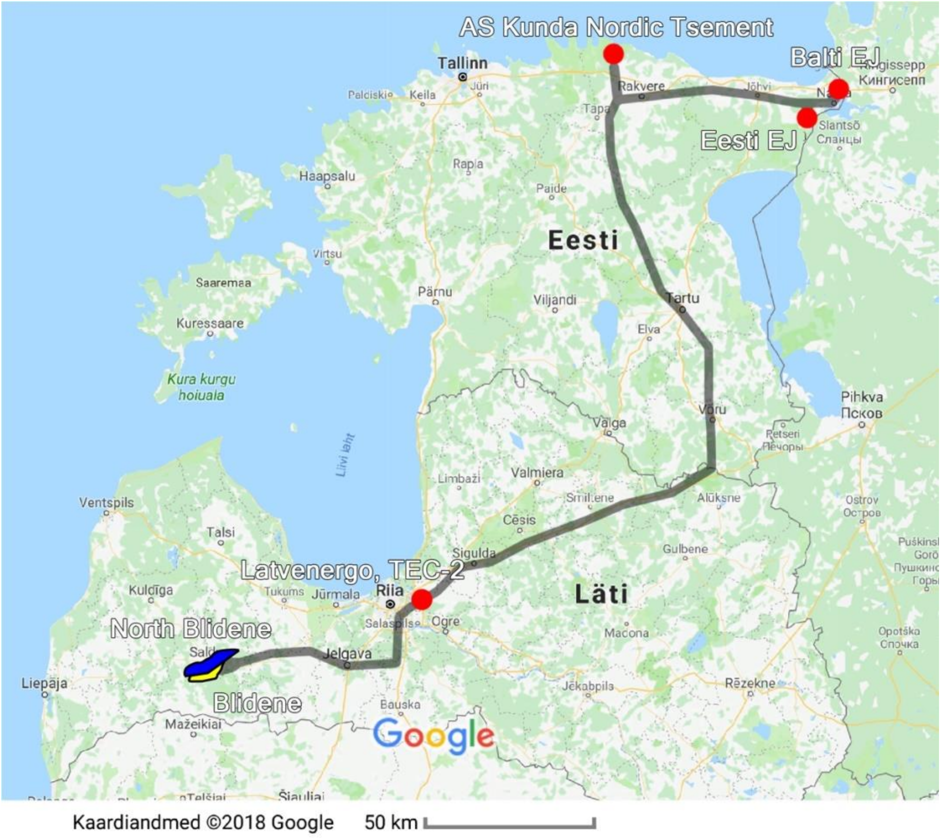

Figure 16. Estonian-Blidene CCS scenario. Blue colour indicates the North Blidene structure, yellow indicated the Blidene structure and red indicated the KNC plant. Map is composed using Adobe Photoshop CS6 software. Base map is from the Google Maps, 2018.

Table 12. Parameters of CCS scenarios

Scenario	Scenario 1 Kunda-Blidene CCS	Scenario 2		
		Estonian-Latvian CCS	Estonian part	Latvian part
Emissions sources	1	4	3	1
Emissions per year, Mt/%	0.56/100	11.26/100	10.52/93.4	0.74/6.6
Total emissions in the project, Mt	16.8	293	274	19.2
Number of Wells	1	8	7	1
Transport, km	750	800	800	70
Pipeline Diameter, mm	300	800	800	800
Storage structures	Blidene	Blidene and North Blidene	Blidene and North Blidene	North Blidene
Duration, years	30	26	26	26
Project start-end year	2023-2053	2024-2050	2024-2050	2024-2050

SUMMARY

The CO2 storage capacity of the Blidene and the North Blidene structures were estimated using improved estimations of all of the needed parameters. Minimum, maximum and average capacities were calculated for optimistic and conservative cases for both structures (Table 9). Their total optimistic capacity (min-max/mean) is 186-380/297 Mt, while the conservative capacity is estimated at 33.6-68.0/53.4 Mt. The average optimistic capacity is more than two times higher than the capacity that had been estimated in previous reports (132 Mt, Vangkilde-Pedersen, et al., 2009a), this is explained by a larger estimated area and a higher CO_2 density in this study. The estimated average conservative capacity in this study is lower by 2.5 times, which is explained by the lower storage efficiency applied.

The first CCS scenario is composed for CO_2 emissions produced by the AS Kunda Nordic Tsement Plant (KNC), which are captured using Ca-looping technology and transported to the Blidene structure. According to the EU Emissions Trading System, KNC produced 0.56 Mt/CO_2 in 2017 and will have had produced about 16.8 Mt/CO_2 emissions for the duration of 30 years. The average conservative capacity of the Blidene structure (17.8 Mt of CO_2) was found to be suitable for the storage of CO_2 emissions produced by KNC for the duration of more than 30 years. This scenario will require the drilling of one injection borehole and the construction of 750 km of CO_2 transport pipelines. However, as the amounts of CO_2 produced by the AS Kunda Nordic Tsement (KNC) are relatively small, this CCS scenario could have very high costs according to the report of (EPRI, 2015). Also CO_2 capture, transport and storage of only KNC emissions, composing only 3.8% of high quantity Estonian CO_2 emissions, will not permit Estonian to reach its strategical emission reduction targets by 2050.

The second CCS scenario is proposed for CO_2 emissions produced and captured by KNC, Eesti Elektrijaam and Balti Elektrijaam, two of the largest industrial CO_2 emission sources in Estonia, and the largest industrial CO_2 emitter in Latvia - Latvenergo, TEC-2, all collaborating in one joint CO_2 transport and storage scenario into both the North-Blidene and the Blidene structures together. The average optimistic capacity of both the Blidene and the North Blidene structures (297 Mt CO_2) will allow for the storage of emissions produced by these four enterprises for the duration of 26 years. Considering, that the maximum optimistic capacity (380 Mt) is enough for the duration of 34 years, this scenario could be enough for a more extended period (about 30 years). This scenario will need the drilling of eight injection boreholes and the construction of about 800 km of CO_2 transport pipelines. The share of Estonian CO_2 emissions in this scenario will be about 93.4%, including 5% by KNC. Latvian emissions will compose 6.6%. Compared to the previously modeled Estonian-Latvian CCS scenario for the Balti and the Eesti power plants with their estimated 8 years of project duration (Shogenova, et al., 2011a), this scenario has the advantage of including the cement industry from Estonia and the Power Plant from Latvia with the probability of the project duration lasting for more than 26 years. This sort of a scenario is elaborated in the Baltic Region for the first time and will help Estonia and Latvia in reaching their national strategic emission reduction targets.

Some of the results of this master thesis will be included in the poster presentation, which will be presented at the IEA Greenhouse Gas Technology Conference (GHGT-14) in Melbourne in October 2018, and will be included in the conference proceedings.

The next steps for this research will include the economic modeling of these scenarios as part of the Horizon 2020 project CLEANKER. Further research will include Estonian-Latvian onshore CCUS

scenarios into the Blidene and the North Blidene structures and offshore scenario into the E6 structure in Latvia. CO_2 use will include CO_2 mineral carbonation with oil-shale ash (Uibu, et al., 2010) for an onshore scenario and CO_2 use for CO_2-EOR (enhanced oil recovery) and CO_2 storage in an offshore scenario (Shogenov, et al., 2017). The offshore scenario will avoid problems with possible public protests and problems with Latvian land owners, but it may have higher estimated transport and storage costs.

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