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Synergy of CO_2 storage and oil recovery in different geological formations: case study in the Baltic Sea

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Abstract

Pilot project for CO_2 storage and CO_2-EOR/EOR+ in different geological formations including two scenarios is proposed for Latvian offshore structure E6. The first "two wells and possible fault-leakage" scenario proposed CO_2 storage in the Cambrian Deimena Formation and oil recovery from the Upper Ordovician Saldus Formation. One common injection well and possible fault leakage to the oil reservoir are considered as a profit. The second "three wells and no leakage" scenario, includes additional CO_2 injection well to oil reservoir. A surplus for both scenarios is increased CO_2 storage capacity. The new pilot project idea supports exploitation of small oil deposits in the Baltic Region.

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Keywords: CO_2 geological storage; CCS, Enhanced Oil Recovery; EOR+; CO_2-EOR; Cambrian Series 3 Deimena Formation; Ordovician Saldus Formation; E6 structure; offshore Latvia

1. Introduction

CO_2 geological storage (CGS) as a part of CCS technology is an efficient tool to mitigate climate change and to continue use of fossil fuels for energy production. Renewable energy is becoming more popular to reduce impact of

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human activity on the Earth. However, oil is still the most profitable energy source and will remain the same in the future. Taking into account the development of CGS and profit of oil production, the combining Enhanced Oil Recovery (EOR) technology in the depleted oil reservoirs with CGS (CO_2-EOR) is a well-known commercial practice and has been already successfully implemented during last decades. The use of CO_2 offers an attractive opportunity to increase effectively oil production in the depleted oil reservoirs. Most of the CO_2-EOR projects operating today in USA use naturally occurring CO_2 extracted from underground specifically for EOR purposes. In most cases CO_2-EOR operations have not been designed with long-term CO_2 storage in mind, and storage-focused activities have not been undertaken (e.g. risk assessment, monitoring and verification). CO_2-EOR ensures permanent storage of large quantities of CO_2 underground (EOR+) [1]. In order to reduce the greenhouse gas effect on the Earth's atmosphere and achieve win-win situation, captured CO_2 produced by power plants or industry should be used for EOR.

Successful synergy of EOR and CO_2 storage has been demonstrated at the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project, located in southeast Saskatchewan, Canada. The project began CO_2 injection in 2000 at Weyburn and in 2005 at Midale, expected to produce at least 220 million barrels of incremental oil through miscible or near-miscible displacement with CO_2. The commercial operations are now the world's largest geologic storage site of CO_2 with about 2.8 million metric tons of CO_2 being stored annually. Both fields combined have stored more than 30 million metric tons (Mt) of anthropogenic CO_2. The CO_2 in these operations is captured from the Great Plains Synfuel plant in Beulah, North Dakota and transported via pipeline 180 miles north to the Weyburn and Midale fields. Around 40 Mt CO_2 will be permanently sequestered over the project's lifespan – 30 Mt at Weyburn and 10 Mt at Midale. CO_2-EOR operations started in 2000 and associated research has successfully demonstrated the safe operation and integrity of CCS at industrial scale [1, 2].

Strategic combination of CO_2 use for EOR with large-volume storage in associated saline formations known as *stacked storage* was discussed earlier in 19 USA basins and motivated by need to achieve emission reduction targets. By spatially and temporally linking CO_2-EOR with vertically and horizontally adjacent saline storage volumes, the infrastructure, experience, and community acceptance developed for EOR can provide a substantive boost for using the entire subsurface for storage of very large volumes [3]. Estimating limitations and risks of the stacked storage, it was concluded that storage in saline aquifer located under the oil trap could be more safe than in case of the more shallow aquifer. The possible risk of leakage through old abandoned wells discussed in [3] is not a case for the Baltic offshore and E6 structure with only one well drilled. The same author reported the following advantages of the stacked storage: limits plume and increase pressure, reduced need for characterisation, possible co-monitoring and reduced public acceptability issues. Potential tensions with oil production, operational and monitoring interference and identifying the sources of small leakages are reported among the disadvantages [4].

The effects of multiple CO_2 storage sites and how pressure build-up due to CO_2 injection at one site could affect neighbouring hydrocarbon reservoirs and other CO_2 storage sites were studied recently for offshore Scotland [5]. Synergy between oil recovery and CO_2 storage was found recently for CO_2-EOR in the North Sea, where greater oil recovery means greater CO_2 storage capacity [6].

Nevertheless, when exploiting underground resources, oil recovery usually has the highest priority and can cause a conflict of interest with other underground uses. Such a case in the Baltic Sea Region was studied for the first time. In our study we are discussing possibility of CGS in the Cambrian Deimena Formation and CO_2-EOR from the Upper Ordovician Saldus Formation. Testing of CO_2-EOR in Ordovician reservoir has not been done yet. Injection of CO_2 into the oil reservoir will significantly increase pressure and consequently oil extraction.

Planning the simultaneous use of the underground at different depths could be made in synergy, supporting profit from EOR and thus reducing the overall costs. This synergy will save resources on infrastructure and logistics and presenting win-win situation, storage of large amount of CO_2 and extracting of oil. Taking into account large area of the oil-bearing structure, we assumed it prospective for EOR+ that means large hypothetical potential for permanent storage of CO_2 in the future depleted oil field.

In the frame of pilot project idea of two possible scenarios are proposed to be considered in this study to support consequent testing, monitoring and common use of the E6 structure: (a) two wells and "fault-leakage" (possible leakage of CO_2 through the faults out of the Deimena Formation to the Saldus Formation), and (b) three wells and "no leakage" scenario.

2. Geological background

Previous studies show that the most prospective structures for CO_2 geological storage (CGS) in the Baltic region (Estonia, Latvia and Lithuania) are available in Latvia represented by number of onshore and offshore anticline structures [7, 8, 9, 10, 11]. The main target is the Baltic Basin (700 km × 500 km synclinal structure), a Late Ediacaran–Phanerozoic polygenetic sedimentary basin that developed in a peri-cratonic setting in the western part of the East European Platform. It overlies the Palaeoproterozoic crystalline basement of the East European Craton, specifically the West Lithuanian Granulite Domain, flanked by terranes of the Svecofennian Orogen southeast of the Baltic Sea [12]. Basin fill consists of Ediacaran–Lower Palaeozoic, Devonian–Carboniferous and Permian–Mesozoic successions, coinciding with what are referred to as the Caledonian, Variscan and Alpine stages of the tectonic development of the basin, respectively. These are separated by regional unconformities and overlain by a thin cover of Cenozoic deposits [13]. Several structures have been singled out in the Latvian part of the Baltic Syneclise [14]. The Estonian–Latvian and Lithuanian monoclines are the marginal structures of the Baltic syneclise. The Liepaja depression (Fig. 1) is a distinctly asymmetrical depression (length 200 km, width up to 70 km, trough amplitude 800 m) with a gentle northern and a steep near-fault southern edge. The Liepaja–Saldus zone of highs crosses the Baltic syneclise, stretching from the Swedish offshore towards the northeast for about 400 km (Fig. 1). The width of the zone is 25–80 km. From northeast to southwest, the basement submerges from 500 to 1900 m. The Liepaja–Saldus zone is a complex system of disjunctive-plicative dislocations, the intensity of which exceeds that in other areas of the Baltic syneclise. The amplitude of uplift in the anticline structures reaches 600 m. The Gdansk–Kura depression (Fig. 1) is only represented by its northern peripheral part. The South Latvian step, about 100 km long, is a sublatitudinal tectonic block in southern Latvia. The amplitudes of boundary faults reach 400–500 m [14].

Clayey Cambrian, Ordovician, and Silurian rocks are principal source rocks of the Baltic syneclise. In Latvia, Cambrian, Ordovician, and Lower Silurian rocks are at the early maturation stage, the depth of the basement being 1300–2000 m. Thus the main oil generation area is the Gdansk-Kura depression. The Liepaya depression, the Pape-Barta trough, and adjacent submerged parts of the Liepaya-Saldus zone of highs may be considered to be the local oil kitchen. One oil field, Kuldiga, was discovered in mid-Cambrian, and nine small accumulations in Ordovician

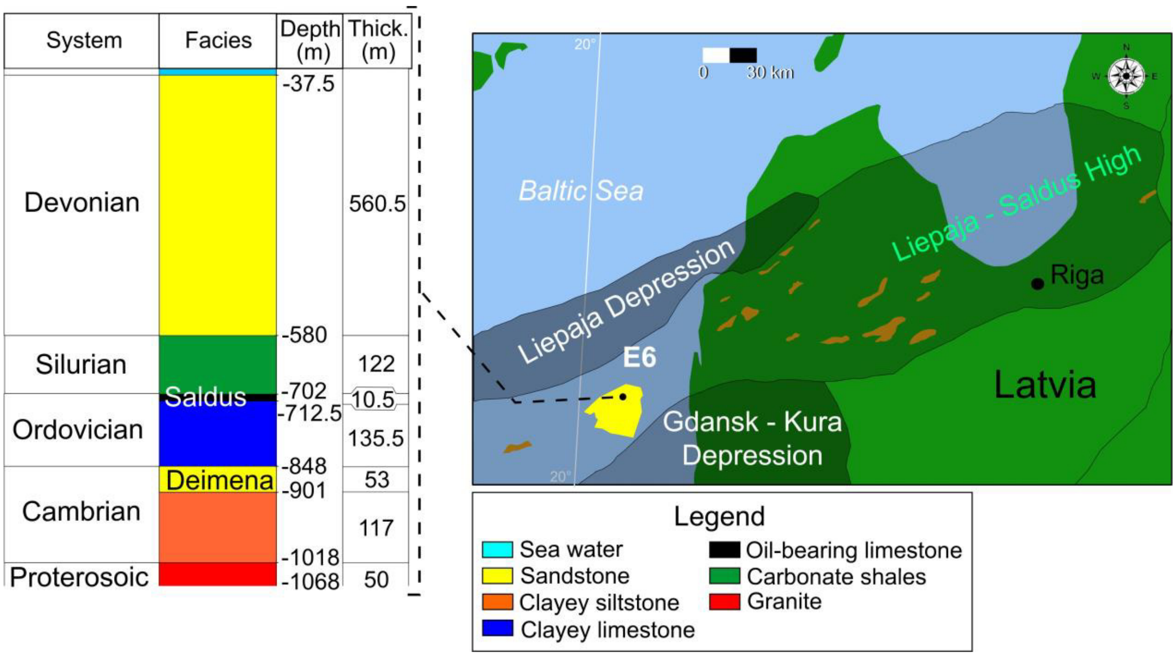

Fig. 1. Locations of Latvian onshore structures and the E7 structure offshore Lithuania (brown) prospective site for CGS (CO_2 storage potential exceeding 2 Mt) in the Cambrian aquifer and the studied E6 structure offshore Latvia (yellow), with the location of the well and full lithological cross-section. The Cambrian Deimena Formation of sandstones prospective for CGS and limestone oil reservoir of the Ordovician Saldus Formation prospective for CO_2-EOR and EOR+ of the E6 structure are shown on the lithological cross-section. Large regional structures complicating the Baltic Syneclise in the study area are shown on the map according to [13].

have been found in Latvia. Some oil prospects can exist in conjunction with Silurian carbonates [14].

The E6 offshore structure (Fig. 1) was found by seismic exploration and explored in 1984 by one well E6-1 (depth 1068 m), located 37 km from coast of Latvia. The structure coincides with the zone of Liepaja-Saldus Uplift and was estimated as prospective for oil in 10.5 m thick oil-bearing reservoir layer of the Saldus Formation in the Upper Ordovician Porkuni Stage [10, 11]. The fractured-porous Ordovician oil reservoir of the Saldus Formation, related to VI class reservoirs [15], is represented mainly by oil-bearing carbonate rocks: coarse clastic limestones with oolites, while oolitic limestones and subordinate calcareous quartzitic aleurolites are also present. From the palaeographical point of view, it means the shallow sediments of the Jelgava Depression and of the SE slope of the Central Baltic Elevation [16]. The rocks have good reservoir properties: the open porosity varies from 10 to 24% (average 18%) and gas permeability reaches 39 mD (average 6 mD) in well E6-1 [16, 17].

According to [18], fault system within the structure has led to the migration of hydrocarbons from the Cambrian reservoir to the upper Ordovician reservoir. The owner of the license for oil exploitation in the E6 structure is Danish oil company Odin Energi A/S. Oil reserves of the E6 structure estimated by the license owner is 362 MMBO (million barrels of oil) equivalent at the maximum closure of 585 km^2. Oil flow was very low during exploration: 2.7 m^3/day from 700 m deep Saldus reservoir due to low pressure within the reservoir and relatively heavy oil. No water flow from Porkuni beds was determined. Therefore, hydrochemical data, as exploration criteria are not available [16].

Oil shows were also found in the sandstones of the Cambrian Series 3 Deimena Formation and in the Devonian rocks of the offshore E6 structure (Fig. 1). Prospective for CGS reservoir of the Cambrian Series 3 Deimena Formation (848–901 m depth at the well E6-1/84) in the E6 structure was assessed as the largest storage site, among all the studied in the Baltic Region structures. Conservative and optimistic CO_2 storage capacity of the structure was estimated in the range of 160–400 million tonnes (Mt), respectively [10, 11]. The rocks of the Deimena Formation composed by dark- and light-grey, fine-grained, loosely and medium-cemented quartz oil-impregnated sandstones. The rocks were deposited in a shallow regressing marine basin subjected to tides and storms and are dominated by quartz sandstones with subordinate claystone layers (mud shelf). The poorly sorted sandstones of various grain size, containing gravel fraction, were deposited at the end of Deimena time. The major Deimena reservoir lies regressively on the Kybartai Formation. The regression was associated with the more sandy composition of deposits. Numerous faults dissect the Cambrian reservoir body. They form important pathways for fluid migration, while high-amplitude faults provide a blockage for fluid migration in the uplifted structures. The structure is an anticline fold bounded on three sides by faults. The E6 structure consists of two different compartments divided by inner fault [11, 17]. The total area of the structure is 600 km^2 considering the closing contour of the reservoir top located at a depth of 1350 m below sea level (BSL). The average thickness of the reservoir unit is 53 m.

Cambrian Series 3 saline aquifer (depth 700–1700 m) located in the central–western part of the Baltic Basin suits best for the CO_2 storage in the Baltic Region. It is composed of 25–80 m thick Deimena Formation sandstone unconformably covered by up to 46 m thick shales and clayey carbonates of primary cap rocks of the Lower Ordovician Zebre Formation. Shale rocks are dark, thin-layered (0.5–2 mm) and highly fissile. A 0.5 m layer of greenish-grey glauconite-bearing sandy marlstones with minor limestone lenses is observed at the base of the onshore Zebre Formation. The reservoir rocks are also covered by 130–230 m thick Ordovician (146 m thick in the well E6-1) and 100–225 m thick Silurian (122 m thick in the well E6-1) impermeable clayey carbonate secondary cap rocks, consisting mainly of shales, marlstones and clayey limestones (Fig. 1, [9]).

The porosity of the Cambrian Series 3 Deimena Formation reservoir sandstones is in the range of 14–33% (21% mean) and permeability is in the range of 10–440 mD (170 mD mean). Average porosity and permeability of the Ordovician cap rock are 3% and <0.01 mD, respectively. The Cambrian aquifer includes potable water in the northern shallow part of the Baltic Basin, mineral water (salinity 10 g/l) in southern Estonia and saline water in the Deimena Formation at more than 800 m depths, with salinity up to 120 g/l in the central and 150–180 g/l in the southern and western parts of the basin, where fluid temperature reaches 88 °C [16]. The last mentioned geochemical and pressure–temperature conditions of formation fluids allow the use of the Deimena Formation reservoir for CGS at depths of 800–2500 m, where CO_2 can be stored in a supercritical state (pressure >73 atm and temperature >31°C).

3. Storage Scenario-1 (SS-1)

The first Storage Scenario-1 (SS-1) presents CGS in the Cambrian Deimena Formation and oil recovery from the Upper Ordovician Saldus Formation (Fig. 2). This scenario gives the opportunity of testing the integrity of the Deimena Formation storage reservoir and monitoring of behavior of CO_2 within the storage site. The SS-1 is a first stage of the pilot project development for common use of underground and synergy of CGS and CO_2-EOR/EOR+ in the E6 structure. The SS-1 considers drilling of two wells: (1) CO_2 injection well into Deimena Formation and (2) oil recovery well into the Saldus Formations. Due to uncertainties of integrity of fault system in the E6 structure and according to theory of oil migration from the Deimena to Saldus Formation [18], we considered in the SS-1 a *"fault-leakage"* (leakage of CO_2 out of the Deimena Formation storage reservoir to the oil reservoir of the Saldus Formation via faults). However, presence of live-oil in the Saldus Formation gives us opportunity to assume integrity of the oil reservoir and impermeability of the Silurian cap rock. Thereby, CO_2 will stay in the Upper Ordovician with link to the Cambrian via faults.

Due to low pressure in the oil reservoir of the Saldus Formation and high viscosity of heavy oil the leakage of CO_2 to the oil reservoir will reduce the viscosity of live-oil and possibly increase inflow and recovery of the oil. The modelled scenario was considered as an economic case and a profit for CO_2-EOR/EOR+ in the Saldus Formation due to increase in oil production and sequestration of large amount of CO_2 at the end of oil recovery cycle. The surpluses of the SS-1 are the common injection well, thus reducing the overall costs, and increased CO_2 storage capacity (Fig. 2).

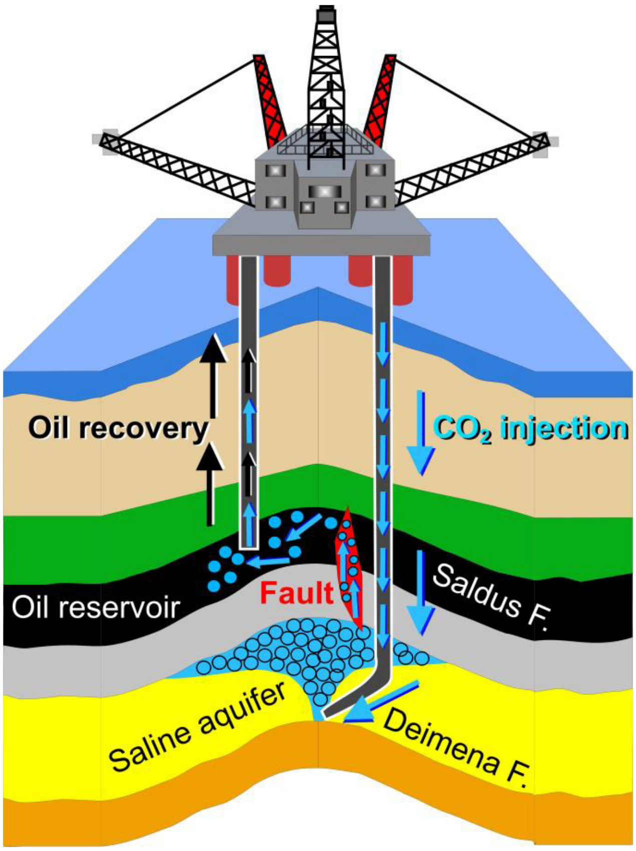

Fig. 2. Storage Scenario-1 (SS-1). Schematic model of the structure E6 (Fig.1) showing concept of synergy of CGS and CO_2-EOR/EOR+ in different geological formations in the same storage site. The SS-1 considers CO_2 leakage after injection to storage reservoir of the Cambrian Deimena Formation via fault system to the oil reservoir of the Ordovician Saldus Formation. The modelled case is considered as a profit for CO_2-EOR/EOR+.

4. Storage Scenario-2 (SS-2)

The second Storage Scenario-2 (SS-2) presents CGS in the Cambrian Deimena Formation and oil recovery from the Upper Ordovician Saldus Formation as well as in the SS-1 (Fig. 3). This scenario is a possible second stage of the pilot project development for the common use of the underground and synergy of CGS and CO_2-EOR/EOR+ in the E6 structure. In case of faults integrity, tested and monitored during the first stage of the pilot project (SS-1, Fig. 2), the SS-2 could be implemented to reach the main goal of the project.

The SS-2 considers drilling of three wells or additional well after the SS-1: (1) CO_2 injection well into the Deimena Formation, (2) CO_2 injection and (3) oil recovery wells into the Saldus Formations. In this scenario we considered "no leakage" of CO_2 out of the CO_2 storage reservoir of the Deimana Formation in the E6 structure via fault system (Fig. 3). Amount of CO_2 trapped in the oil reservoir depends on the distance between the CO_2 injection and oil recovery wells: longer distance between wells means more CO_2 trapped in the storage site. In a contrast with conventional CO_2-EOR, in the SS-2 we planned CO_2-EOR in the beginning of oil production. As a result, more oil will be produced than in conventional CO_2-EOR.

Surplus for SS-2 is increased CO_2 storage capacity: greater oil recovery means greater CO_2 storage capacity.

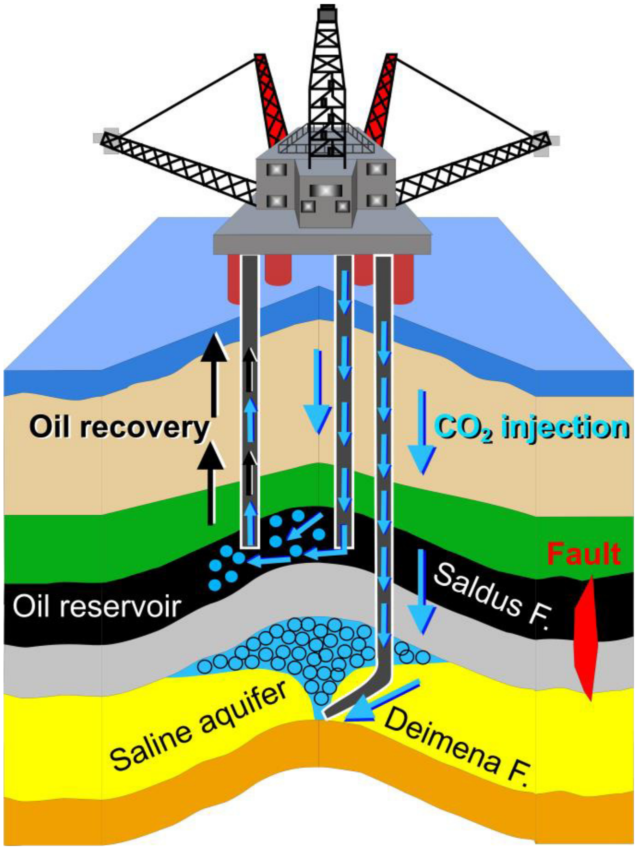

Fig. 3. Storage Scenario-2 (SS-2). Schematic model of the structure E6 (Fig.1) showing concept of synergy of CGS and CO_2-EOR/EOR+ in different geological formations at the same storage site. The SS-2 considers zero or very low vertical migration of CO_2 out of the CO_2 storage reservoir of the Cambrian Deimena Formation via fault system. The modelled case considers drilling of additional CO_2 injection well into the oil reservoir of the Ordovician Saldus Formation for CO_2-EOR/EOR+.

5. Discussion

In our study we are discussing the possibility of CGS in the Cambrian Deimena Formation and CO_2-EOR from the Upper Ordovician Saldus Formation in one geological structure offshore Latvia. During exploration, the inflow of heavy oil was insignificant due to low pressure in the reservoir and high viscosity of the oil. Injection of CO_2 into the oil reservoir will reduce the viscosity of heavy-oil and consequently will significantly increase oil extraction. CO_2-EOR method has been already tested for the Cambrian Deimena Formation ROZ (residual oil zone) in the Baltic Sea Region by the oil company. Two pilot injections have been made into Lithuanian onshore oil fields (about 2 km depth) for EOR-CCS in 2013, investigating potential of CO_2 to be used for EOR. The results showed that one tonne of injected CO_2 could produce one tonne of oil from Cambrian reservoir [19]. Testing of CO_2-EOR in Ordovician reservoir has not been done yet.

Planning the simultaneous use of the underground at different depths could be made in synergy, supporting profit from EOR and thus reducing the overall costs. This synergy will save resources on infrastructure and logistics and presenting win-win situation, storage of large amount of CO_2 and extracting of oil. Taking into account large area of the oil-bearing structure, we assumed it prospective for EOR+ that means large hypothetical potential for permanent storage of CO_2 in the future depleted oil field. Considering that the field is not yet depleted, it is possible to start simultaneous drilling of injection well for CO_2 storage into Deimena Formation and oil production well into Saldus Formation, implementing SS-1 as a first stage of the pilot project development. This scenario, in addition to being a profit for CO_2-EOR and EOR+, will provide the testing of integrity of the Deimena Formation storage reservoir during oil recovery cycle from the Saldus Formation, monitoring of CO_2 migration within the storage site and presents the most economic case for pilot project.

Fault system within the structure which possibly led to the migration of hydrocarbons from the Cambrian reservoir to the upper Ordovician reservoir [18] can represent possible leakage pass way during CO_2 storage. The risk of CO_2 leakage from the Deimena Formation due to uncertainties of the fault system was considered as a profit for EOR+ in the Upper Ordovician Formation. Fault integrity risk assessment study should be made to prevent possible CO_2 leakage from the oil reservoir via fault system. No transmissivity values are available for the faults in the area. The vintage seismic reflection data were insufficient for a detailed geometrical characterization of faults. Nevertheless, presence of live-oil in the Saldus Formation gives us opportunity to assume integrity of the oil reservoir and impermeability of the Silurian cap rock. Thereby, CO_2 will stay in the Upper Ordovician with link to the Cambrian Formation via faults. Furthermore, the largest onshore Inčukalns structure, with a structural setting comparable to E6, has been successfully used for underground gas storage for many years, serving for gas supply to Latvia, Estonia and Lithuania. This fact indicates that faults in the region may have enclosed, impermeable structure [20] and as suggested in [11], faults in the E6 structure can act as sealing surfaces. In case of zero or very low vertical migration of CO_2 out of the Deimena Formation, the CO_2 injection could be made into the third well to the Saldus Formation, which could be drilled simultaneously with production well for CO_2-EOR, implementing the second stage of the pilot project development (SS-2), or after depleting of the Saldus Formation. In case of the SS-2, CO_2-EOR was planned in the beginning of oil production, which is in a contrast with conventional CO_2-EOR. This fact will provide production of more oil than in conventional CO_2-EOR. The SS-2 considers synergy of CGS and CO_2-EOR/EOR+ in a different geological formations (closed geological systems) at the same storage.

6. Conclusions

In the present study, for the first time, the prospects of synergy of CGS and CO_2-EOR/EOR+ in different geological formations at the same storage site were discussed and two possible scenarios (SS-1 and SS-2) for the E6 offshore storage site were proposed. Profits of the synergy and possible risks were analysed for two possible scenarios. All available data from the E6 offshore structure including detailed description of the oil-bearing Upper Ordovician Formation, 3-D models, results of the petrophysical alteration effect on the rocks of storage reservoir induced by CO_2 and incorporated into the numerical seismic modelling were analysed together in this study. Proposed scenarios are the first of this type in the study area, presenting consequent development of the CGS and CO_2-EOR pilot project in the E6 offshore structure. The SS-1 in addition to being a profit for CO_2-EOR and EOR+, will provide the testing of integrity of the Deimena Formation storage reservoir during oil recovery cycle from the Saldus Formation and monitoring of behavoir of CO_2 within the storage site and presents the most economic case.

The surplus of the SS-1 is the common injection well, thus reducing the overall costs. In case the monitoring of the implemented SS-1 will show integrity of CO_2 storage reservoir in the Deimena Formation, the SS-2 could be applied. In a contrast to the conventional CO_2-EOR, in the SS-2 we planned CO_2-EOR in the beginning of oil production. As a result, more oil will be produced than in the conventional CO_2-EOR. Surplus for both scenarios is increased CO_2 storage capacity: greater oil recovery means greater CO_2 storage capacity.

Proposed scenarios should be developed in more details, when funded, can serve as examples and have an importance for further studies in the field of common use of the underground, when CGS and CO_2-EOR/EOR+ can meet in different storage formations of one geological structure. Implementation of the proposed scenarios will permit to clarify the history of oil migration within the E6 structure and will make input into geological history of the study area.

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