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The Role of CCUS Clusters and Hubs in Reaching Carbon Neutrality: Case Study from the Baltic Sea Region

Alla Shogenova[a,b]*, Kazbulat Shogenov[a,b], Saulius Sliaupa[c], Rasa Sliaupiene[c]

[a]Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[b]SHOGenergy,www.shogenergy.eu
[c] Nature Research Center, Institute of Geology and Geography, Akademijos 2, LT-08412 Vilnius, Lithuania
alla.shogenova@taltech.ee

The cross-border case study for the Baltic Sea Region includes the large emission sources from energy production, the cement industry, refineries, waste-to-energy plants and other large bio-emissions, identified in the Baltic States. The need to combine CO_2 emission sources from three countries into large CCUS cluster projects is explained by geological and regulatory limitations. Estonia, Latvia and Lithuania are situated within the common Baltic sedimentary basin. The best geological conditions for CO_2 geological storage are available in Latvia. In 2021 three countries produced about 15.9 Mt of large CO_2 emissions, including more than 2.2 Mt of bio-CO_2 emissions, located not far from the existing gas pipelines, which could connect emitters with storage sites and ports. The average optimistic storage capacity of the Cambrian Deimena Regional stage sandstones in the E6 structure, located 80 km from the Port of Klaipeda, is about 365 Mt CO_2. The largest onshore storage sites Dobele, North-Blidene and Blidene have a total average optimistic storage capacity of about 402.6 Mt. CO_2 emissions from three countries, including bio-emissions, could be captured, transported, used and stored in geological structures during more than 50 years. The regulatory process to permit CO_2 storage in Latvia has been started, initiated by Latvian largest CO_2 producers. Considering that 14% of the reported emissions are of biological origin, carbon neutrality could be reached in the Baltic States. Hydrogen production and storage and geothermal energy recovery using CO_2 could be combined in the proposed CCUS clusters, using for H_2 storage small E6-B compartment of the E6 structure offshore and Blidene structure onshore.

1. Introduction

Today, CCUS projects around the world store about 45 million tons of CO_2/per year. To reach climate neutrality we need to increase CO_2 storage from millions into billion tons/year. CCUS clusters and hubs are one of the options to accelerate this needed scale-up. We revealed at least 10 advantages of using CCUS clusters and hubs: 1) faster scale-up, 2) decrease the unit cost, 3) reduce the risk of investment, 4) reduce cross-chain risk, 5) governmental support, 6) new jobs, 7) CO_2 use revenues, 8) synergy with renewables, 9) synergy with CO_2 negative technologies and 10) increased public awareness and improved perception.
The objective of this study is to propose cross-border CCUS clusters and hubs which could help Baltic States to become carbon-neutral, or even negative in situations of geological and regulatory limitations and uneven distribution of the produced large CO_2 emissions in three countries.
The largest total CO_2 emissions (8.2 Mt, Table 1) and 11.5 t per capita are produced in Estonia, and the lowest in Latvia (1.8 Mt, Table 2 and 3.85 t per capita) (EU ETS, 2022, Cripa et al, 2022). Estonia, Latvia and Lithuania are located in the common Baltic Sedimentary Basin, while the best CO_2 storage capacity and geological conditions for gas storage are available in Latvia. In Estonia sedimentary basin is too shallow and there are no suitable structures found. In Lithuania, the depth of the prospective Cambrian Deimena Formation sandstone is increasing for more than 2 km and reservoir properties became less favourable for CO_2 gas storage (less porosity and higher temperature).
At the present time, CO_2 geological storage is forbidden in all three countries. In Estonia, such regulations were implemented based on the lack of suitable CO_2 geological storage sites, while in Lithuania CO_2 storage was permitted before 2019 when the new government banned it. CO_2 injection for research purposes is permitted in

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Latvia and Estonia. The process of changing climate strategy, policy and CCS regulations is ongoing in Latvia initiated by the largest CO_2 producers (Latvenergo and Schwenk Latvia). Among the Baltic States, only Estonia is a member of the London Protocol and implemented an amendment to Article 6 permitting the export of CO_2 for offshore storage under the seabed in deep geological structures. In this situation, Estonia, Latvia, and Estonia can share their efforts and available resources to create common CCUS clusters.

2. Data and methods

CO_2 emissions produced in 2021 and reported in EU ETS (2022) were used for the CCUS scenario. Additionally, bio-CO_2 emissions were assessed from national reports for Estonia and data on bio-CO_2 for Lithuania were added from data from CaptureMap provided by Endrava used in the mapping of CO_2 emissions sources in the CCUS ZEN project. Minimum, maximum, and average capacities were estimated using minimum, maximum, and average porosities for optimistic and conservative cases for all structures in our previous research (Shogenov 2013a, 2013b; Simmer, 2018). Data on CO_2 storage sites and CO_2 emission sources collected by the CCUS ZEN project in the Q-GIS system was used and updated to propose Baltic onshore and offshore CCUS clusters. We applied 95% as an average CO_2 capture rate, considering 90, 95 and 99% capture rates for various advanced capture technologies (IEAGHG, 2019).

3. CO_2 emission sources

The largest fossil CO_2 emission sources in Estonia are represented by four power plants (PP) and three shale oil plants (SOP) (Table 1). All these plants, located in the North-East of Estonia, use Estonian oil shales for energy and oil production. Among them, Eesti Energia (Enefit) PPs also produce bio-emissions during the co-combustion of wood waste together with oil shale. Additionally, several Estonian plants produce bio-emissions, including paper and pulp production (Horizon Paper Factory), energy co-generation plants (Fortum plant in Pärnu and Anne plant in Tartu) and one waste-to-energy plant (WtE) located in Iru near Tallinn. In total about 8.2 Mt CO_2 was produced in 2021, including 6.4 Mt from fossil fuels and 1.76 Mt of bio- CO_2.

Table 1: Large CO2 emissions produced in Estonia in 2021

N	Plant Name	Region	Sector	CO_2 produced in 2021, kt		Total CO_2, kt
				Fossil CO_2	Bio- CO_2	
1	Eesti PP	Auvere	Power	2,607,958	16,000	2,623,958
2	Auvere PP	Auvere	Power	885,666	409,944	1,295,610
3	Auvere SOP	Auvere	SOP	788,760	-	788,760
4	Balti PP	Narva	Power	645,847	187,767	833,614
5	VKG SOP	NEE	SOP	697,209	-	697,209
6	VKG Energia North TP	NEE	Power	593,857	-	593,857
7	Kiviõli Chemical Plant	NEE	SOP	159,357		
8	Horizon Paper Factory	Kehra	Paper	12,888	239,481	252,369
9	Utilitas Tallinn PP	Tallinn	Power	9,796	259,000	268,796
10	Fortum Cogeneration Plant	Pärnu	Power		268,000	268,000
11	Anne Cogeneration Plant	Tartu	Power		244,450	244,450
12	Iru Waste to Energy Plant	Iru	WtE		138,483	138,483
Total CO_2 produced				6,401,338	1,763,125	8,164,463

The largest CO_2 emissions in Latvia are produced by four plants including Schwenk Latvia cement plant in Broceni and three PPs located near Riga (two Latvenergo PPs and one Rigas Siltums thermal plant). Together they produced 1.75 Mt CO_2 in 2021 (Table 2). Bio-emissions were not reported by emitters to national authorities in Latvia.

Table 2: Large CO2 emissions produced in Latvia in 2021

N	Plant Name	Region	Sector	CO_2 produced, kt
1	Schwenk Latvia	Broceni	Cement	752,118
2	Latvenergo Tec-2	Riga	Power	675,287
3	Latvenergo Tec-1	Riga	Power	227,341
4	Rigas Siltums TP	Riga	Power	99,743
Total CO_2				1,754,489

The largest CO_2 emissions in Lithuania are produced by five plants including Achema, Orlen refineries, Akmenes Cement and two power plants in Vilnius. Together with two WtE cogeneration plants 5.54 Mt CO_2 were produced in Lithuania and reported in EU ETS in 2021. Another three waste-to-energy plants produced together 0.45 Mt bio-CO_2. About 6 Mt of CO_2 emissions were produced in Lithuania by large emitters in 2021 (Table 3).

Table 3: Large CO_2 emissions produced in Lithuania in 2021

N	Plant Name	Region	Sector	CO_2 produced in 2021, kt		Total CO_2, kt
				Fossil CO_2	Bio-CO_2	
1	Achema	Kaunas	Chemicals	2,208,916		
2	Orlen Lietuva	Telšiai	Refineries	1,501,524		
3	Akmenės Cement	Šiauliai	Cement	997,056		
4	Lietuvos Energijos Gamyba, PP	Vilnius	Power	304,646		
5	Vilniaus Šilumos Tinklai PP N2	Vilnius	Power	293,090		
6	Kaunas WtEP	Kaunas	WtE		198,000	
7	Vilnius WtEP	Vilnius	WtE		169,000	
8	Fortum Klaipeda WtEP	Klaipeda	WtE	126,007		
9	UAB "Toksika" hazardous WtEP	Šiauliai	WtE		79,000	
10	UAB Kauno WtEP	Vilnius	WtE	112,704		
Total CO_2				5,543,943	446,000	5,989,943

4. CO_2 storage sites

The most prospective CO_2 storage reservoir in the Baltic States is related to Deimena Regional stage sandstones of the Cambrian Wuliuan Stage. Estimated earlier storage capacity is about 400 Mt onshore and 300 Mt CO_2 offshore (Šliaupa, 2013). Since 2013 CO_2 storage capacity of the largest structures has been re-estimated and static structural geological models were constructed for four west Latvian onshore structures (Dobele, South-Kandava, Blidene, and North Blidene) and offshore structure E6 (Shogenov et al. 2013a, 2013b; Simmer 2018). The largest storage capacity onshore is available in the North-Blidene and Dobele structures and the largest storage site offshore is E6 structure (Table 4).

The North Blidene and Blidene structures located in western Latvia were recently applied in the Estonian-Latvian onshore CCUS scenario (Shogenova et al, 2021). Their optimistic and conservative CO_2 storage capacity was estimated by Simmer (2018), (Table 4). The North Blidene is an anticlinal uplift cut by west-east striking fault. The Blidene uplift is located in the down-dip block confined by the paralleling fault to the south and verging SW-NE of, the amplitude of down-thrust fault is about 400 m. These two structures are studied by five wells (Figure 1). The estimated area of the Dobele structure considering closing contour of 1075 m is 70 km^2 and amplitude is up to 110 m. The tectonic structure is located on the hanging-wall of the west-east oriented fault. These three structures are confined to the common Saldus-Inčukalna elevated fault zone. The Dobele uplift was drilled by 17 deep wells penetrating the Cambrian Deimena Formation and 5 wells were drilled in the hanging wall of the controlling fault (Figure 2). The Cambrian reservoir is represented by quartz sandstones interbedded by thin layers of sandy siltstone and mudstones. Deimena Formation sandstones were defined at 965−1013 m depth in the Db91 well, and 1346−1390 m depth in the Db92 well (Shogenov 2013a, Janson and Zeltins, 2015).

The E6 offshore structure (Figure 3, right) was discovered by seismic exploration and drilled in 1984 by well E6-1 (1068 m depth) located 37 km from the coast of Latvia. The structure coincides with the zone of Liepaja-Saldus uplifts and was estimated as prospective for oil exploration in the 10.5 m thick Upper Ordovician Saldus Formation reservoir. The structure is an anticline bounded on three sides by faults. The E6 structure consists of two different compartments (E6-A and E6-B) divided by the inner fault. 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 (BSL). The area of the larger E6-A part is 553 km^2. Prospective for CO_2 storage Cambrian Deimena Formation reservoir in the E6 structure was assessed as the largest storage site in the region. The Deimena Formation consists of quartz oil-stained sandstones with subordinate shale layers deposited in a shallow marine basin. The major Deimena reservoir overlies the shales of the Kybartai Regional stage (40 m thick). The Cambrian reservoir is sealed by large thick Silurian-Ordovician shale cap rock of 268 m thick in well E6-1. Offshore E6 structure has a smaller depth compared to onshore structures. Both onshore and offshore structures have good reservoir properties, while the temperature is higher offshore (36ºC) compared to 18−23ºC onshore. Because the lower temperature is more suitable for CO_2 storage, the density of CO_2 stored will be higher onshore than in offshore structure (Table

4). All structures discussed in the paper were drilled by one (E6) to 23 (Dobele) wells that can be rated as an Optimistic scenario, rather than Conservative scenario, considering of seismic exploration, drill cores, logging, hydrogeological, geothermal and other data available.

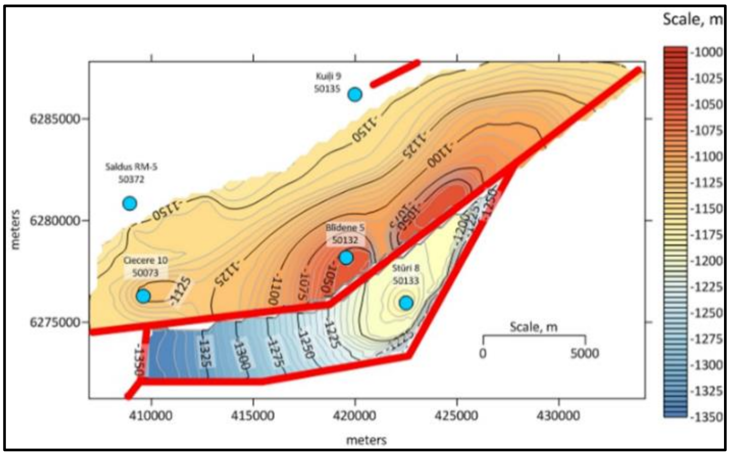


*Figure 1: Contour maps of the Deimena Formation in the North Blidene (above) and the Blidene (below) structures. A fault line is indicated with a red polyline (*Shogenova et al, 2021*).*

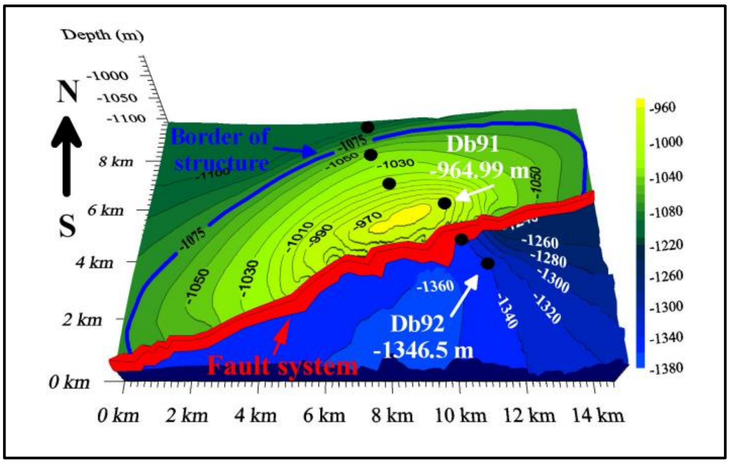


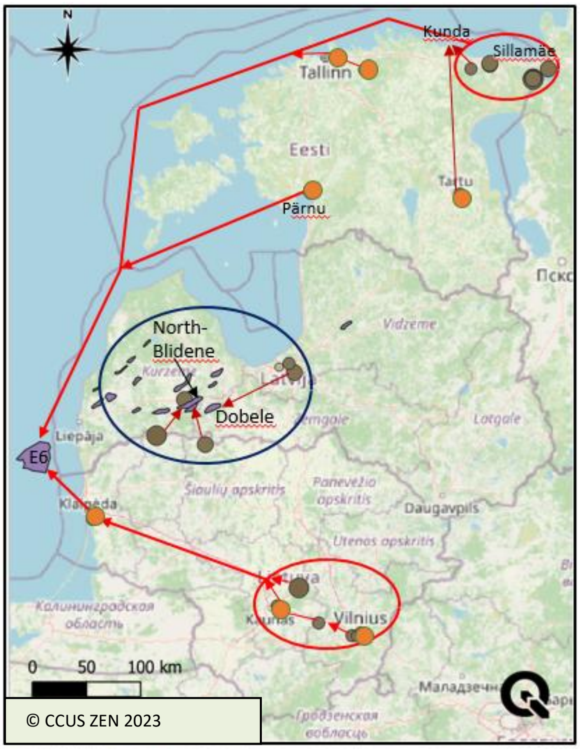
Figure 2: Structural model of the Dobele onshore storage site in Latvia (Shogenov et al., 2013a, b).

Table 4: Parameters of CO_2 storage sites selected for the Baltic scenario

Parameters	North Blidene	Blidene	Dobele	E6-A
Depth of reservoir top, m	1035-1150	1168-1357	965-1013	848-901
Reservoir thickness, m	48	66	52	53
Trap area, km^2	141	62	70	553
CO_2 density, kg/m^3	881	866	900	658
Net to gross ratio, %	75	80	85	90
Salinity, g/l	100-114	100-114	108-119	99
Permeability, mD ($10^{-16} m^2$)	370-850	370-850	0.1-670/360	10-440(170)
T, ºC	18	22.9	10.2-18.2	36
Storage efficiency factor Optimistic/Conservative (%)	30/4	5/3	20/4	10/4
Porosity (min-max/avg), %	12.5-25.6/20	13.5-26.6/21	10-26/19	14-33/21
Optimistic CO_2 storage capacity (min-max/avg), Mt	167-342/267	19-37.5/29.6	56-145/106	243-582/365
Conservative CO_2 storage capacity (min-max/avg), Mt	22.2-45.5/35.6	11.4-2.5/17.8	11-29/21	97-233/146

5. Technical modelling of the Baltic CCUS clusters

Two large CCUS clusters could be composed of Estonian, Latvian, and Lithuanian large emission sources and the most prospective storage sites in Latvia (Figure 3).



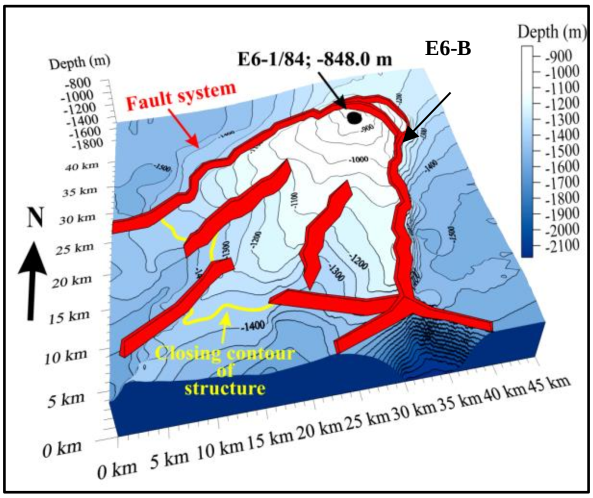


Figure 3: Right: Structural model of E6 storage site offshore Latvia (Shogenov, 2013a, b).
Left: Estonian-Latvian-Lithuanian CCUS clusters. Large fossil CO_2 *emissions reported in EU ETS are shown by brown circles. Bio-*CO_2 *emissions and waste to energy plants (not reported in EU ETS) are shown in orange points. The onshore cluster is shown by the large blue oval, while the offshore CCUS cluster is shown by red circles and arrows (updated after the CCUS ZEN project Q-GIS database).*

The Baltic offshore cluster includes all large Estonian and Lithuanian fossil and bio-emission sources – one of which Klaipeda WtE Plant and other sources located in central and south-eastern Lithuania. The CO_2 is supposed to be transported from proximal emitters by pipelines, while the E6 structure is to be linked by pipelines and ships, located as far as 80 km from Klaipeda Port. Estonian north-east cluster, composed of seven emission sources (four plants produced only fossil emissions and three power co-generation plants using both oil shales and biomass for energy production) will use CO_2 pipeline or truck/train transport to Sillamäe and Kunda ports and then ship CO_2 to the E6 storage site in Latvia (615 km by ship from Sillamäe). This cluster will be able to capture and store annually 11.1 t CO_2, including 9 Mt of fossil and 2.1 Mt of bio-CO_2.
The Baltic onshore cluster includes four of the largest Latvian CO_2 emitters and two Lithuanian plants located close to the Latvian-Lithuanian border (Orlen refinery and Akmenes cement plant, owned by Schwenk).

Table 5: CCUS full value chain clusters

N	Cluster Name	Number of emitters	Fossil CO_2 Mt	Bio- CO_2 Mt	Total CO_2 Mt	Storage site	Capacity Opt/Cons. Mt	Trans-port	Distance km
1	Latvian Onshore	3	1.0		1.0	Dobele	106/21	Pipelines	150
2	Lat-Lit Onshore	3	3.25		3.25	North-Blidene & Blidene	267/35.6 29.6/17.8	Pipelines	15-185
3	Est-Lit Offshore E6	20	9.45	2.21	11.66	E6A	365/146	Pipelines Ship	30-140 80-645
	Total produced	26	13.7	2.21	15.91		767.6/220.4		
	Total stored	26	13.02	2.1	15.23				

This cluster will store annually 3.1 Mt CO_2 from three plants (Latvian and Lithuanian Schwenk-owned cement plants and Orlen Refinery) in the onshore North Blidene and Blidene structures. Latvian two Latvenergo PP and one Rigas Siltums TP located in the Riga region will transport about 0.95 Mt CO_2 in the Dobele storage site in western Latvia using up to 150 km CO_2 pipelines.
The alternative CO_2 use option for Estonia is the application of CO_2 for mineral carbonation of Estonian burned oil shale (BOS) (Shogenova et al, 2021). Another option is the use of CO_2 for geothermal energy recovery in the E6 structure for the local energy needs of the drilling rig. The Baltic countries are looking forward to produce hydrogen. It can be stored in the smaller E6-B compartment of the E6 structure offshore and/or in the Blidene structure onshore (Figures 1-3).
Total amount of 15.23 Mt of fossil and bio- CO_2 emissions could be captured, transported, used and stored, while only 13.7 Mt of fossil CO_2 gas was produced in 2021. The negative balance is calculated about 1.53 Mt CO_2.

6. Conclusions

- The two largest onshore and one offshore storage sites in Latvia have the capacity to store all large Estonian, Latvian, and Lithuanian fossil and bio-CO_2 emissions.
- A total 15.1 Mt of fossil and bio- CO_2 could be captured, transported, used and stored, while only 13.7 Mt of fossil CO_2 produced annually. The negative balance is about 1.4 Mt CO_2.
- Additional revenues will come from geothermal energy recovery in Latvia for local heating and cooling needs, CO_2 mineral carbonation of BOS in Estonia and hydrogen production and storage in the Baltic CCUS clusters.
- The average optimistic storage capacity of the studied structures will be enough for more than 50 years, while conservative for 14.5 years. The CCUS cluster scenario represents the substantial volume to store the emitted CO_2 for the long transitional period Additional structures in the wester Latvia located near the largest ones could be also developed for CO_2 and H_2 storage.

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