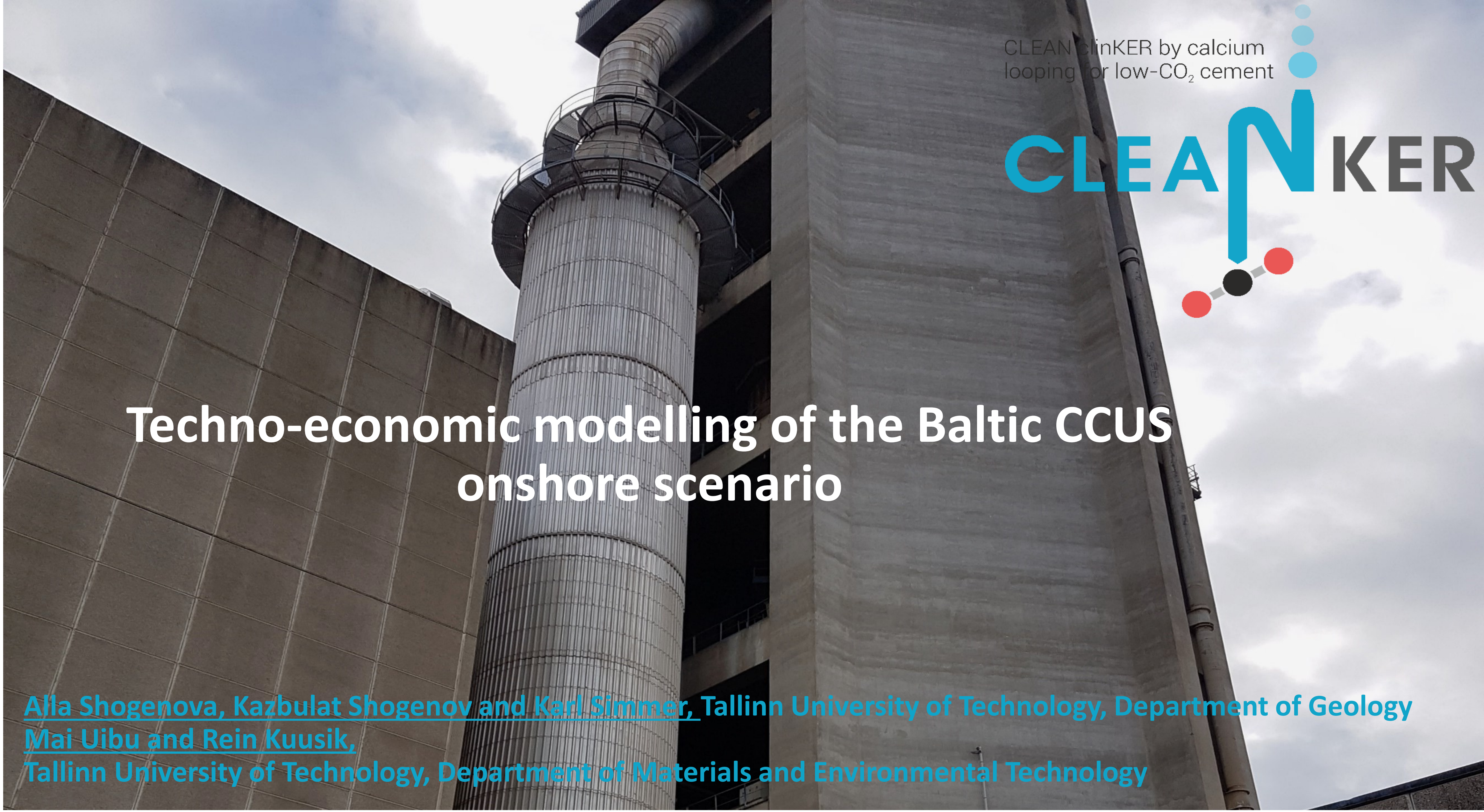

CLEAN clinKER by calcium looping for low-CO_2 cement

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Techno-economic modelling of the Baltic CCUS onshore scenario

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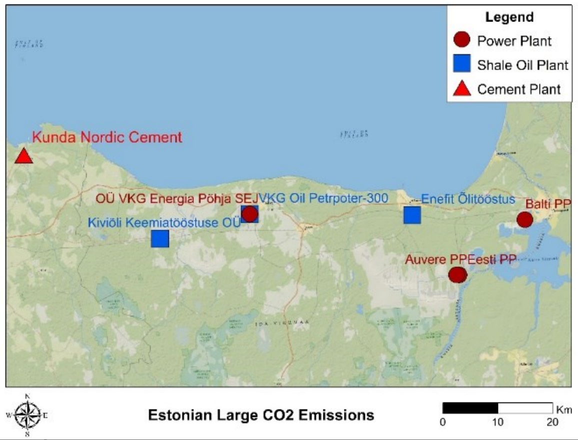
Techno-economic modelling of the Baltic CCUS onshore scenario

Introduction

- Baltic regional onshore scenario included Kunda Nordic Tsement (KNC), main Estonian cement producer, and CO_2 mineral carbonation of the oil shale ash, as possible CO_2 use option (Shogenova et al, 2019, 2021).
- Total CO_2 emissions per capita (14.2 t) produced in Estonia in 2019 was at the second place in Europe (after Luxemburg).
- Nearly 50% of the total fossil fuel emissions (7.9 Mt) were produced by 8 largest emission sources. (All CO_2 emission data for plants are obtained from EU ETS)
- CO_2 emissions produced in Estonia in 2019 were lower compared to 2018, after closing of some blocks at the Eesti Energia power.
- Large CO_2 emissions decreased again in 2020 for 2.7 Mt, caused by decrease of energy and no clinker production.
- In the end 2021 Estonia increased again energy production from oil shales, but it did not help to decrease high energy prices during energy crisis started at the end of 2021.
- CO_2 emissions produced in 2019 were used for techno-economic modelling of the Baltic CCUS scenario.
- Our scenario demonstrates how to continue using local Estonian oil shale for energy production, to get revenues, to safe economic and energy independency and to stop CO2 leakage to the countries supporting Estonia with energy and clinker.



Name of the Plant	Company owner	CO2 total emissions (Mt/year)				
		2017	2018	2019	2020	2021
Eesti PP	Eesti Energia	8.36	7.76	3.43	1.65	2.61
Auvere PP	Eesti Energia	1.36	1.52	0.65	0.8	0.89
Balti PP	Eesti Energia	1.6	1.13	0.92	0.4	0.65
Enefit Õlitööstus (shale oil)	Eesti Energia	0.82	0.84	0.84	0.8	0.79
VKG Oil Petrpoter-300 (shale oil)	VKG Oil, Viru Keemia Grupp	0.594	0.67	0.72	0.72	0.7
North PP	VKG Energia	0.6	0.59	0.68	0.63	0.6
Kunda Nordic Tsement	Heidelberg Cement Group	0.56	0.55	0.55	0.04	Account closed
Kiviõli Keemia	Alexela Group	0.15	0.15	0.17	0.17	0.16
	Total for Estonia	14.03	13.2	7.94	5.21	6.4

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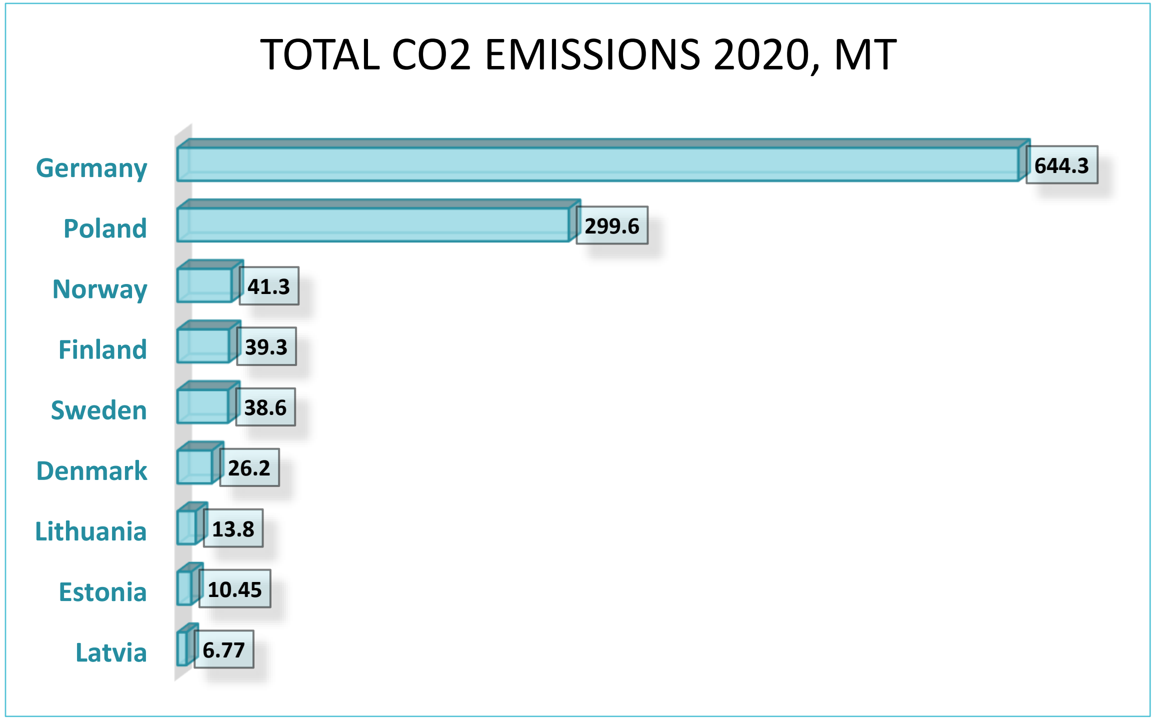
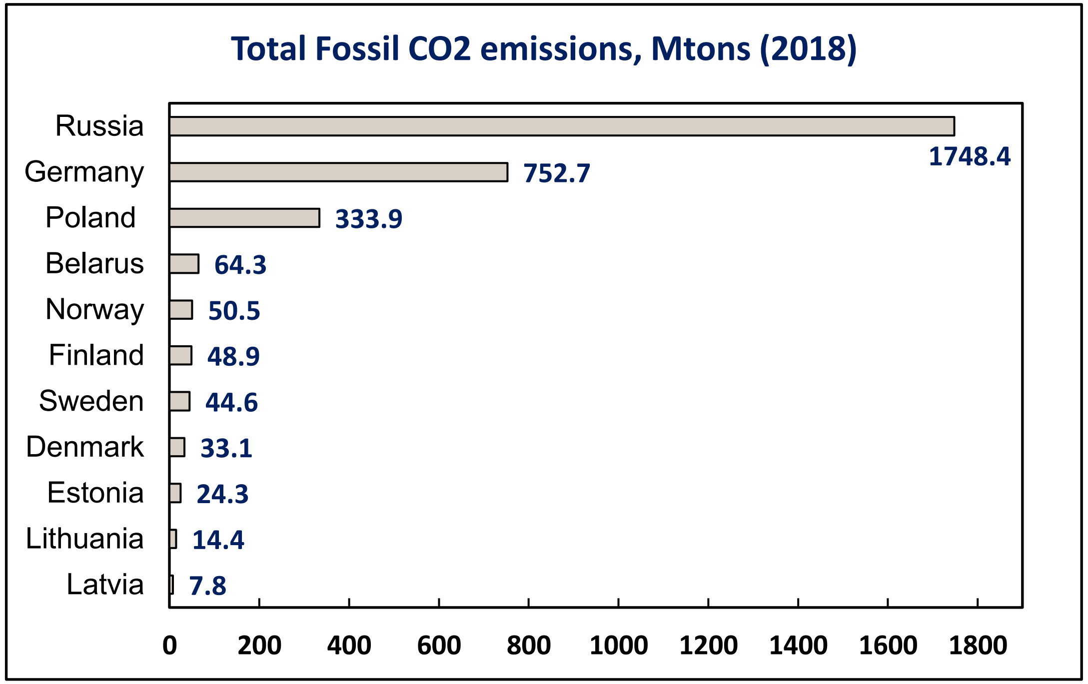
CO_2 emissions in the BSR

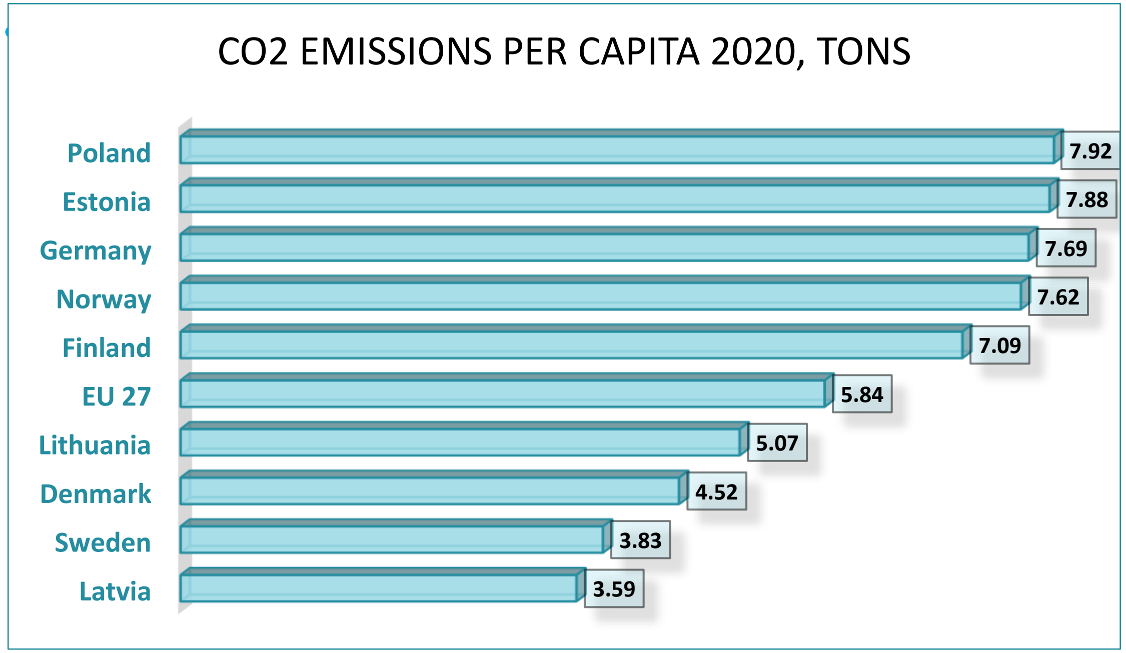


Data from: https://ourworldindata.org/co2-emissions#per-capita-co2-emissions



Data from:
EC JRC EDGAR - Emissions Database for Global Atmospheric Research; 2020.

CO_2 emissions per capita



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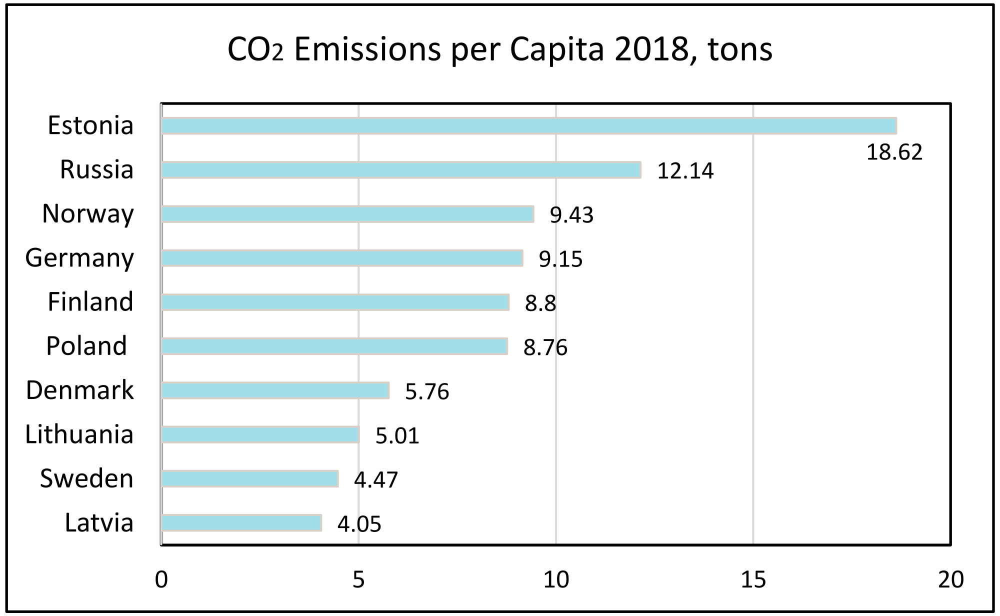

Data from:
EC JRC EDGAR - Emissions Database for Global Atmospheric Research; 2020.

Scenario includes: 6 plants and Mineral Carbonation from 3 plants

Baltic transboundary CCUS scenario includes:

- CO_2 emissions from six largest CO_2 producers from Estonia and Latvia
- CO_2 mineral carbonation (MC) of Estonian oil shale ash (OSA) produced by 3 power plants
- pipeline transport of captured and compressed CO_2
- storage of compressed CO_2 in the North-Blidene structure in the western Latvia.

The cluster of CO_2 emitters:

- HCG Kunda Nordic Cement (KNC)
- Eesti Energia power plants (PP):
  - ✓ Eesti
  - ✓ Balti
  - ✓ Auvere
- VKG Energia North PP
- Latvenergo TEC-2 PP

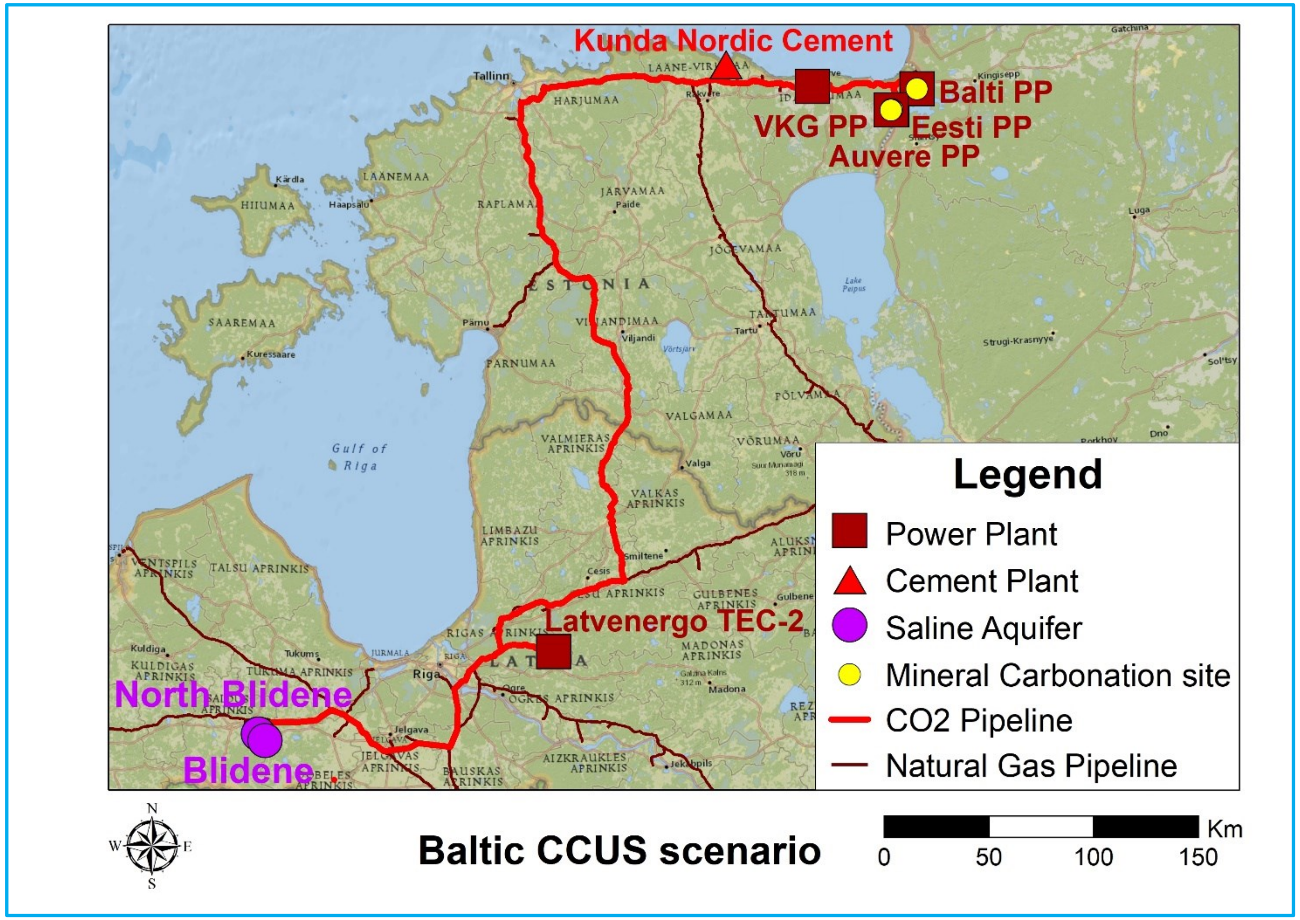

Fig 1. Baltic CCUS scenario for six CO2 emission sources, mineral carbonation and storage in North-Blidene storage site

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Techno-economic modelling of the Baltic CCUS onshore scenario

Data and methods

- Data were collected into ArcGIS database.
- Building block datasets were used to estimate costs for CO_2 transport and storage (EPRI, 2015, Shogenova & Shogenov 2018)
- All costs were calculated proportionally to CO_2 flow of the plants

Estimated earlier costs were applied

- CO_2 capture and compression: 25.5 and 2.8 €/t CO_2 (Shogenova et al, 2011)
- Direct MC of CO_2 captured by OSA from flue gas 15 €/t CO_2 [4]
- EU Emission Allowance Price was considered 40 Euro/t CO_2

Applied parameters

- Capital charge rate : 8%
- Interest during construction (2 years): 1.5%.

Annual fixed O&M cost :

- 1% for pipelines
- 2% for wells
- 4% for the booster pumps and storage facilities

Annual onsite operating costs (design, engineering, environmental assessment, supervision, management, logistics and equipment/project contingencies): 40% from Bare Erected Cost for transport and storage

- Decommissioning: 25% from Total Plant Cost (2 years following the end of the project,may include costs for site remediation and equipment dismantling)

Techno-economic modelling of the Baltic CCUS onshore scenario

The average cost per ton of CO_2 injected, or per ton of CO_2 avoided for the project duration (30-years) is calculated using below formulas (EPRI, 2015):

- **CAPEX/**t_{CO_2}= $\frac{CCRxTPC+FOM}{CO_2\ injected}$ **, (€/t CO_2),** OPEX/t_{CO_2}= $\frac{CCRxCOSToper}{CO_2\ injected}$ **, (€/t CO_2)**
-
- MVEX/t_{CO_2}= $\frac{COSTmv}{CO_2\ injected}$ **, (€/t CO_2),** ENEREX/t_{CO_2}= $\frac{COSTenergy}{CO_2\ injected}$ **, (€/t CO_2)**
-
- **COSTtotal/**t_{CO_2}**= CAPEX/t_{CO2} + OPEX/t_{CO2} + MVEX/t_{CO2} + ENERGEX/$t_{CO2;}$ TPC = BEC + Decom + interest**
- CAPEX/t_{CO_2} – total capital expenses (pipeline, booster, wells or/and storage facilities) per one tonne of CO_2 injected/avoided during project duration
- OPEX/t_{CO_2} – operational and maintenance expenses per one tonne of CO_2 injected/avoided during project duration
- MVEX/t_{CO_2} – monitoring and verification expenses per one tonne of CO_2 injected/avoided during project duration
- ENEREX/t_{CO_2} – energy expenses per one tonne of CO_2 injected/avoided during project duration
- COSTtotal/t_{CO_2} - total transport and storage costs per one tonne of CO_2 injected/avoided during project duration
- CCR – capital charge rate (%), TPC – total plant cost = BEC + decom + interest, BEC – bare erected cost for pipeline, booster, wells or/and storage facilities
- Decom – decommissioning cost , Interest – interest paid during construction, FOM – annual fixed operating and maintaining cost (Euro/year)

Techno-economic modelling of the Baltic CCUS onshore scenario

- **Proposed scenario:**
- ✓ 6 CO2 emission sources
- ✓ CO2 use: Mineral Carbonation Plant (CO2+ Oil Shale Ash)
- ✓ Pipeline transport
- ✓ North-Blidene Storage site in Latvia
- ✓ Cambrian saline aquifer: Deimena Formation sandstones
- ✓ CO2 emissions: 2019

Mineral Carbonation Plant
- 110 kg of CO_2 /t OSA
- 250 kg of PCC (precipitated $CaCO_3$) from one t OSA
- 0.42 Mt CO2+3.8 Mt OSA= 0.95 Mt PCC/year

Revenues
- avoided EEAP 40 Euro/t CO_2
- 3 €/t OSA for OSA disposal
- 50 €/t PCC

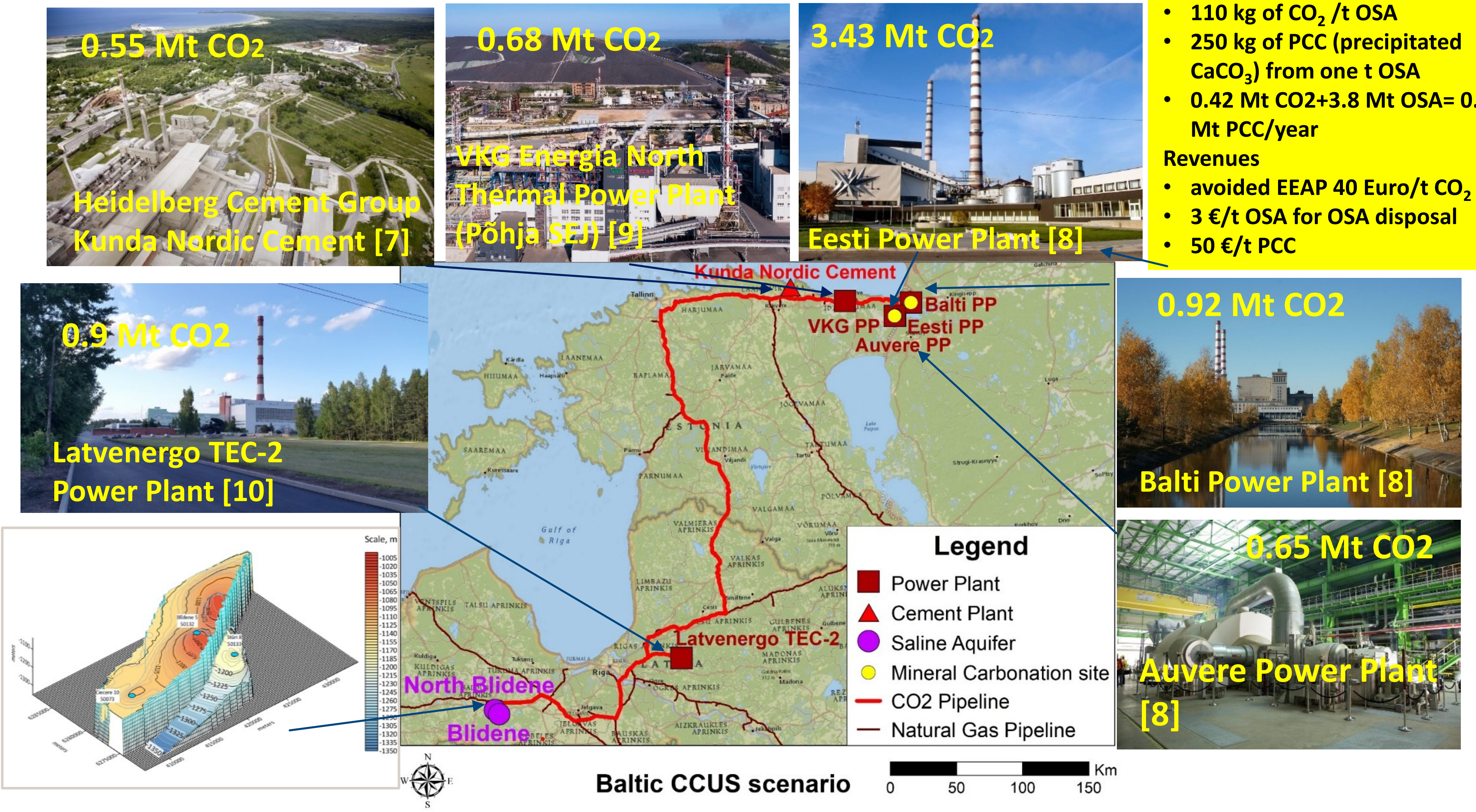
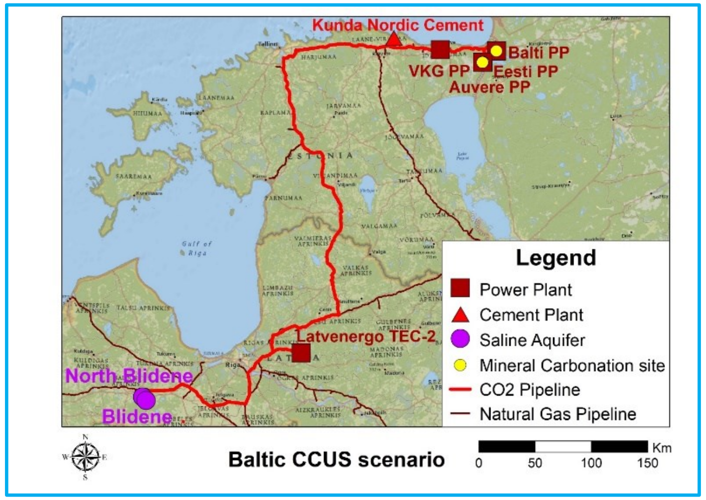
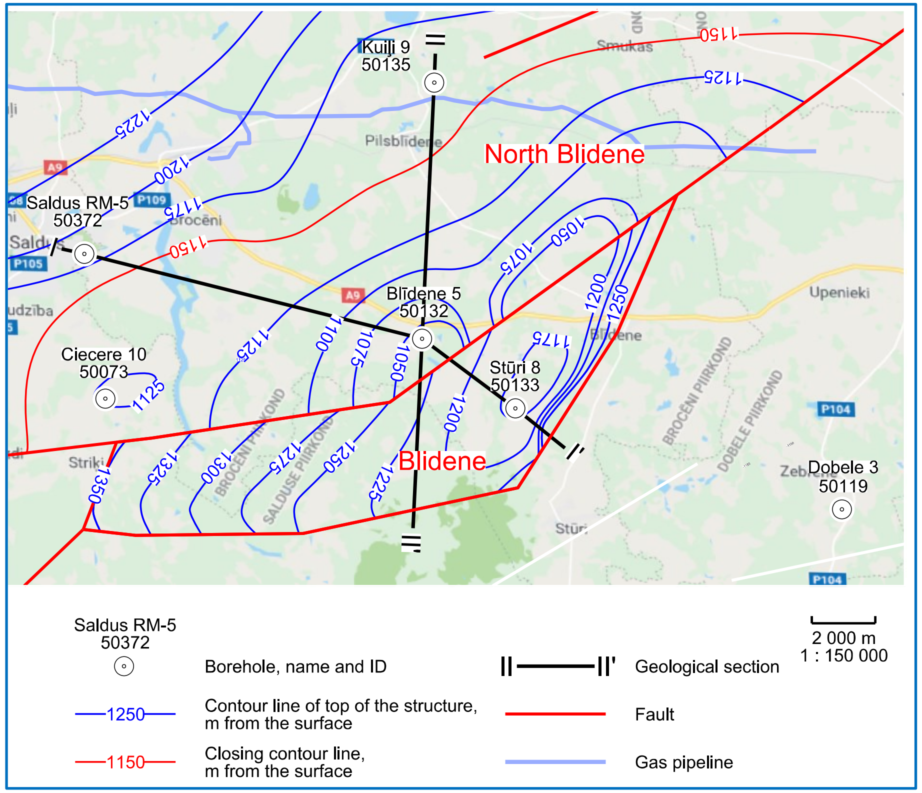
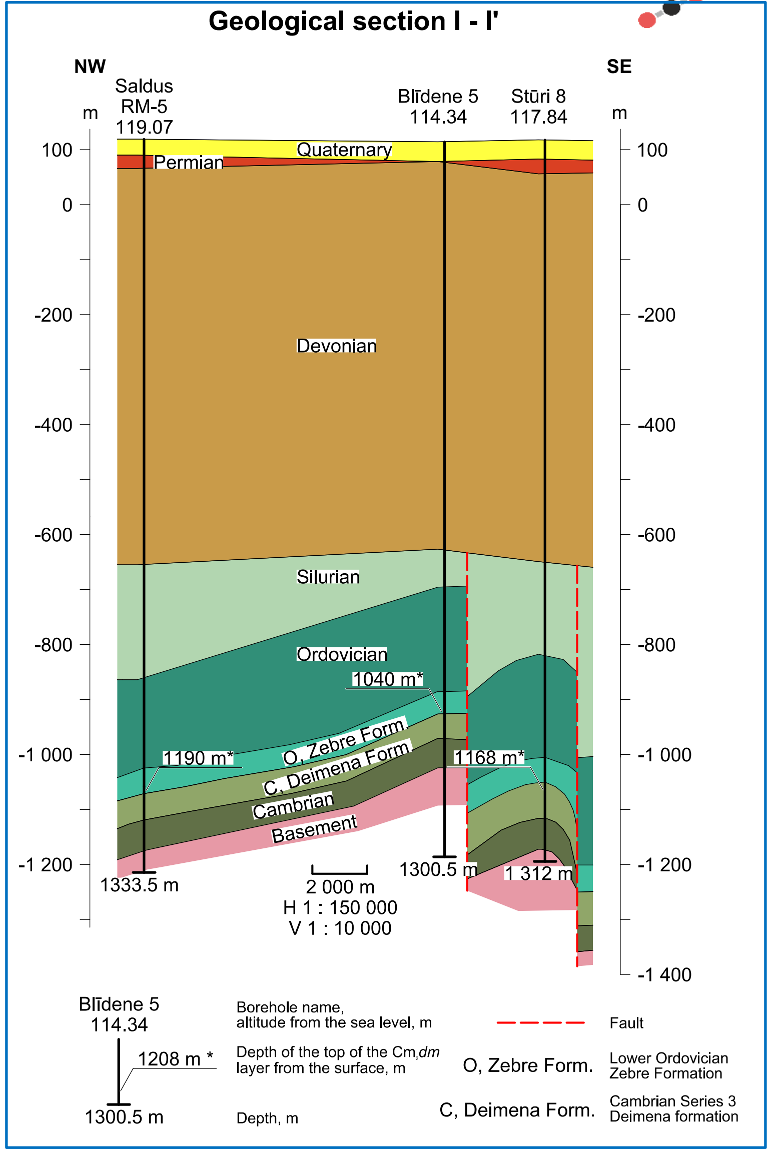


Fig 2. Baltic CCUS scenario.CO2 emissions produced in 2019 are shown in yellow colour

CO_2 storage site: Blidene and North-Blidene structure in the Western Latvia

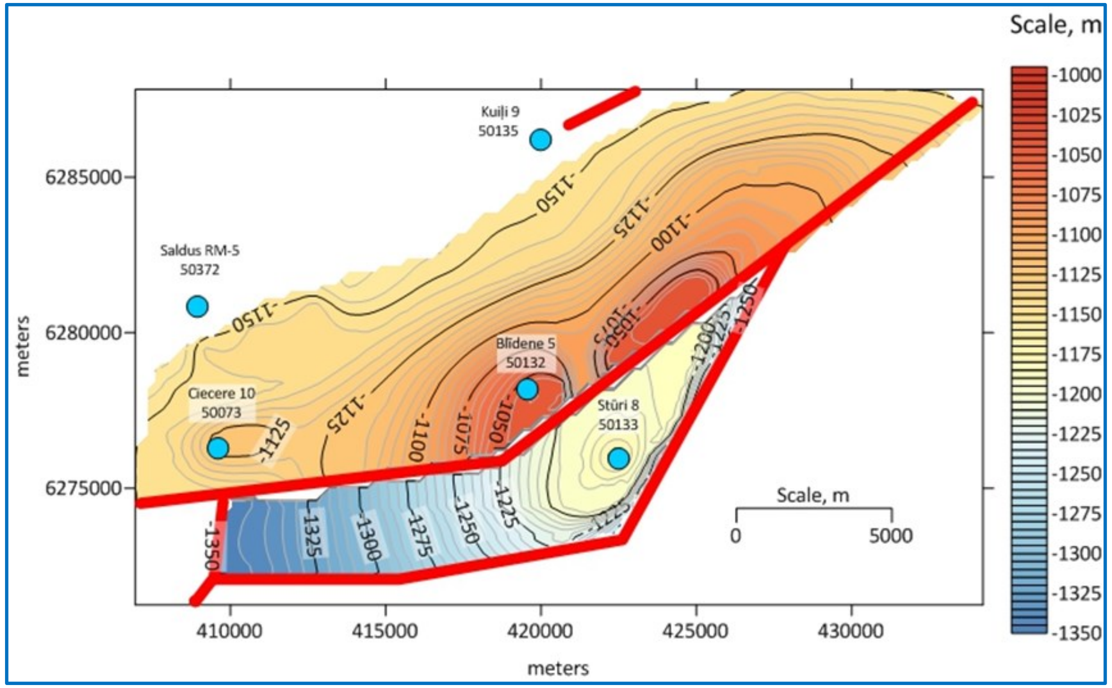


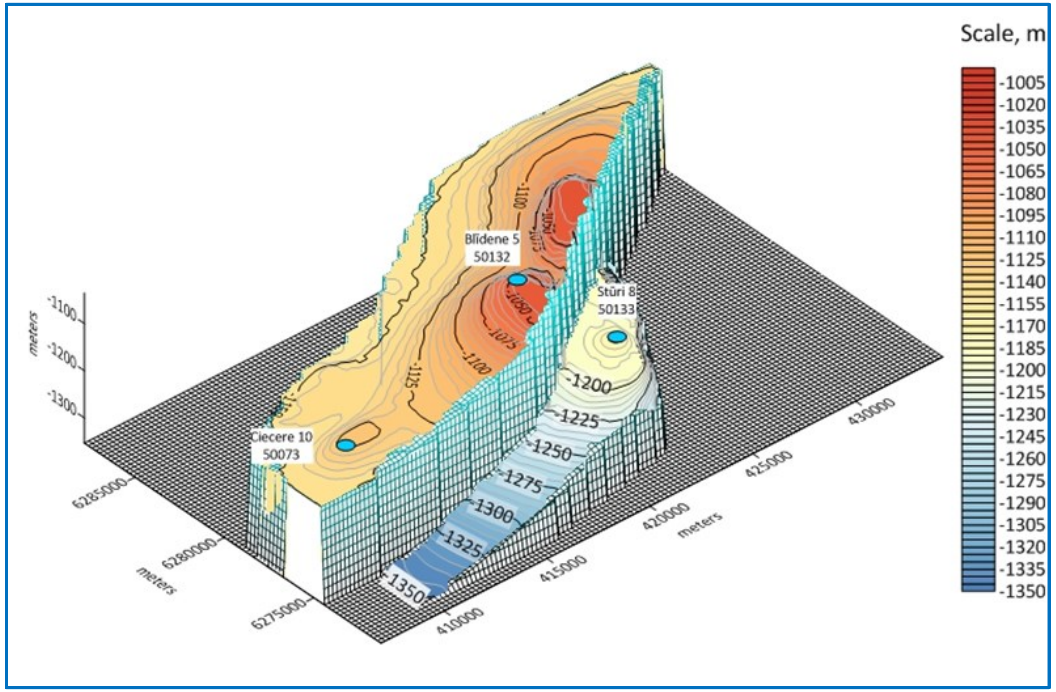




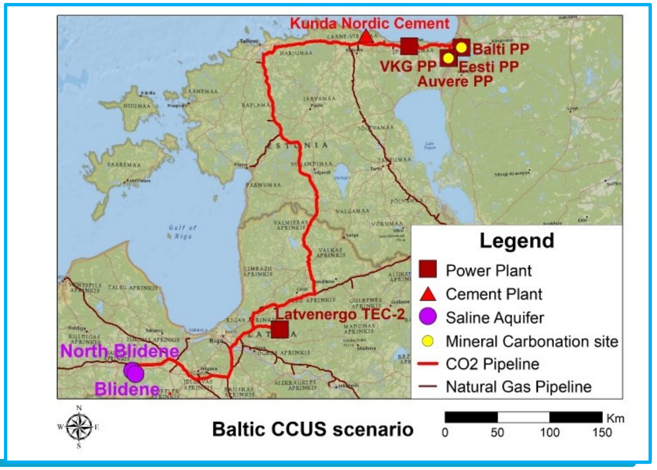
- Fig 3- Left: Storage site location
- Fig 4 - Centre: Structure map of the the top o the Cambrian Series 3 Deimena Formation sandstones in the North Blidene and the Blidene structures. Base map is from the Google Maps, 2018 (Simmer, 2018).
- Fig 5 -Right: Geological sections across line I-I' shown at the Fig.4.
- The map and section are composed using Bentley PowerCivil for Baltics V8i (SELECTseries 2) software (Simmer, 2018).

CO2 storage site: Blidene and North-Blidene structure in the Western Latvia





- Fig 1. Left: Contour maps of the top o the Cambrian Deimena Formation in the North Blidene (left) and the Blidene (right) structures. Fault line is indicated with red polyline;
- Right: 3D structure maps of the Deimena Formation in the North Blidene (above) and the Blidene (below) structures. Both pictures are composed using Golden Surfer 15 software (Simmer, 2018).



Parameters of the Cambrian Deimena Formation Reservoir sandstones in the storage structure

Parameters	North Blidene	Blidene
Depth of reservoir top, m	1035-1150	1168-1357
Reservoir 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
Permeability, mD	370-850	370-850
T, ºC	18	22.9
Storage efficiency factor (S_{eff}) Optimistic/Conservative (%)	30/4	5/3
Porosity (min-max/avg), %	12.5-25.6/20	13.5-26.6/21
Optimistic CO_2 storage capacity (min-max/avg), Mt	167-342/267	19-37.5/29.6
Conservative CO_2 storage capacity (min-max/avg), Mt	22.2-45.5/35.6	11.4-22.5/17.8

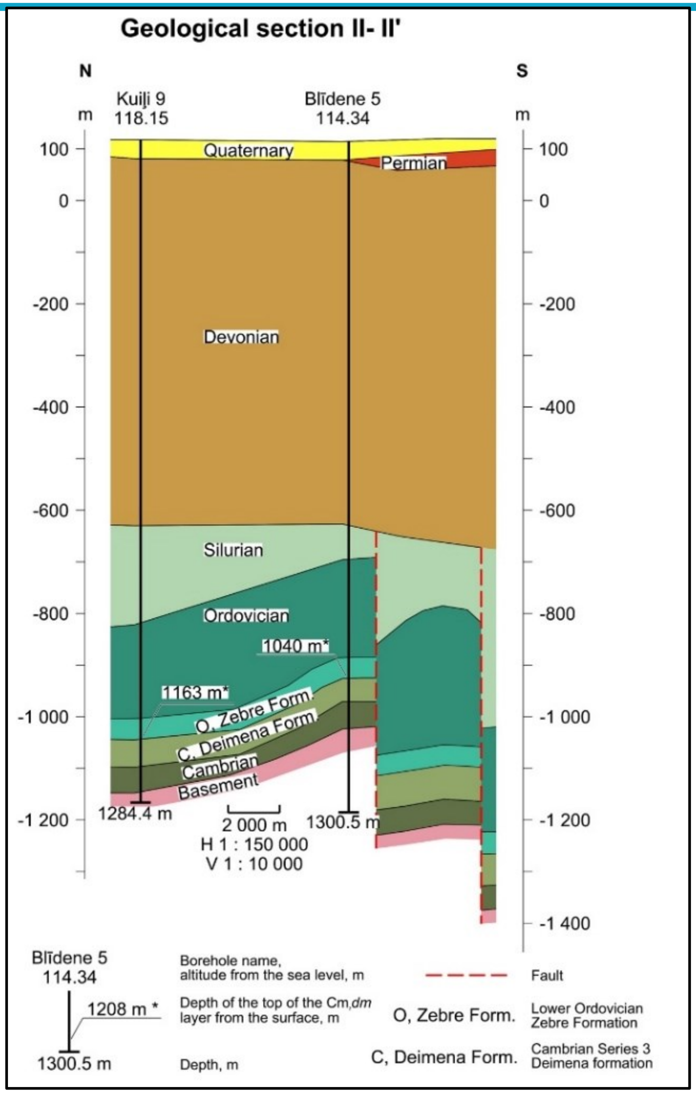


Fig 5. Geological sections of the Blidene and North-Blidene structure across line II-II' shown at the Fig.4.

CO2 Use for Mineral Carbonation (MC) of the Oil Shale Ash (OSA)

- In 2019 oil shale production decreased to 12 Mt (16 Mt in 2018) and of oil shale ash to 6.5 Mt (9.4 Mt in 2018).
- Eesti Energia plants produced about 3.9 Mt of OS ash in 2019 and used 1.8% for construction and agriculture (Eesti põlevkivitööstuse aastaraamat 2019).
- Estonian burnt oil shale could be used as an effective sorbent in the CO_2-mineralization process,

  binding in a range of **0.043-0.18 kg CO_2** per kg of waste (average **0.092 kg CO_2**).
- It was estimated that **3.81 Mt** of OSA produced at 3 largest Eesti Energia PP could be used for CO_2 MC annually.
- In average **250 kg of PCC** (precipitated $CaCO_3$) could be produced from **t/OSA**.
- Annually **3.81Mt*0.25=0.95 Mt of PCC** could be produced,
- **28.6 Mt during 30 years**.
- **110 kg of CO_2 per/ton OSA** could be avoided
- Annually **3.81 Mt*0.11=0.42 Mt** of CO_2 could be carbonated (avoided),
- **12.6 Mt CO_2 avoided per 30** years.
- Considering that only 90% of CO_2 could be captured from flue gas, **0.47 Mt of produced CO_2 should be** could be used for MC **per year.**

CO_2 emissions produced, captured and avoided from six Baltic plants.

Location	Estonia						Latvia	Total
Company	Heidelberg Cement	Eesti Energia (Enefit Energia)			VKG Energia	Total for 5 Estonian plants	Latvenergo	Estonian-Latvian scenario
Plant / Parameters	KNC	Eesti PP	Auvere PP	Balti PP	North PP		TEC2 PP	
CO_2 emissions produced per year in 2019, Mt	0.55	3.43	0.65	0.92	0.68	6.23	0.90	**7.13**
CO_2 use for mineral carbonation, Mt		0.47				0.47		**0.47**
CO_2 emission captured per year (95%)	0.52	2.81	0.62	0.87	0.65	5.47	0.85	**6.33**
CO_2 emission produced during capture and storage (5%)	0.03	0.14	0.03	0.04	0.03	0.27	0.04	**0.32**
CO_2 emissions avoided per year, Mt	0.49	2.67	0.59	0.83	0.61	5.20	0.81	**6.01**
CO_2 emissions avoided per 30 years, Mt	14.8	80.1	17.6	24.9	18.4	155.9	24.3	**180.2**
CO_2 emissions per year avoided, % from total	8.2	44.5	9.8	13.8	10.2	86.5	13.5	**100**

CO_2 transport infrastructure and costs

- The pipelines will be designed using X70 steel and 1500 lb flange rating (rated to 25.5 Mpa upper working pressure) with a maximum allowable working pressure of 15 MPa.
- The pipeline diameter was determined depending on the distance and flow rate of CO_2 calculated for the specific scenario according to (EPRI, 2015).
- The annual flow rate for the local pipelines from KNC and VKG Energia North plants and Latvenergo TEC2 is less than 1 Mt per year and distance to the shared (common) pipeline is 3.5-24 km. Therefore 120-160 mm diameter could be sufficient.
- The common pipeline is designed for 710 km and 6.33 Mt of CO_2 flow.

CO_2 pipelines parameters and costs (*total for 3 Eesti Energia plants) for Estonian-Latvian onshore CCUS scenario

Company	Heidelberg Cement	Eesti Energia (Enefit Energia)			VKG Energia	Total for 5 Estonian plants	Latvenergo	Total for Estonian-Latvian scenario
Plant Parameters	KNC	Eesti PP	Auvere PP	Balti PP	North TPP		TEC2 PP	
Pipeline distance to common pipeline, km/diameter, mm	9/120	12/250	1+12/250	19/200	3.4/120		25/160	
Capital costs for individual pipeline, M€	1.24	2.72	0.72	3.16	0.37	8.21	4.45	12.66
Common part of CO_2 pipeline, km	615	710	710	710	666		164	710
CAPEX for common pipeline, M€	61.24		603.18*		83.36	747.78	24.06	771.84
Total pipeline CAPEX, M€	62.48		609.78*		83.73	755.99	28.51	784.50
Annual pipeline OPEX, M€	0.63		6.1*		0.84	7.56	0.28	7.85

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CO_2 compression, injection and monitoring costs

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- Recompression using booster pumps will be needed to keep CO_2 in a dense phase when the pressure will drop below 8 Mpa.
- The capital costs of booster pumps is a function of CO_2 flow-rate, and recompression duty is a function of discharge pressure, which is different for various CO_2 flow-rates.
- Considering the average price of electricity in 2019 in Estonia, Latvia and Lithuania, 45 €/per MW was taken for the scenario.
- CO_2 injection costs include: well drilling, storage site facilities and monitoring.
- In total 4 injection and 2 monitoring wells are planned for CO_2 storage and monitoring
- Corring and logging are included for all six wells. Total capital costs for all wells is **17.75 M€.**

Company	HCG	Eesti Energia			VKG	Total for 5 Estonian plants	Latvenergo	Estonian-Latvian scenario
Plant / Parameters	KNC	Eesti PP	Auvere PP	Balti PP	North PP		TEC2 PP	
Total CAPEX for all wells and storage facilities, M€	1.46	7.89	1.73	2.45	1.81	15.35	2.39	17.75

- Cost for onshore 3D seismic survey (C) depends on area.
- For our scenario C=0.76 M€, considering 141 km^2 area of the North Blidene structure, taken for seismic monitoring.
- Baseline monitoring before injection and every year during injection is needed according to the European regulations .
- After closure of CO_2 storage site, it will be done annually during three years and then every five years during 30 years .
- Altogether monitoring should be made and reported 40 times: baseline before injection, 30 (during injection), and 9 (after closure).
- Additional monitoring expenses in monitoring and injection wells could be covered by 40% O&M costs (on-costs).

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Total costs for CO_2 transport and geological storage for 30 years project

Company	HCG	Eesti Energia (Enefit Energia)			VKG Energia	Total for 5 Estonian plants	Latvenergo	Total for Estonian-Latvian scenario
Plant / Parameters	KNC	Eesti PP	Auvere PP	Balti PP	North TPP		TEC2 TPP	
CO_2 injected per year, Mt	0.52	2.81	0.62	0.87	0.65	5.47	0.85	6.37
TPC (Total Plant Cost), M€	81.68		793.26*		109.19	984.14	40.39	1024.55
CAPEX, €/tCO_2 injected	13.87		16.22*		14.91	15.82	4.16	14.14
OPEX total (40% from BEC), M€	25.83		250.83*		34.53	311.19	12.77	323.97
OPEX, €/tCO_2 injected	3.98		4.66*		4.28	4.55	1.20	4.07
MVEX (annual monitoring and verification cost), M€	0.09	0.49	0.11	0.15	0.11	0.95	0.15	1.09
MVEX, €/tCO_2 injected	0.17	0.18	0.17	0.17	0.17	0.18	0.17	0.17
ENEREX (annual energy cost for boosters), M€	0.0002	0.0012	0.0003	0.0004	0.0003	0.0023	0.0004	0.0027
ENEREX, €/tCO_2 injected	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
COSTtotal, €/tCO_2 injected	**18.02**		**21.06***		**19.36**	**20.54**	**5.54**	**18.38**

CO_2 Mineral Carbonation Costs and Revenues

Mineral Carbonation Plant at Eesti Power Plant:

- **110 kg of CO_2 /t OSA**
- **250 kg of PCC (precipitated $CaCO_3$) from one t OSA**
- **0.42 Mt CO2+3.8 Mt OSA= 0.95 Mt PCC/year**

Revenues

- **avoided EEAP 40 Euro/t CO_2**
- **3 €/t OSA for OSA disposal**
- **50 €/t PCC**

Mineral Carbonation Costs

15 €/t CO2 (Reddy et al, 2010, Christensen, 2010)

Annually 0.42Mt*15€=6.3 M€

OSA will be transported from Auvere PP (1 km) and Balti PP (20.9 km) to MC plant (at Eesti PP).

Transport by trucks: 0.07 Euro per km per/t of OSA

Annual transport cost 1.06 M€

Total annual cost 7.36 M€.

Annual revenues:

PCC production: 47.63 M€ per year

EEAP 40 Euro/t CO_2:16.8 M€

3 € per t of OSA for OSA disposal: 11.43 M €

Total annual revenues: 75.86 M€

Revenues – Costs = 69.56 M€

Techno-economic modelling of the Baltic CCUS onshore scenario

Total economic results for CO_2 use, transport and storage scenario (* total for 3 Eesti Energia plants)

Company	Heidel-berg Cement	Eesti Energia (Enefit Energia)			VKG Energia	Total for 5 Estonian plants	Latv-energo	Total for Estonian-Latvian scenario
Plant	KNC	Eesti PP	Auvere PP	Balti PP	North PP		TEC2 PP	
COSTtotal (T&S), €/t CO_2	18.02		21.06*		19.36	20.54	5.54	18.38
Balance per one year (revenues-costs), M€	-4.94		24.2*		-5.69	14.47	3.77	18.44
EEAP needed for zero balance, €/t CO_2	48.0				49.4			

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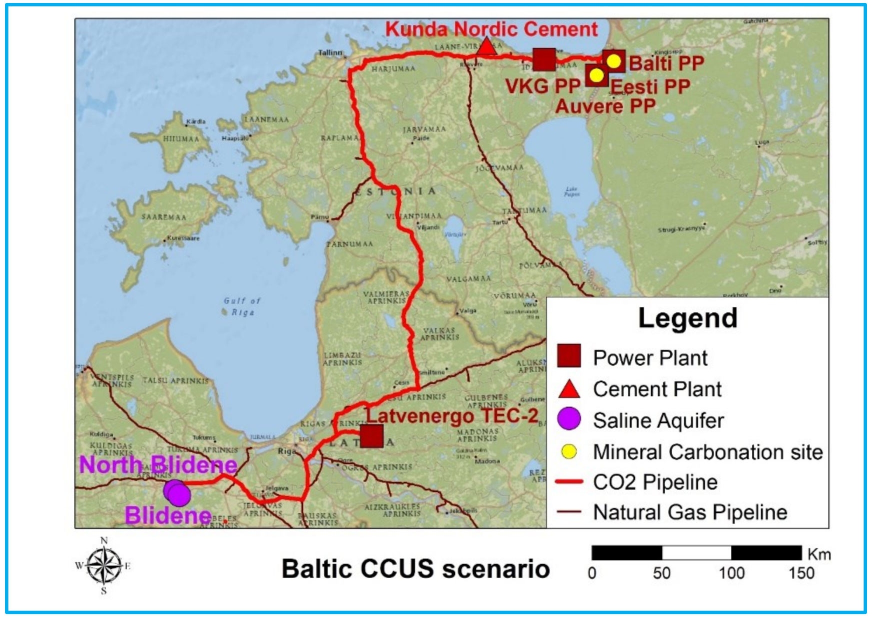
Conclusions

1. The Estonian-Latvian transboundary CCUS scenario includes cluster of six largest CO_2 producers in 2019, including one cement plant from Estonia and five PPs from Estonia and Latvia. One cement and three energy companies were involved in the scenario, which includes CO_2 use for Mineral Carbonation of Estonian OSA and production of high quality Precipitated Calcium Carbonate.
2. Annually 6.8 Mt CO_2 could be captured, transported and injected, including 6 Mt CO_2 avoided using transport and storage and 0.42 Mt avoided using MC of Estonian OSA. During 30 years nearly 204 Mt CO_2 will be captured, used and stored, while 193 Mt CO_2 could be avoided.
3. CCUS scenario includes CO2 use of 0.47 Mt CO_2 produced at Eesti PP and using 3.8 Mt of fresh OSA produced during combustion of OS at three Eesti Energia PP. OSA will be transported from Auvere and Balti PPs to MC plant using trucks.
4. 6.4 Mt of captured and compressed CO_2 were planned to be transported annually for onshore CO_2 storage site in Latvia (North Blidene) via pipelines. Small pipelines of 120-250 mm diameter from plants and one large common pipeline of 710 km length and diameter of about 700 mm were planned to be built during two years of construction period.

Mineral Carbonation Plant at Eesti Power Plant:
- **110 kg of CO_2 /t OSA**
- **250 kg of PCC (precipitated $CaCO_3$) from one t OSA**
- **0.42 Mt CO2+3.8 Mt OSA= 0.95 Mt PCC/year**

Revenues
- **avoided EEAP 40 Euro/t CO_2**
- **3 €/t OSA for OSA disposal**
- **50 €/t PCC**



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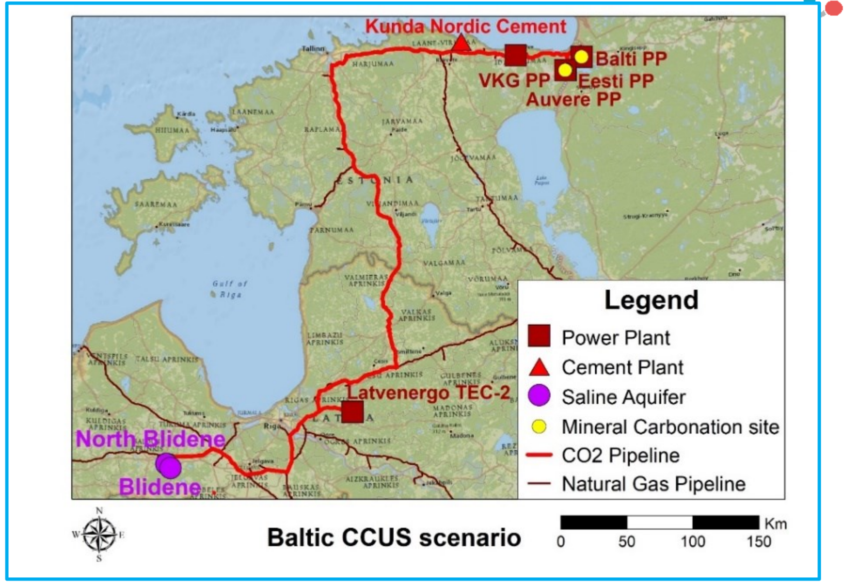
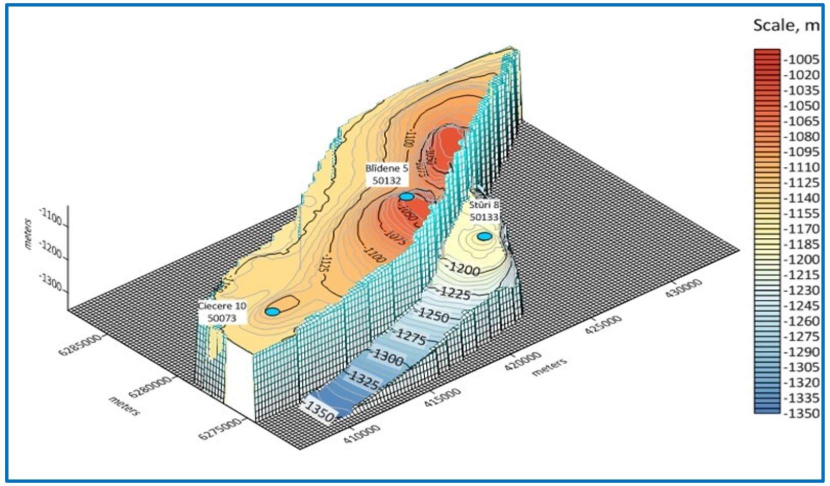
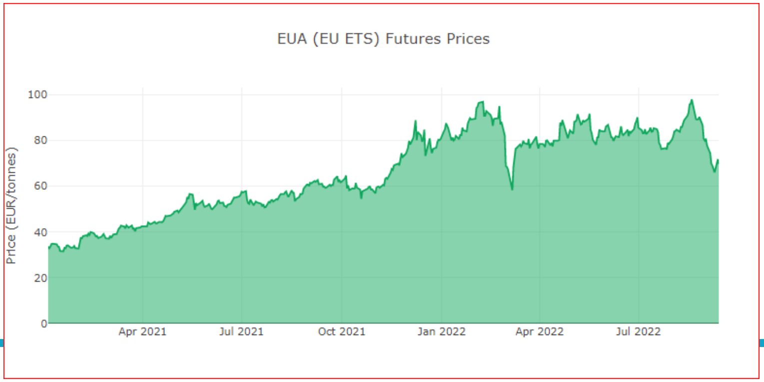
Conclusions

5. CO_2 injection into the 50 m thick Cambrian Series 3 Deimena Formation reservoir sandstones at the depth of 1035-1150 m with 370-850 mD permeability was planned including four injection and two monitoring wells. Monitoring program included baseline research before injection and had to be repeated according to EU CCS regulations every year, and in the post-injection period during 30 years (in total 40 monitoring campaigns).
6. The total average transport and storage cost of the scenario is 18.4 €/tCO_2 injected. This cost depends on the transport distance, according to the applied methodology, and it is the most expensive for the Eesti Energia PPs. The lowest T&S cost of 5.54 €/tCO_2 injected will have Latvenergo TEC2 PP located at the smaller distance from storage site.
7. At the present EEAP reaching already 96 €/t CO2 in July 2022, all the participating plants will get benefits from the proposed scenario.







https://ember-climate.org/data/carbon-price-viewer/

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