Zero Emission Network to facilitate CCUS uptake in industrial clusters
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CCUS ZEN

Deliverable 1.1

High-level regional mapping of CO_2 emission sources, utilization industry and infrastructure in the Baltic Sea and Mediterranean Sea regions

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Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
WP1 Leader	Cathrine Ringstad		12/06/23
Project Coordinator	Eirik Falck da Silva		12/06/23

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Executive summary

High-level mapping of CO_2 emission sources and potential CO_2 storage sites has been performed for the Baltic Sea and Mediterranean Sea regions defined by CCUS ZEN. Excel-templates with attributes characterise the emission sources and storage sites were made and populated for all countries covered by the CCUS ZEN regions and imported into QGIS for visualisation.

A high-level mapping of possible CO_2 transport options and intermediate storage solutions in the two CCUS ZEN regions have, in addition, been performed. This includes existing oil and gas pipelines, ship transport, railways and roads, and corridors with high voltage lines.

Finally, the CCU database developed by CO_2 Value Europe was described.

Based on the high-level mapping of CO_2 emission sources, possible transport options and potential storage sites, the four most promising CCS value chains in each of the two CCUS ZEN regions will be identified for further analyses in the project. In these analyses, based on the CO_2 utilisation database, existing and future industries using CO_2 as feedstock will be added.

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Acronyms	Full name
BAT	Best Available Technology
BGR	Institute for Geosciences and Natural Resources (Germany)
BIL	BOTAS International Limited Company (Türkiye)
BOF	Basic Oxygen furnaces
BOTAS	BOTAŞ Petroleum Pipeline Corporation (BOTAS) is the state-owned crude oil and natural gas pipelines and trading company in Türkiye.
BTC	Baku-Tblisi-Ceyhan Crude oil Pipeline (Türkiye)
BTE	Baku-Tblisi-Erzurum Natural Gas Pipeline (Türkiye)
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CFB	Circulating fluidized bed
CGS	Carbon dioxide Geological Storage
CKD	Cement Kiln Dust
COP	Crude Oil Pipeline
DEPA	Public Gas Corporation of Greece
DEUDAN	Deutsch/Dänische Erdgastransport
DAC	Direct Air Capture
DME	DiMethyl Ether
E-PRTR	European Pollutant Release and Transfer Register. Old version
E-PRTR IRDb	European Pollutant Release and Transfer Register. New version implemented after February 2020
EAF	Electric arc furnace
EEA-EFTA	European Economic Area-European Free Trade Association
EEZ	Exclusive Economic Zone
EIGL	Energy and Industry Geography Lab
ENTSOG	European Network of Transmission System Operators for Gas
EU ETS	EU Emission Trading System
EUGAL	European Gas Pipeline Link
FLSU	Floating Liquefaction and Storage Units
FSI	Floating Storage and Injection unit
FSU	Floating Storage Unit
HC	Hydrocarbon
IEAGHG	International Energy Agency GreenHouse Gas
IF	Induction Furnace

Acronyms	Full name
IGME	Geological and Mining Institute of Spain
INOGATE	Interstate Oil and Gas Transport to Europe
IPCC	Intergovernmental Panel on Climate Change
ITG	Türkiye-Greece Natural Gas Interconnection
JRC	Joint Research Centre (EU)
KPI	Key Performance Indicator
LCO_2	Liquid CO_2
LCA	Life Cycle Assessment
LPG	Low Pressure Gas
METU	Middle East Technical University (Türkiye)
MOF adsorption	Metal-Organic Frameworks based adsorption
NACE hierarchy	Statistical Classification of Economic Activities in the European Community *(nomenclature statistique des activités économiques dans la Communauté européenne)*
OPAL	Ostsee-Pipeline-Anbindungsleitung
OPEX	Operating Expenses
PCCC	Post-combustion Carbon Capture
PCI	Project of Common Interest
PFC	Perfluorocarbons
PRTR	Pollutant Release and Transfer Register
QC	Quality Control
REC	Regional Environmental Center
RWGS	Reverse Water Gas Shift
SEF	Storage Efficiency Factor
SEPA	Scottish Environmental Protection Agency
SEWGS	Sorption Enhanced Water Gas Shift
SGU	Geological Survey of Sweden
SMR	Steam Methane Reforming
SOCAR	State Oil Company of the Republic of Azerbaijan
SPE-SRM	Society of Petroleum Engineers – Storage Resources Management
SRL	Storage Readiness Level
STAR	SOCAR Türkiye Aegean Refinery
TANAP	Trans-Anatolia Natural Gas Pipeline
TAP	Trans-Adriatic Pipeline
TCM	Technology Centre Mongstad

Acronyms	Full name
TEIAS	Turkish Electricity Transmission Corporation
TRL	Technology Readiness Level
TSO	Transmission System Operator
TÜPRAŞ	Türkiye Petrol Rafinerileri A.S.
UGS	Underground Natural Gas Storage
WP	Work package
WtE	Waste to Energy
ZEN	Zero Emission Network

1 Introduction

This document is Deliverable 1.1 of the CCUS ZEN project. The **overall objective** of the project is to explore the potential for CCUS value chain deployment in two regions with lower maturity level for CCUS compared to the current development in the North Sea region. The two selected regions are the Baltic Sea region and the Mediterranean Sea region.

The **CCUS ZEN mission** is to contribute to the accelerated deployment of CCUS throughout Europe. It aims to enable mutual, continuous learning between different stakeholder types and between European regions, drawing on learnings from ongoing and past projects, creating shared understanding of mission-critical implementation elements that need to work like clockwork, and building a coherent ecosystem of CCUS actors in Europe able to credibly deliver the requisite contribution to European climate policy.

To achieve this, CCUS ZEN has **five objectives**:

1. **Technical mapping**: For each region, map and understand the nature and longevity of emission sources, identify transport corridors and modalities, assess cost-effective ('bankable') storage capacity in the selected regions, and define interactions between CCUS hubs-and-clusters, renewable-based integrated energy systems, and/or circular production modes.
2. **Non-technical mapping**: Identify and involve relevant end users, public authorities and social stakeholders and analyse their concerns and needs using appropriate techniques and methods from the social sciences and humanities.
3. **Value chain scenarios**: Elaborate detailed plans for the integration of CCUS in hubs and clusters linked to CO_2 storage sites via hubs, pipeline networks and shipping routes, with due attention to national and border-crossing permits and regulatory issues.
4. **Local business model**: Perform initial impact assessment and develop local business models for delivery of CO_2 capture, transport, utilisation and/or storage, including the separation of responsibilities across the CO_2 value chain.
5. **Knowledge sharing, dissemination, and communication**: Facilitate the exchange of knowledge and know how across CCUS projects, by continuing the activities of the existing European CCUS project network.

The five objectives are integrated in the project framework illustrated in Figure 1.1. Technical and non-technical mapping constitute a high-level regional screening of CCUS opportunities in the two CCUS ZEN regions. This is followed by a selection and analyses of the four most promising value chains in both regions. Based on the analyses, the most promising CCUS value chain in each region will be selected for further development, including local business models. The work will throughout the project be supported by knowledge sharing, dissemination and communication with network partners and other relevant stakeholders.

This document is the first step of **Objective 1: Technical mapping** and summarises high-level regional mapping of emission sources, utilisation industry and infrastructure in the two CCUS ZEN regions. In this context, infrastructure refers to CO_2 transport, intermediate storage solutions and geological structures identified as potential CO_2 storage sites.

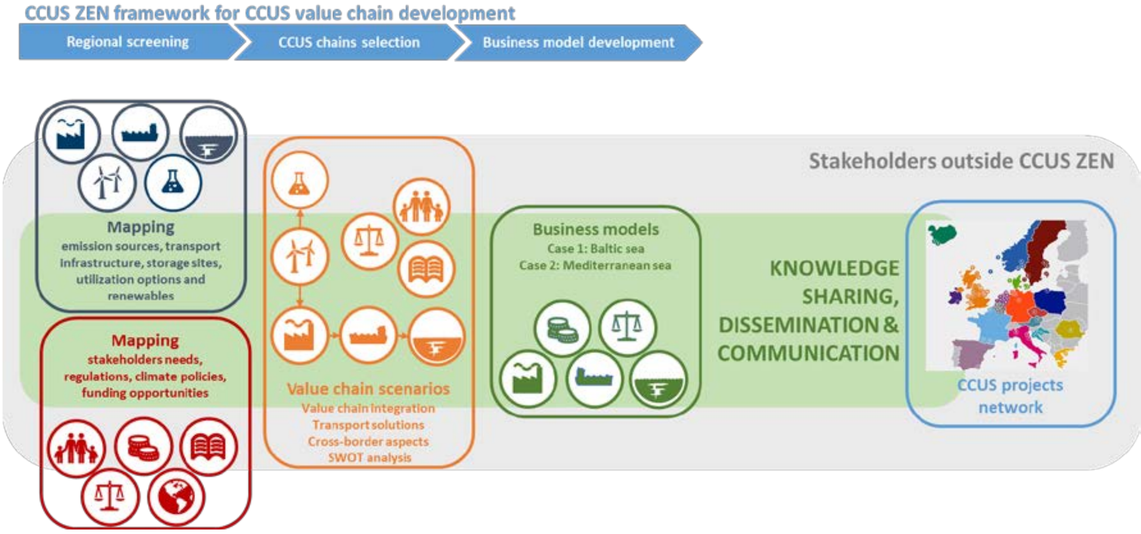

Figure 1.1 CCUS ZEN framework for CCUS value chain development

2 CCUS ZEN regions

The two regions explored by CCUS ZEN are the Baltic Sea region and the Mediterranean Sea region (Figure 2.1):

Baltic Sea region

The Baltic Sea region defined in CCUS ZEN covers Denmark including its inland waters and the easternmost of Northern Sea, Sweden, Finland, Germany, Estonia, Latvia, Lithuania, Poland and the Baltic Sea.

Mediterranean Sea region

The Mediterranean Sea region defined in CCUS ZEN covers France, Spain, Italy, Greece, Türkiye and the Mediterranean Sea.

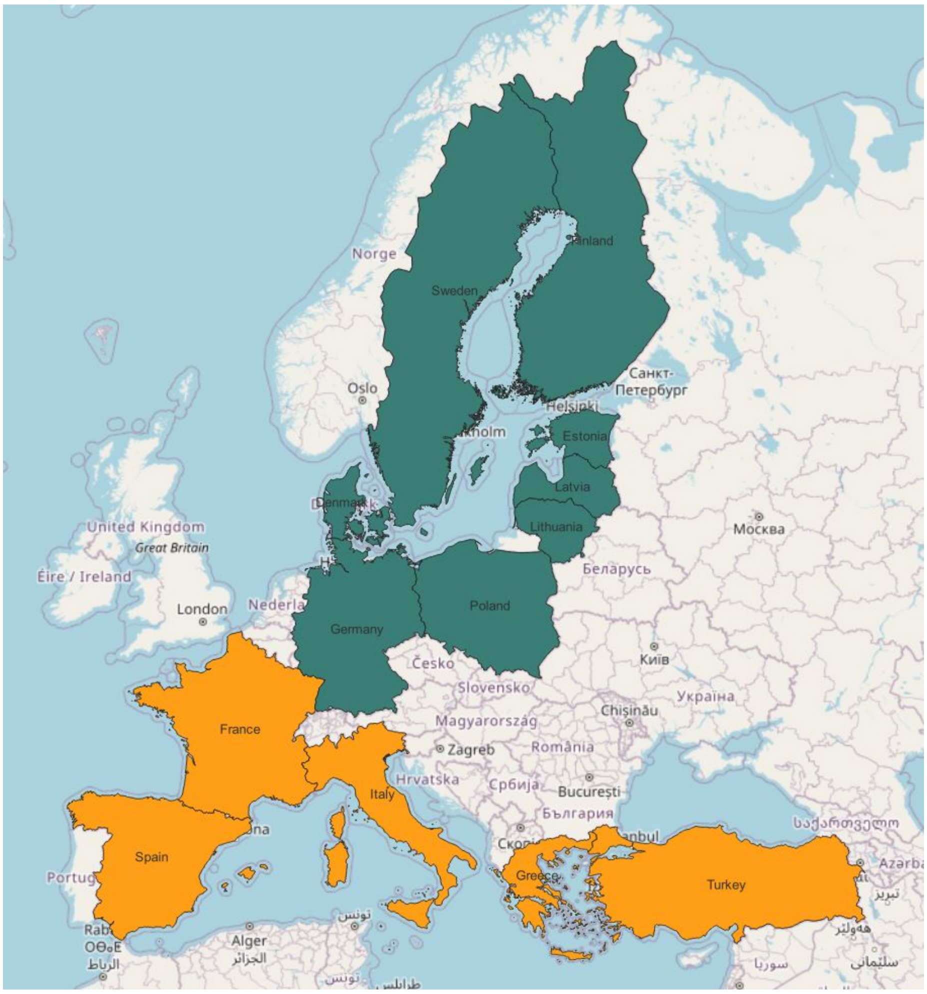

Figure 2.1 The two regions explored by CCUS ZEN: The Baltic Sea region (countries in green) and the Mediterranean Sea region (countries in orange).

3 CO_2 emission sources and best available technologies

3.1 Mapping methodology

As a starting point, data from CaptureMap provided by Endrava have been used in the mapping of CO_2 emissions sources. This applies to all CCUS ZEN countries except Türkiye since Turkish emission sources is not yet included in CaptureMap. All data in CaptureMap is QC'ed by Endrava. Additional QC was undertaken for countries with partners in CCUS ZEN. This has not been possible for countries without partners in the project: Germany, Spain, Italy and Greece.

Section 3.1.1 describes how the CaptureMap data has been collected and processed, with the corresponding QC. CO_2 emission sources in Türkiye have been collected and estimated by the Middle East Technical University in Türkiye as part of their CCUS ZEN activity. A summary of their methodology is given in Section 3.1.2.

3.1.1 Mapping of CO_2 emissions sources in all CCUS ZEN countries except Türkiye

CaptureMap is a web-based tool that provides a comprehensive overview of emission sites (or sources), covering both fossil and biogenic CO_2 emissions. At the time of analysis for this project, CaptureMap contained more than 10 000 sources in 33 countries.

To make CaptureMap, Endrava imports emission data from several sources; the two most important for Europe being the EU Emissions Trading System (EU ETS) and the European Pollutant Release and Transfer Register (E-PRTR), see Table 3.1 for details.

EU ETS has registered emissions from installations in the power sector and manufacturing industry for all EU countries plus Iceland, Lichtenstein, and Norway (EEA-EFTA states). Emissions from airlines operating between these countries are also registered, covering around 40% of the EU's greenhouse gas emissions. The EU ETS covers fossil CO_2 emissions from electricity and heat generation, and energy-intensive industry sectors including: oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals (EU ETS). In addition to fossil CO_2 emissions, the EU ETS covers smaller amounts of nitrous oxide (N_2O) emissions from the production of various chemicals, and perfluorocarbons (PFCs) from production of aluminium. The EU ETS database is updated every year in April (Union Registry).

E-PRTR provides key environmental data from industrial facilities in European Union Member States, plus Iceland, Liechtenstein, Norway, Switzerland, Serbia and the UK. The database includes both fossil and biogenic CO_2 emissions, although the distinction between both types is not always provided by the reporting countries. In addition, emissions are expected to be reported every year, but the latest data is missing for some specific countries in the dataset. To make up for both gaps in the E-PRTR reporting, Endrava uses data from the EU ETS along with an analytics model to estimate the missing data in E-PRTR. Endrava also combines two different versions of the E-PRTR database (noted as "E-PRTR" and "E-PRTR IRDb" in Table 3.1), along with a Germany-specific PRTR database to make-up for the lack of updates from this country.

Data from the EU ETS and E-PRTR are analysed and compared by Endrava before being uploaded in CaptureMap. Note that the E-PRTR dataset only includes facilities with CO_2 emissions above 100 000 ton per year, while the EU ETS dataset also includes smaller emission volumes. Endrava use the E-PRTR system as their basis for facilities in Europe, and many facilities from the EU ETS database with emissions less than 100 000 ton CO_2 per year are therefore not included in CaptureMap. CO_2 emissions typically vary from year to year, and CaptureMap includes estimates when CO_2 emissions decreased below the 100 000 ton/year threshold at known E-PRTR facilities, as long as they have an EU ETS record available. Consequently, some sources with emissions below 100 000 ton per year are included in CaptureMap.

Note also that there is some inconsistency between the EU ETS and E-PRTR databases for several facilities.

Data exported from CaptureMap has been QC'ed by the partners in CCUS ZEN, except for Germany, Spain, Italy and Greece. Only a few discrepancies were identified, mainly from recent updates from facilities in Estonia, Lithuania and Poland; two Estonian facilities were removed as they will be closed in near future, and new emission sources were added to Estonia, Lithuanian and Poland. Biogenic CO_2 emissions have, in addition, been updated when such data have been available to the project.

The reported CO_2 emissions are in general from 2021, except for some facilities where only older data are available.

Table 3.1 External data sources used in the CaptureMap tool for Europe.

Database	Date last update of CaptureMap	Date CCUS ZEN download from CaptureMap	Emission coverage	Comment
EU ETS	3 September 2022	22 November 2022	Only fossil CO_2 emissions subject to the EU Emission Trading Scheme, includes smaller amounts of N_2O and PFCs	
E-PRTR	1 May 2021	21 November 2022	Both fossil, biogenic and sometimes undefined CO_2, depending on the sites and countries	Old version of E-PRTR. Last dataset downloaded by CaptureMap February 2020
E-PRTR IRDb	24 May 2022	22 November 2022	Both fossil, biogenic and sometimes undefined CO_2, depending on the sites and countries	New version of the E-PRTR database implemented after February 2020: E-PRTR IRDb
German PRTR	22 November 2022	22 November 2022	Both fossil and biogenic CO_2 into a combined CO_2 amount without details. All sites with emissions >100ktpa.	Contains data from the German PRTR database: German PRTR

3.1.2 Mapping of CO_2 emission sources in Türkiye

The mapping of CO_2 emission sources in Türkiye has been restricted to emissions from refineries, petrochemical industry, power plants, iron and steel industry and cement industry.

Refineries and Petrochemical industry

There are 5 operational refineries in Türkiye. Four of these refineries are operated by TÜPRAŞ (Türkiye Petrol Rafinerileri A.S.), which is owned by Koç Holding. The oldest of these refineries is the Batman Refinery, operational since 1955, and has a refining capacity of 1.4 million tons per year. Since then three additional refineries have been constructed: The Izmit Refinery, operational since 1961 and with a capacity of 11.3 million tons/year, the Izmir Refinery, operational since 1972 and with a capacity of 11.9 million tons/year, and the Kirikkale Refinery, operational in since 1986 with a capacity of 5.4 million tons/year. The total CO_2 equivalent emissions from all four TÜPRAŞ refineries in 2021 are reported as 5 875 393 tons for Scope 1 (combustion of fossil fuels), and 48 368 tons for Scope 2 (refining). The emissions for each TÜPRAŞ refinery have been calculated according to their process capacities. TÜPRAŞ has announced that they aim to be a carbon-neutral company by 2050 (TUPRAS, 2021).

The fifth refinery in Türkiye is the STAR, SOCAR Türkiye Aegean Refinery owned by SOCAR, the State Oil Company of the Republic of Azerbaijan. It was established in 2018 and has 10 million tons of oil processing capacity. STAR Refinery aims to reduce CO_2 emissions by 40% by 2035 and be carbon-neutral by 2050. STAR Refinery reported its CO_2 emissions for Scope 1 (combustion of fossil fuels) as 2 010 170 and Scope 2 (refining) as 428 453.97 tons for 2021.

SOCAR is also the owner of Petkim, Türkiye's only integrated petrochemical producer. Petkim has reported greenhouse gas emissions as 1 881 861 tons (Scope 1) and 101 690 tons (Scope 2) for 2021 (SOCAR, 2021). TÜPRAŞ refineries are shown in Figure 3.1, whereas STAR and Petkim refineries are shown in Figure 3.2. As indicated in the figures, the refining activities are mainly carried out in the western part of Türkiye.

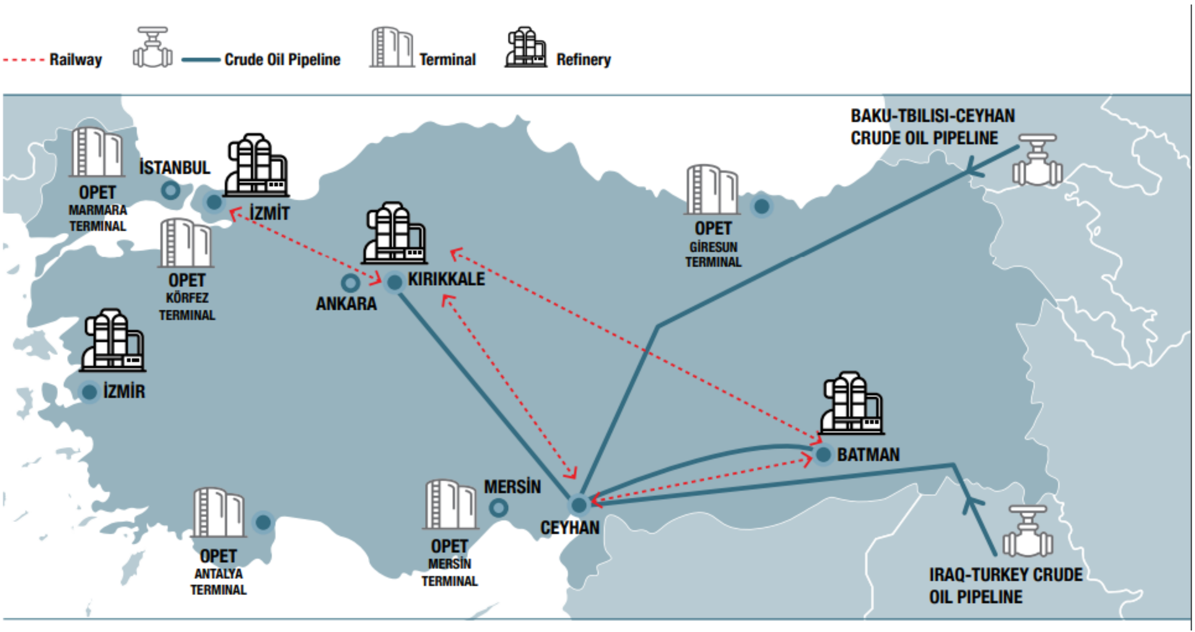

Figure 3.1 Locations of the TÜPRAŞ refineries.

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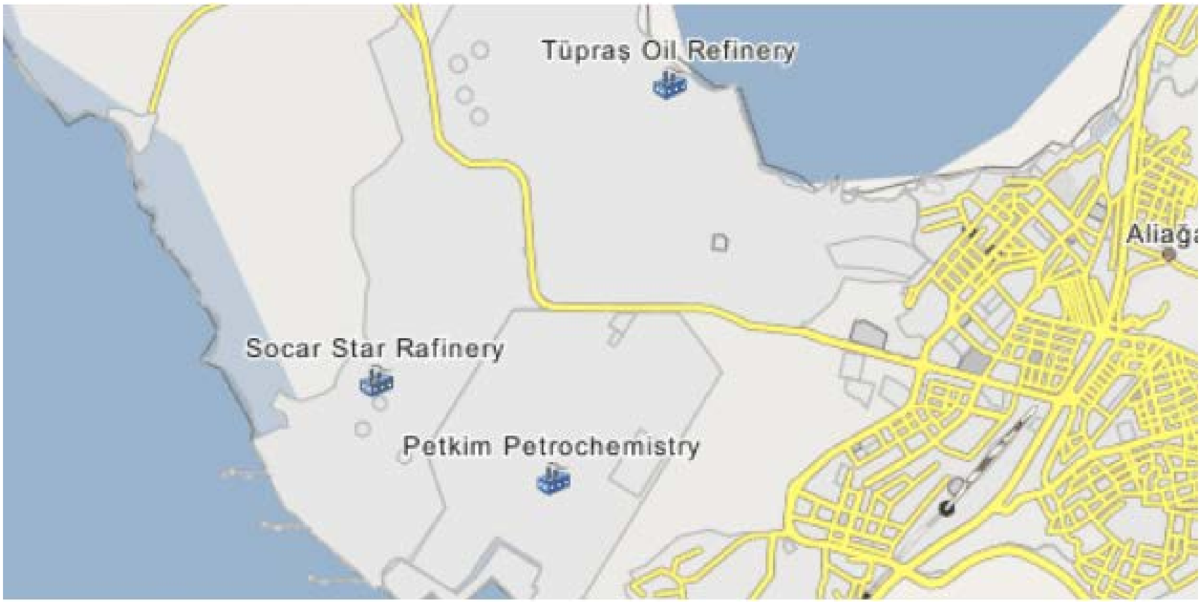


Figure 3.2 Locations of the SOCAR STAR Refinery and Petkim Petrochemistry Facility.

Power Plants

There are 53 active thermal power plants in Türkiye. Most of these plants are fuelled by local lignite or hard coal sources. Others use imported coal, asphaltite, or fuel oil. Natural gas-powered facilities cover 21.54% of the installed power capacity. There are 202 natural gas power plants operating in Türkiye. Only those emitting more than 100 000 tons of CO_2 are included in the database. The Ministry of Energy and Natural Resources has reported the amount of CO_2 emission for each produced MWh electricity as given in Table 3.2 for the year 2020.

Although actual power production could be less than the capacity, the maximum power capacity has been used to calculate CO_2 emissions from the thermal power plants.

Table 3.2 Emission factors for different fuel types

Fuel Type	Emission Factor (ton CO_2 / MWh)
Lignite	1.274
Hard coal	1.095
Asphaltite	1.171
Exported coal	0.868
Natural gas	0.371
Fuel oil	0.643
Diesel	0.644

Iron and Steel industry

There are three integrated iron and steel production facilities in Türkiye. These facilities use basic oxygen furnaces (BOFs) during crude steel production. Other factories use electric arc furnace (EAF) and induction furnace (IF) technologies, which generate fewer CO_2 emissions compared to the BOF technology. The iron and steel facilities in Türkiye were classified in Figure 3.3 following the production methodologies and the production capacities. To illustrate, the three integrated iron and steel production facilities (Isdemir, Erdemir, and Kardemir) are written by blue colour, whereas the annual production capacities higher than 2 000 000 tons of steel are shown with red symbol on the map. The Türkiye Steel Industry Report (2022) gives the annual crude steel production capacity of active facilities, which produce more than 1 000 000 tons of crude steel per year in Türkiye.

The CO_2 emission data is obtained by using the IPCC Report on Metal Industry Emissions (IPCC, 2006b). Tier 1 Methodology has been implemented in CO_2 emission estimation using the following equation:

$$E_{CO_2,\,\text{non-energy}} = BOF \times EF_{BOF} + EAF \times EF_{EAF} + OHF \times EF_{OHF} \qquad \text{Equation 3.1}$$

where:

BOF = quantity of crude steel produced using basic oxygen furnaces (tons)
EAF = crude steel produced using electric arc furnaces and induction furnaces (tons)
OHF = quantity of crude steel production using open-heart furnaces (tons)

Open-heart furnaces are not available in Türkiye (OHF = 0). The emission factors based on the steelmaking method are given as EF_{BOF} = 1.46 tons and EF_{EAF} = 0.08 tons of CO_2 per ton of steel production for BOF and EAF, respectively. The EAF emission factor does not include emissions from iron production.

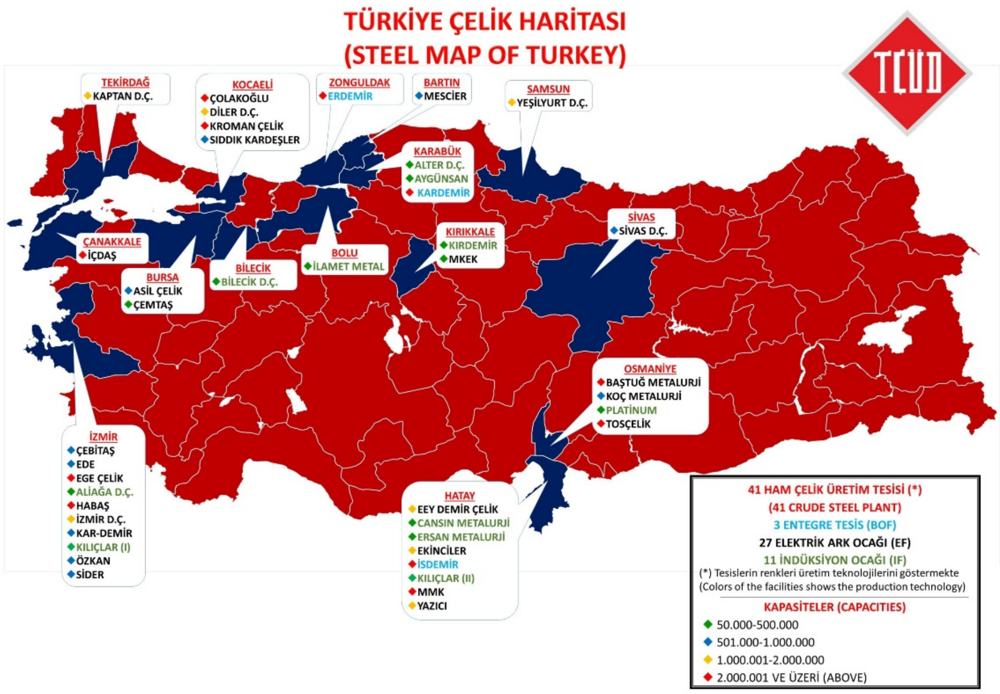


Figure 3.3 Steel Map of Türkiye (Turkish Steel Producers Association, 2022)

Cement industry

According to the 2006 IPCC Guidelines, alternative methods are proposed to estimate the CO_2 emissions during cement production. In Tier 1 method, weight of produced cement and clinker fraction of cement are used to determine CO_2 emissions. On the other hand, in Tier 2 method, only weight of produced clinker is used to calculate CO_2 emissions (IPCC, 2006a).

To determine the CO2 emissions of cement plants in Türkiye, data on cement and clinker production were gathered using available public data. Tier 1 or Tier 2 methods are applied depending on the data availability.

In the Tier 1 method, CO_2 emissions based on cement production are calculated by using the following equation (IPCC, 2006a):

$$CO_2\ Emissions = [\textstyle\sum_i (M_{ci} \cdot C_{cli}) - Im + Ex] \cdot EF_{clc} \quad \text{Equation 3.2}$$

where:

$CO_2\ Emissions$ = Emissions of CO_2 from cement production (tons)
M_{ci} = Weight (mass) of produced cement of type *i* (tons)
C_{cli} = Clinker fraction of cement of type *i* (fraction)
Im = Imports for consumption of clinker (tons)
Ex = Exports of clinker (tons)
EF_{clc} = Emission factor for clinker in the considered cement, corrected for CKD (Cement Kiln Dust) (tons CO_2 per ton of clinker)

A default CaO content for clinker of 65% is used, assuming 1 ton of clinker contains 0.65 tons CaO from $CaCO_3$. An emission factor (tons CO_2 per ton of carbonate) of 0.43971 is used assuming 100% calcination with 56.03% CaO and 43.97% CO_2 by weight (IPCC, 2006a). Moreover, a correction addition of 2% to account for CKD is assumed and the default clinker emission factor (EF_{clc}) is used as 0.51×1.02= 0.52 tons CO_2 / ton clinker in Equation 3.2 (IPCC, 2006a). Clinker imports and exports are not taken into consideration.

In the Tier 2 method, CO_2 emissions are calculated by clinker production data using the following equation (IPCC, 2006a):

$$CO_2\ Emissions = M_{cl} \cdot EF_{cl} \cdot CF_{ckd} \quad \text{Equation 3.3}$$

where:

$CO_2\ Emissions$ = Emissions of CO_2 from cement production (tons)
M_{cl} = Mass of clinker produced (tons)
EF_{cl} = Emission factor for clinker (ton of CO_2 per ton of clinker)
CF_{ckd} = Emissions correction factor for CKD, dimensionless.

Since there is no available data for the determination of CF_{ckd}, a default CKD correction factor (CF_{ckd}) of 1.02 is used. EF_{cl} is taken as 0.51 (IPCC, 2006a). In the calculations, it is assumed that all the available cement and or clinker production capacity of cement factories is used.

Cement factories in Türkiye and their locations (2022) are shown in Figure 3.4.

Figure 3.4 Cement factories in Türkiye (TURKCIMENTO, 2022)

3.2 High level mapping in the Baltic Sea region

High level mapping of CO_2 emissions in 2021 in the CCUS ZEN countries in the Baltic Sea is shown in Figure 3.5. The emissions are summarised country wise in Table 3.3. The table shows that Germany and Poland are the two countries with largest CO_2 emissions in the Baltic Sea region. The emissions are shown on country wise figures in Section 12 (Appendix C). In addition, the country wise emissions are summarised in tables, grouped by the different industry sectors.

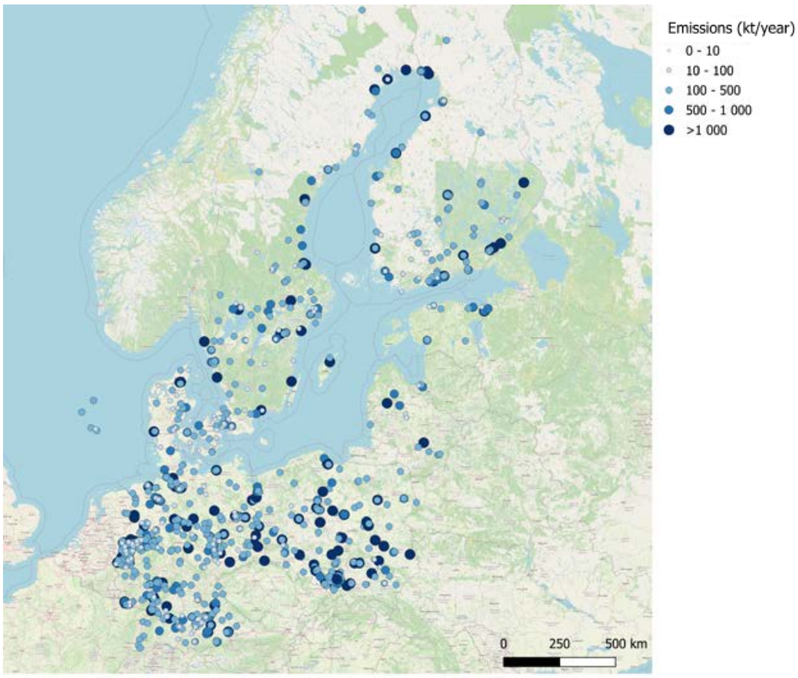


Figure 3.5 **CCUS ZEN Baltic Sea region**: High level mapping of CO_2 emission. The mapping methodology is described in Section 3.1.

Table 3.3 Number of facilities and corresponding CO_2 emissions for countries in the **CCUS ZEN Baltic Sea region**. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1 .

Country	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Denmark	22	1 342	33	11 834
Sweden	25	1 742	95	51 036
Finland	14	652	74	46 033
Germany	58	3 721	405	365 840
Estonia	5	236	13	8 643
Latvia	1	100	3	1 654
Lithuania	2	99	9	5 588
Poland	30	1 668	164	189 159
Sum	**157**	**9 560**	**796**	**689 347**

3.3 High level mapping in the Mediterranean Sea region

High level mapping of CO_2 emissions in 2021 for the CCUS ZEN countries in the Mediterranean Sea region is shown in Figure 3.6. The emissions are shown country wise in Table 3.4. The emissions are shown on country wise figures in Section 13 (Appendix D). In addition, the country wise emissions are summarised in tables, grouped by the different industry sectors.

In terms of emission volumes, the table shows that Türkiye takes the first place in Mediterranean region, whereas it takes the second place after Germany (366 million ton per year) in general. However, it should be noted that the Türkiye's CO_2 emissions are not reported values but rather calculated by using theoretical methods proposed by IPCC (2006). Furthermore, the maximum installed capacities of facilities have been used in proposed equations, which would most probably provide overestimated emission volumes.

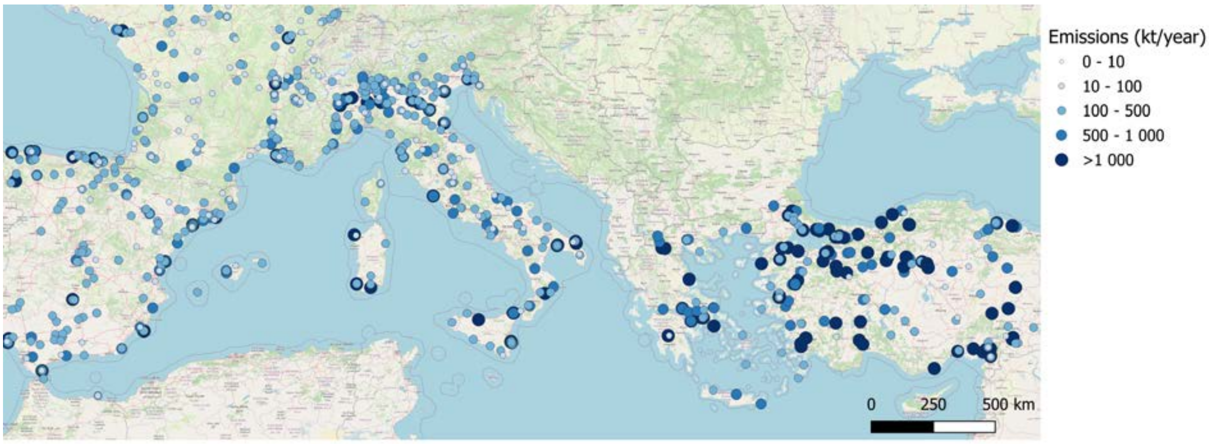


Figure 3.6 **CCUS ZEN Mediterranean Sea region**: High level mapping of CO_2 emission sources. The mapping methodology is described in Section 3.1.

Table 3.4 Number of facilities and corresponding CO_2 emissions for countries in the **CCUS ZEN Mediterranean Sea region**. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1 .

Country	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
France	87	6 446	258	99 995
Spain	34	2 281	199	90 475
Italy	30	1 958	204	120 538
Greece	1	57	39	32 242
Türkiye	15	955	175	357 888
Sum	**167**	**11 697**	**875**	**701 137**

3.4 Best available technologies for CO_2 capture

3.4.1 Introduction

Applications separating CO_2 in large industrial plants (among others: natural gas treatment plants and ammonia production facilities) are already in operation today. Examples are natural gas treatment plants and ammonia production facilities where the CO_2 is removed to purify other industrial gas streams. Technologies that separate CO_2 from gas streams at industrial scale have consequently existed for a while, even though the purpose is not the same as for CO_2 capture. In the following sections, these separation processes will be referred as **industrial processes**.

The IPCC special report CARBON DIOXIDE CAPTURE AND STORAGE (2005) introduces in detail different technology options for CO_2 capture. Alongside the existing **industrial processes** already in operation, three main categories for capture technologies are described in the IPCC report (Figure 3.7): Post-combustion, Pre-combustion and Oxyfuel.

Post combustion technologies are based on separating out CO_2 from the flue gas produced by the combustion of primary fuel in the air. By their very nature these technologies can be deployed without interfering significantly with the industrial process. They are also relatively easy to deploy in a brownfield setting. Post combustion capture can be based on several separation principles: absorption (solvent-based capture), adsorption (capture on solids), membranes and cryogenic separation.

Pre combustion technologies process the primary fuel before combustion. A first reaction between the fuel with oxygen or air and/or steam gives mainly a 'synthesis gas (syngas)' composed of carbon monoxide and hydrogen ($CO + H_2$). The carbon monoxide is then reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen ($CO + H_2 + H_2O \rightarrow CO_2 + 2H_2$). CO_2 is then separated, usually by a physical or chemical absorption process. If the CO_2 is stored, the remaining Hydrogen is referred to as blue hydrogen.

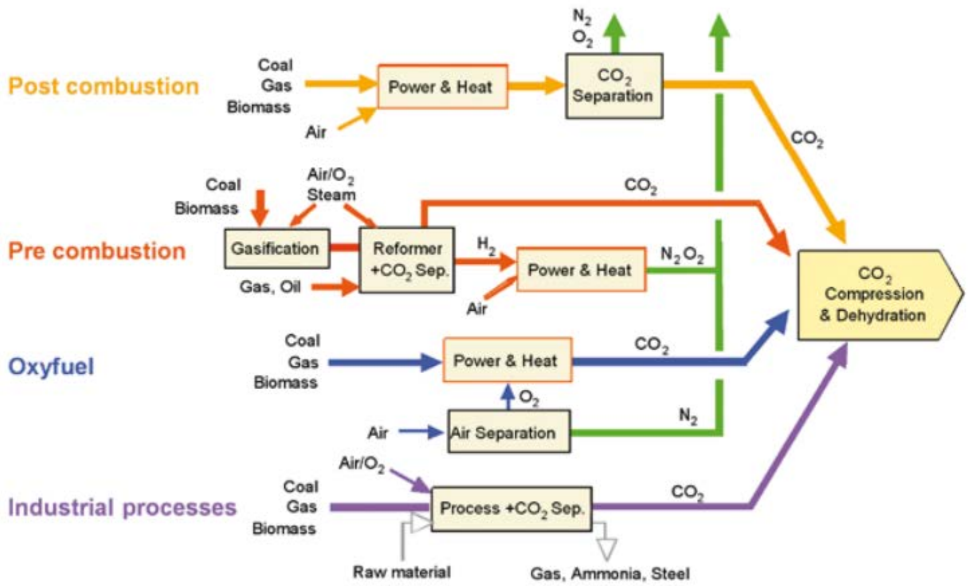


Figure 3.7 Overview of capture technologies. Reproduced from IPCC report CARBON DIOXIDE CAPTURE AND STORAGE (2005).

The utilization of hydrogen in industry does however come with numerous technical issues beyond the production of the hydrogen itself. In many cases pre combustion technology can clearly be deployed in brownfield settings.

Oxyfuel technologies are based on combusting fuels with pure oxygen instead of air. The flue gas produced is this way mainly CO_2 stream and water steam. These technologies require the separation of Oxygen from the air with a high purity (95%-99%) and eventually further treatment of the flue gas to remove the remaining nitrogen. Oxygen is usually produced by low temperature (cryogenic) air separation and novel techniques to supply oxygen to the fuel, such as membranes and chemical looping cycles are being developed.

3.4.2 Technical maturity

A report commissioned by the IEAGHG (IEAGHG, 2019) provides a summary of the state of development of different capture technologies. They used the Technology Readiness Levels (TRL) from 1 to 9 to evaluate the maturity of each capture technology. This study was focused on CO_2 capture applied to the power sector, but we believe the conclusions can be applied more broadly.

Post-combustion technologies are the most mature and deployed technologies, as they are used for industrial processes in the ammonia or steel production. Absorption is commercially deployed today and is the most mature technology option. Most advanced absorption technologies are identified as having TRLs between 6 and 9. Adsorption and Membrane technology were both given a TRL of 6. Cryogenic separation was reported as having a TRL of 5.

No pre combustion technology has a higher TRL than 6 in the study. This conclusion only holds for the power sector. In the Quest CCS project CO_2 is captured from hydrogen production. There are mature technology options for pre combustion or blue hydrogen production, but hydrogen technologies are however not yet available for industrial application.

The study identifies no oxyfuel technology above TRL 7. The development of oxyfuel technologies has however been relatively slow. This is consistent with our knowledge of the field.

A summary of the capture technologies and the corresponding TRLs is given in Table 3.5. In the following we will focus our analysis on post-combustion technologies, as they are the most mature and deployable at an industrial scale.

Table 3.5 Technology Readiness Level (TRL) for the different capture technologies.

Technologies	Process	TRL
Post-combustion	Absorption	6-9
	Adsorption	6
	Membranes	6
	Cryogenic separation	5
Pre-combustion	-	< 6
Oxyfuel	-	< 7

3.4.3 Post-combustion technologies

General benefits of post-combustion technologies are that they can be readily deployed in brownfield settings and that the impact on the industrial process the CO_2 is captured from can be kept to a minimum.

Absorption (Solvent Based CO_2 Capture)

Absorption of the CO_2 through a solvent is already deployed industrially on a limited number of plants (such as Boundary Dam and Petranova). The technology is also mechanically robust and does not rely on novel components or materials.

There are several vendors for solvent-based CO_2 capture technology that are ready to offer technology today. While the technology is commercially available today it must be recognized that the plants in operation and being built are first-of-a-kind. Therefore, there is relatively little experience data and potential for further improvement of the capture process.

Solvent-based capture is a post-combustion technology that can be applied to most flue gas sources and most industries. It is normally a heat-driven process, and the energy is normally supplied as steam. In a setting where heat is not readily available solvent-based capture may still be an option, where heat pumps is one alternative.

The UK Government (Environment Agency) has prepared a Best Available Technology document on post-combustion CO_2 capture. Overall, we think this BAT document is reasonably good and indicative of the requirements that will be in place for solvent based CO_2 capture. We do have some disagreements on specific points regarding handling of solvent degradation and emissions. We believe the BAT is making statements on some issues where ongoing technology development could suggest other solutions.

Adsorption (Solid Based CO_2 Capture)

In this case, the flue gas circulates through a porous solid material which have a great affinity to CO_2. The CO_2 is then bound on the surface of the pores of the material and removed from the flue gas.

Adsorption of CO_2 on a sorbent present several advantages compared to the absorption. For instance, the absence of water (or another inert solvent component) means that energy losses associated with heating the solvent and evaporative losses can be reduced. On the other hand, heat-transfer tends to be more demanding in technologies based on solids, and also the volumetric sorption capacity tends to be lower than for amine-based solvents leading to increased process footprint.

The potential of adsorption to be an energy efficient capture technology is a specific example of a question that is hard to judge given the current maturity of the technology. There are also several different adsorption technologies under development, notable examples being: fluidized bed systems, rotating fixed beds and moving beds. It is hard to draw firm conclusions on performance until one has settled on a specific optimized process design and choice of sorbent materials.

Membrane separation

The flue gas circulates in this case through a membrane permeable to CO_2, but impermeable to the other gases. Membranes present the advantages of smaller unit size, simpler operation, simpler up- and down-scaling due to modularity and lower environmental impact as no harmful chemicals are involved in the separation. However, a positive CO_2 partial pressure difference across the selective layer is required to make the separation happening, making membranes more suited for applications with larger CO_2 concentration in the feed gas or requiring costly overpressure (i.e., compression) of the feed gas stream.

Membrane-based gas separation has been recognized as a promising second-generation technology for end-of-pipe or post-combustion CO_2 capture (PCCC). For flue gas containing >13% CO_2, membranes offer a cost-efficient alternative to capture CO2 at a recovery rate of around 90%. The performance of membrane process improves, and the energy and membrane area requirements reduce with increasing CO_2 concentration. However, it has been shown that while a capture rate of 90% is feasible, the optimal CO_2 capture rate for membranes is below 90%.

The correct estimation of CAPEX and OPEX for membrane technology is also limited by the few high TRL demonstrations reported to date.

Other Post-Combustion Technologies (cryogenic and hybrid)

The main additional separation principle of relevance to post-combustion CO_2 capture is cryogenic separation. There are however fewer technology developments in this field for post-combustion CO_2 capture application. Cryogenic processes do obviously have a substantial need for cooling duty.

There are also hybrid concepts for example combining cryogenic capture with adsorption and/or membranes. Such a hybrid process scheme is based on the principle of combining two different separation technologies, both of which are not perfectly suited for stand-alone capture of CO_2. As mentioned above, polymeric membranes are generally suited for bulk separation of CO_2 and can typically result in product purity of 50 to 70% CO_2, while the CO_2 liquefaction process is very well suited for purification of CO_2 from a gas stream with moderate to relatively high CO_2 concentration (typically >50%). This means that the final membrane separation stages which are less efficient can be replaced by the more efficient low temperature process in the CO_2-rich permeate gas stream. Liquefaction allows the hybrid process to meet the high CO_2 purity requirements for CO_2 transport and utilization simultaneously that membranes alone cannot meet. Membranes in such a scheme act as a low-cost way to concentrate CO_2 so that the liquefaction process can operate efficiently.

In Table 3.6 we list the three main types of post-combustion capture technology and highlight some of their main strengths and weaknesses. It is noteworthy that all these separation processes also play a role in conventional gas treating (associated with production of natural gas). Some aspects of technology performance can be extrapolated from gas treating, but one should also be mindful that there are substantial differences. The energy efficiency of the capture process is for example in general expected to be of much greater importance in post-combustion CO_2 capture.

Direct comparison between technologies is difficult for several reasons. First of all, they are at different levels of technical maturity. Absorption is very well known because a few full-scale plants have been in operation. The performance that can be expected of absorption technology is fairly well understood. However direct comparison with lower-TRL technologies figures is much more approximative. One should be especially careful in comparing performance data obtained in very different manner (industrial demonstration or process simulation for example). The awareness of potential issues that may impact industrial scale CO_2 capture may also vary between technologies at different TRLs.

Secondly, CAPEX aspects must not be ignored when comparing technologies. The energy efficiency of most capture processes can be increased if one invest more in equipment (for example, heat exchangers for absorption). At some point this may result in too high CAPEX and the technology could not be economically feasible. When comparing technologies, it is important to keep things consistent in terms of their CAPEX. In principle the solution would be to compare technologies on cost of avoided CO_2. But comparison of CO_2 avoided calculations are very uncertain when technologies are at different TRL. So one must be careful in comparing numbers from different sources.

Finally, each technology also comes with a number of variations. There are for example different varieties of absorption configurations. Conventional design is based on absorber and stripper columns, but other types of contactors exist, such as membrane contactors and rotating packed beds. In terms of physical design these technologies would have very different layout. Note that Table 3.6 does not describe these details.

Table 3.6 Post-combustion capture technologies

KPIs / Boundary conditions	Comment
Absorption	• Mature technology • In most cases operated as a temperature swing process • Most solvents require emission control and emission permitting • Usually heat-driven process, but can be adapted to use of electricity • Energy is supplied as low grade heat, highly compatible with utilization of excess heat available in process industries • High-capture rates (>95%) • Delivers CO_2 at relatively high purity • Well-suited for large capture plants
Adsorption	• Energy performance vs absorption remains uncertain • Temperature swing processes are the most common and can operate similar to absorption based when Circulating Fluidized Bed (CFB) reactors are used • Can be an emission-free technology • Operation complexity is a potential issue for configurations using reactor cluster with cyclic reactor operation mode • Finding the adsorbent compatibility with the reactor and the regeneration mode can bring substantial cost saving • Configurations based on circulating modes can deliver high purity CO_2 • Technologies can operate both on heat and electricity depending on the adopted configuration
Membranes	• Mechanically simple and robust • Inherently electricity driven • No free chemicals • More suited for flue gases with higher CO_2 content • Small footprint and modular • Optimal costs for partial capture (~70%), if not combined with another capture technology. • Does not by itself deliver high-purity CO_2 (>99.9%). Multiple stages required, or combination with liquefaction is an option

3.4.4 Selection of capture technologies

Capture technologies are commonly compared on energy performance, but there is in fact a broader range of performance indicators to consider. In Table 3.7 we have listed what we believe some of the main performance indicators and boundary conditions that should be considered in the choice of capture technology.

Two of the most important issues to consider in the choice of CO_2 capture technology are the composition of the flue gas and the availability of energy to drive the capture process. The content of CO_2 in the flue gas directly impacts the design of the capture installation.

Generally, it is more costly to capture CO_2 from more dilute sources. Impurities in the flue gas such as NO_x, SO_x and particulate matter impact the capture process and must be considered in the design of the capture plant.

Post-combustion processes are often expected to operate at ambient pressure. If the gas to be treated is available at higher pressure, that is likely to influence the choice of technology.

Table 3.7 Key Performance Indicators (KPIs) and main boundary conditions

KPIs / Boundary conditions	Comment
CO_2 content in flue gas	Key parameter driving choice of technology
Flue gas impurities	Capture technologies will vary in how well they tackle flue gas impurities
Target capture rate	Capture technologies vary in how easily they can achieve higher capture rates
Target CO_2 purity and plan for use of CO_2	Capture technologies vary in how easily they can achieve high CO_2 purity in the product stream
Heat and electricity consumption	All capture processes require energy, but vary in energy requirements and the form of the energy required
Cooling duty	Many capture processes are heat-driven and will have a corresponding cooling need
Other utility requirements and/or availability	**Comment**
Plot space	Capture technologies vary in plot space requirements and layout
Emissions and waste	Solvent based processes tend to have some emissions and will require emission permits. Other processes can be emission free
Ease of operation	Capture processes vary substantially in mechanical and operational complexity and flexibility
CAPEX	Capture technologies vary substantially in components used and cost of equipment
Scale of capture process	Different capture technologies vary in how well suited they are for capture at different scale
Utility availability	Availability of excess can affect choice of technology

In this respect, however, it is difficult to generalize results as one technology can easily be favourable over another, or vice-versa, depending on site specific requirements and/or the availability of utilities, e.g., if excess heat is available, or not. With these features in mind, a site specific and quantitative case study, will be required in order to make specific recommendations for CO_2 capture technologies. A framework with standardized assumptions should be used to enhance the credibility of a such benchmarking exercise.

3.4.5 Legal aspects

Most solvent-based capture technologies utilize amine chemicals. Capture plants using amines will have some level of solvent related emissions. This is a manageable issue, but it does mean that a capture plant will require an emission permit and well-designed emission control system.

Since CO_2 capture plants represent new technology, regulators have limited experience in giving emission permits. Regulators in Norway and the UK are perhaps the most mature in Europe in terms of dealing with emission permitting for CO_2 capture plants. Technology Centre Mongstad (TCM) operates a demo-scale amine-plant in Norway. TCM has operated under an emission permit since the plant become operational over 10 years ago.

Both Norway and the UK have moved towards emission permits based on environmental assessments considering the location of the capture plant.

The composition of the flue gas being treated is an important factor that can potentially impact emissions. It is important that the emission control system chosen is de-risked for the specific flue gas.

The Scottish Environmental Protection Agency (SEPA) has written a fairly comprehensive review of amine emissions from carbon capture plants. The review was completed in 2015, so it will not cover recent developments, but the science has not changed significantly. We believe the SEPA review is useful for anyone that wants to understand the emissions issue in detail.

3.4.6 Conclusions

As discussed, there are several KPIs that must be considered in selecting a capture technology. In considering best available technology for different industries there are a few points to consider.

Absorption being both mature and versatile is today the best available technology for many industrial settings. This is a picture that can change with further technology development.

Some industries are quite varied in terms of KPI conditions. An obvious example is refineries that will usually have multiple stacks with different flue gas composition. The ability to deliver energy to the capture plant (in form of either heat or electricity) is also something that will depend on both the industry and geographical location.

4 CO_2 storage sites

This section describes the mapping of potential geological CO_2 storage sites in the two CCUS ZEN regions. The mapping includes also possible co-location with the protected Natura2000 areas.

Data from previous projects and publications have been used including deep saline aquifers and oil and gas fields as storage sites. Geological storage through mineral carbonation is consequently not included since such sites have not been mapped in detail by previous projects. Nevertheless, a short review of the concept is given in Section 4.1.4.

4.1 Mapping methodology

Mapping of potential CO_2 storage sites in the two CCUS ZEN regions has been based on the workflow developed by the Strategy CCUS project (Carneiro and Mesquita, 2020; Veloso, 2021), as well as the template for entering data. The template and its attributes are presented in Section 11.

The following attributes are described in more detail in the subsequent sections:

- Classification of storage structures (Section 4.1.1)
- Calculations of storage capacity (Section 4.1.2)
- Storage Readiness Level (SRL) indicating the maturity of the storage sites (Section 4.1.3)

4.1.1 Classification of storage structures

CCUS ZEN has adapted the classification of storage structures made by Gammer et al. (2011) when estimating the CO_2 storage capacity of possible storage sites for UK. The classification is illustrated in Figure 4.1 and described further in Table 4.1.

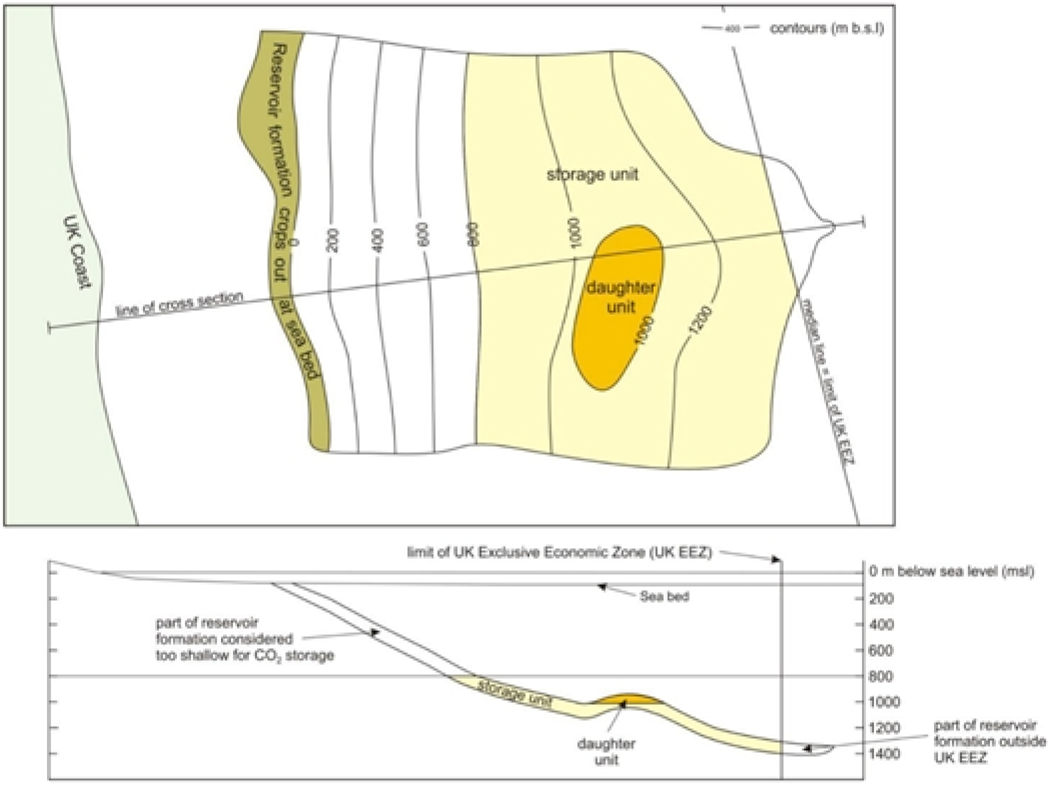


Figure 4.1 The relation between a reservoir formation, a storage unit (yellow) and a daughter unit (orange). After Gammer et al. (2011).

Table 4.1 Definition of a reservoir formation, a storage unit (yellow), a daughter unit (orange) and a prospect unit, with reference to Figure 4.1 After Gammer et al. (2011).

Reservoir formation	Regionally extensive formations with suitable reservoir properties for CO_2 storage.
Storage units	A storage unit is a mappable subsurface body of reservoir rock that is at depths below 800 meters, has similar geological characteristics, and has the potential to retain CO_2.
Daughter units	Structural and stratigraphic traps within the storage unit. Depleted hydrocarbon fields are daughter units by definition.
Prospect units	A prospect unit is a daughter unit that has proven to be bankable and commercial.

4.1.2 Calculation of storage capacity

The capacity formula proposed by Vangkilde-Pedersen et al. (2009) for deep saline aquifers has, in general, been applied by the projects and publications used in the CCUS ZEN mapping:

$$MCO2 = A \times h \times NG \times \phi \times \rho CO2 \times Seff \quad \text{Equation 4.1}$$

where:

- $MCO2$ = calculated estimate storage capacity (in kg)
- A = considered area (regional or trap aquifer) (in m^2)
- h = average thickness of the regional or trap aquifer suitable for CO_2 storage (in m)
- NG = average net to gross ratio of regional and trap aquifer (in %). This factor represents all the formation irregularities within the bulk volume.
- Φ = average reservoir porosity of the effectively porous rocks in the regional or trap aquifer (in %)
- $\rho CO2$ = CO_2 density at reservoir conditions (in kg/m^3)
- S_{eff} = Storage Efficiency Factor (in %).

The product $A \times h$ represents the bulk volume. h, NG, Φ, $\rho CO2$ and S_{eff} are estimated giving the amount of data available. The uncertainty on $MCO2$ will depend on the uncertainties on all these quantities.

The storage efficiency factor S_{eff} is the adjustment factor of the formula and is defined as the fraction of total volume pore that can effectively be filled by CO_2. The storage efficiency factor depends on whether the area under consideration as a regional aquifer (storage unit) or a trap aquifer (daughter unit). If the considered area is a storage unit, S_{eff} is usually chosen at 2%. The value varies between 3% and 40% for a daughter unit since the factor is related to general morphometric features, such as the boundary conditions. This is illustrated in Figure 4.2.

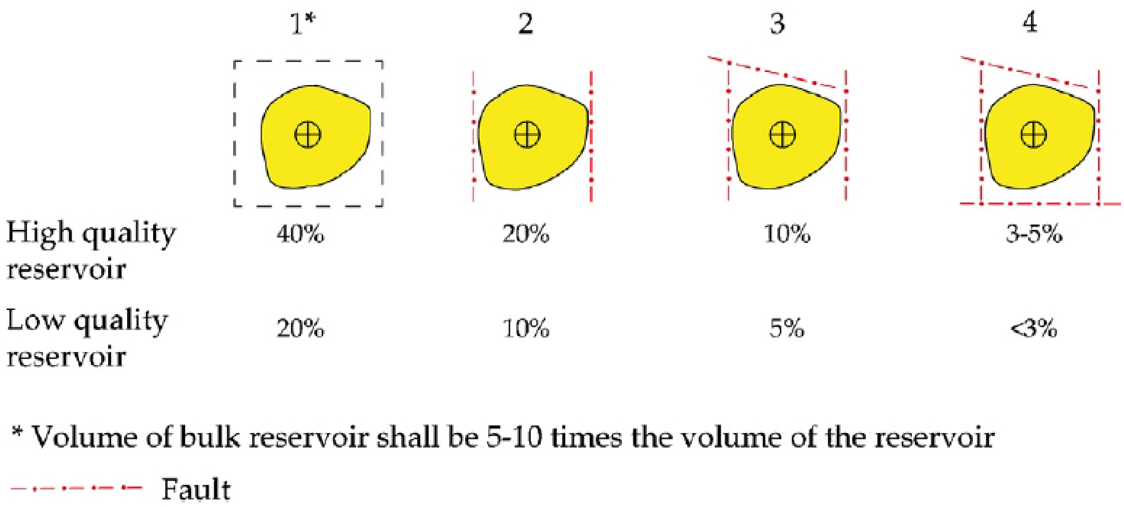


Figure 4.2 Scheme of potential variability and "rule of thumb" estimate of the storage efficiency for different structural configurations. 1) represents an open (unconfined) system, 2) and 3) semi-closed systems and 4) a closed system. A high-quality reservoir represents a reservoir with high porosity and permeability. From Vangkilde-Pedersen et al. (2009).

4.1.3 Storage Readiness Level (SRL)

The CO_2 storage capacity provides important information about a CO_2 storage site. However, the estimation alone does not consider all factors that influence feasibility of a prospective site for an operational CO_2 storage project.

To communicate the maturity of a CO_2 storage site and what remains for it to become operative, Akhurst et al. (2021) introduced the CO_2 Storage Readiness Level (SRL) concept. The schema is based on learning gained from the experience of the UK, Norway and the Netherlands from the 1990s and is presented in Figure 4.4 and Figure 4.3.

A hydrocarbon field that is well known from hydrocarbon licensing and production but has not been assessed in terms of risks to containment of CO_2 as a prospective storage site would be at SRL 3.

CCUS ZEN has applied the SRL scheme when evaluating the maturity of potential CO_2 storage sites in the two CCUS ZEN regions.

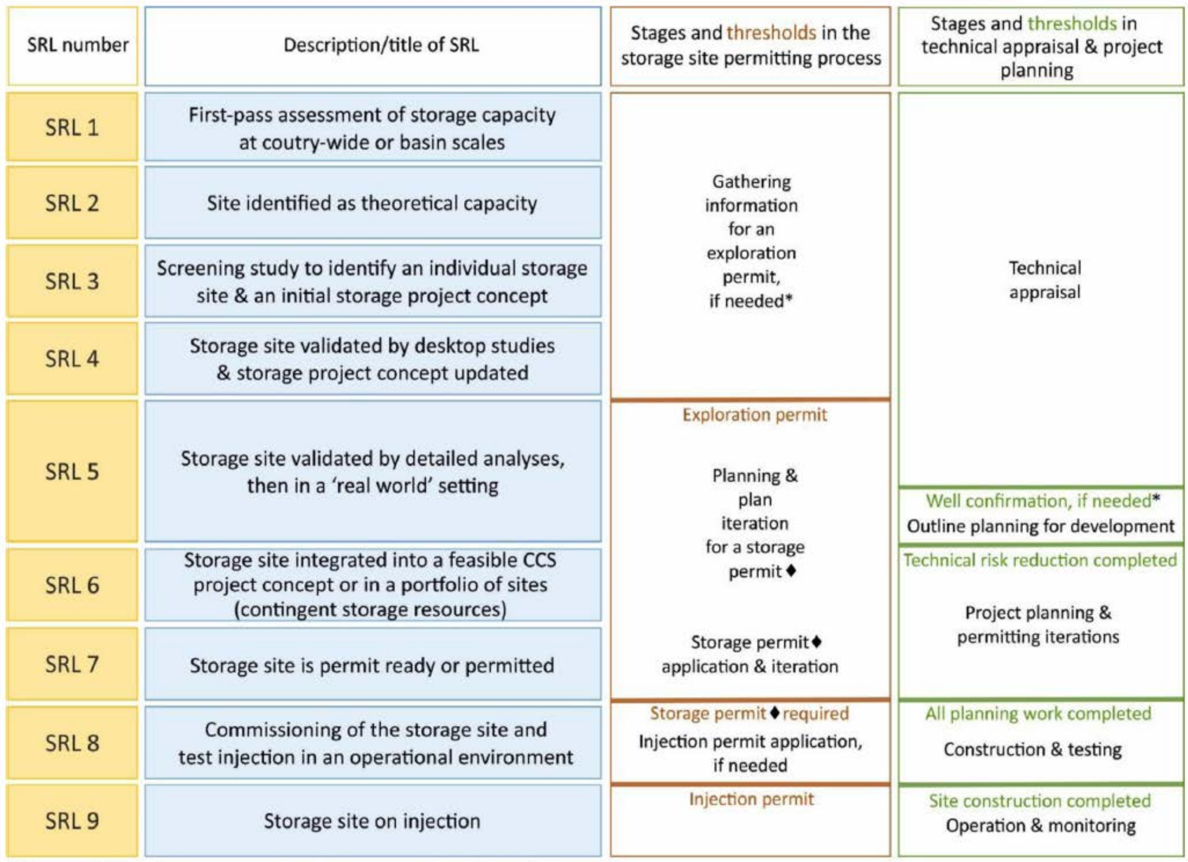


Figure 4.3 SRL framework, stages and thresholds in the storage site permitting process (brown) and storage technical appraisal and planning (green).*An exploration permit or well confirmation may not be needed for re-use of a hydrocarbon field for CO_2 storage. ♦Equivalent of storage permit relevant to national jurisdiction. From Akhurst et al. (2021).

SRL	Descriptive title	Activities likely to have been undertaken at each SRL
SRL 1	First pass assessment of storage capacity at country-wide or basin scales	At SRL 1 an appraisal to identify the CO_2 storage potential has been completed, as a first pass assessment, although this potential may not have been fully quantified. Characteristics suitable for CO_2 storage have been identified within an area, country or region.
SRL 2	Site identified as theoretical capacity	At SRL 2 there has been assessment of the storage potential by systematic mapping of an area, whole region, country or jurisdiction's potential storage resource. A consistent and referenced methodology will have been followed and applied to calculate the theoretical storage capacity.
SRL 3	Screening study to identify an individual storage site and initial storage project concept	At SRL 3 a screening study will have been completed, achieved after a ranking exercise based on the storage site's expected performance against a set or subset of geological, technical, economic and geographical criteria. An initial project concept will have been outlined and a CO_2 storage site may have been identified, either individually or as a group of sites, as having high potential for storage. Any major risks to containment and capacity will have been identified.
SRL 4	Storage site validated by desktop studies and storage project concept updated	At SRL 4 a detailed desktop characterisation of the storage site will have been completed to validate the selection as potentially suitable for storage. For a site to qualify for SRL 4 it will have an initial static geological model or conceptual geological model. Available site-specific data will have been interpreted. There is sufficient information for preparation of an exploration licence application and submission to the relevant authority, if needed.
SRL 5a 5b 5c	Storage site validated, firstly, by detailed analysis, then in a relevant 'real world' setting	At SRL 5a detailed risk assessment-led investigations and risk reduction activities required to inform a storage permit application specific to a given site based on existing information will have been completed. At SRL 5b new data is acquired, where needed, to assure the storage site, this may include direct evidence of the storage strata, or equivalent structure or site, and to inform an EIA. Well test data will have been acquired and/or assessed. At SRL 5c all storage site data will have been acquired, analysed and technical appraisal completed to reduce or mitigate storage risks to an acceptable level and sufficient for a storage permit application.
SRL 6	Storage site integrated into a feasible CCS project concept or portfolio of sites (contingent storage resource)	At SRL 6 a storage site will have been integrated into a feasible CCS project or a portfolio of sites. The assured storage capacity will have been defined. An EIA will have been completed. All concerns regarding subsurface containment, migration and capacity to store CO_2 for a project will have been addressed.
SRL 7	Storage site is permit ready or permitted	At SRL 7 all of the CCS project planning work, based on the technical appraisal and as required for a storage permit application, will have been completed. An application for a CO_2 storage permit has been either submitted to the Competent Authority and permitted or is ready to be submitted.
SRL 8	Commissioning of the storage site and test injection at the site	At SRL 8 the storage permit has been issued and the investment decision to construct and operate the site for a CCS project has been made. All legal and practical activities needed to implement site commissioning have been completed and the storage site has been tested in an operational environment.
SRL 9	Storage site on injection	At SRL 9 the site is operational as a component of an integrated CCS project.

Figure 4.4 Descriptive tile and activities likely to have been undertaken, from initial capacity assessment to project operation, by Storage Readiness Level (SRL). EIA stands for Environmental Impact Assessment. (Akhurst et al., 2021).

4.1.4 Mineral carbonation

Mineral carbonation occurs naturally through the interaction of CO_2 charged water with rocks, and notably basaltic and ultramafic rocks. CO_2 charged water is acidic, which promotes the dissolution of cation bearing silicate minerals. For example, the dissolution of pyroxene, a common mineral in basalts, can be expressed as (Snæbjörnsdóttir et al., 2020):

$$2H^+ + H_2O + (Ca,Mg,Fe)SiO_3 = Ca^{2+}, Mg^{2+}, Fe^{2+} + H_4SiO_4$$ Equation 4.2

The CO_2 reacts then with the metallic cations to form stable carbonate minerals which precipitates. The chemistry and reactivity of the rock as well as the pressure and temperature of the reservoir are strongly influencing the rate of dissolution and carbonation reactions. Other important factors are the permeability and the porosity of the host-rock formation. These provide pathways for the migrating fluids, access to mineral surfaces and space for the carbonate to precipitate.

The concept of CO_2 storage in basalts is based on the injection of CO_2 charged water into basaltic rocks to enhance natural mineral carbonation. It was proposed by McGrail et al. (2003) and then developed using laboratory and numerical simulations, later resulting in two pilot projects in Wallula, USA and at Hellisheiði, Iceland. Only the CarbFix project at Hellisheiði, Iceland is currently ongoing as they continued with industrial scale injections after the pilot phase (Snæbjörnsdóttir et al., 2020).

Basaltic rocks are one of the most reactive rock types of the Earth's crust and contain reactive minerals with high potential for CO_2 sequestration. The largest occurrences of basalt are in the ocean floor that is almost completely made up by basalt. Above sea level basalt is common in hotspot islands (Iceland, Hawaii etc) and around volcanic arcs, especially those on thin crust. Figure 4.5 shows the largest volumes of basalt on land correspond to continental flood basalts which are known to exist in North and South America, Africa, Russia, India, Australia and other non-European regions (Sanna et al., 2014). Figure 4.6 shows further favourable geology with respect to the CarbFix method. The map serves as a first indicator for the geological feasibility of the Carbfix technology - but does not consider other necessary factors such as water availability or permeability of the bedrock which can vary greatly between regions. The map must be interpreted with this in mind (https://www.carbfix.com/atlas).

Basalt rocks have not been mapped in detail by previous projects in the two CCUS ZEN regions. However, it is generally believed that they are old, and that natural precipitation over time has made them low permeable and with less reactive minerals left for further carbonation (in contrast to the basalts along the active Mid-Atlantic ridge crossing Island). Geological storage of CO_2 through carbonatation is therefore not included in the CCUS ZEN project.

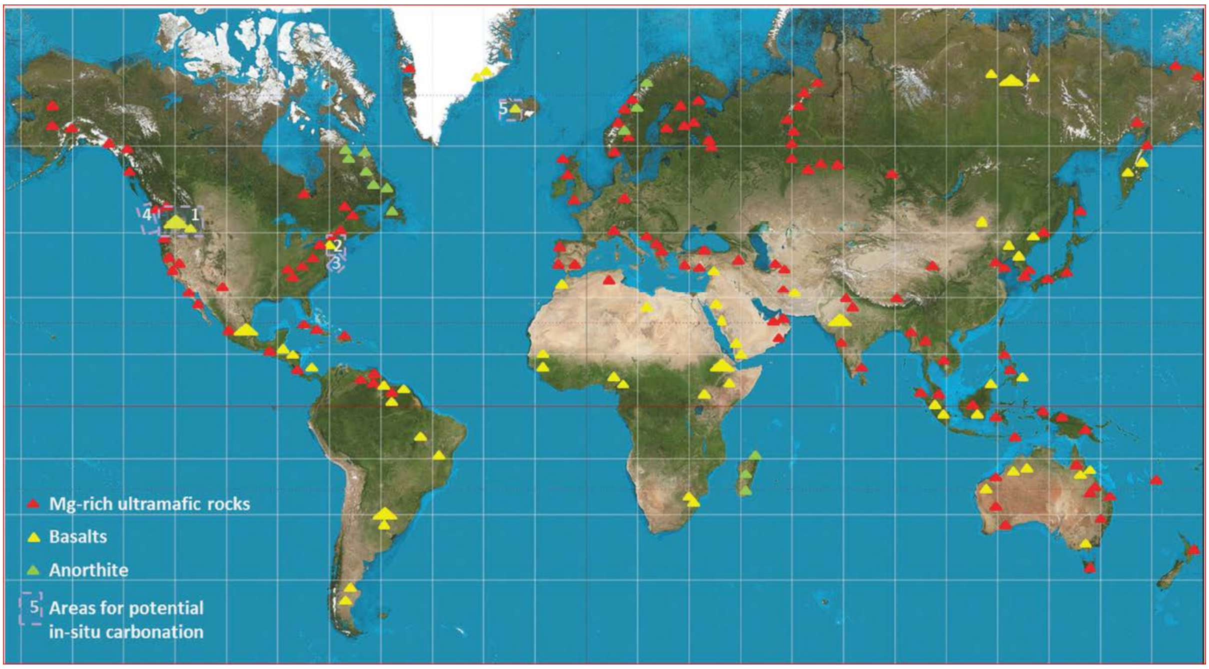


Figure 4.5 Mineral feedstock available for CO_2 mineral carbonation (Sanna et al., 2014). Basalts (yellow triangles) are not available in the CCUS-ZEN studied regions.

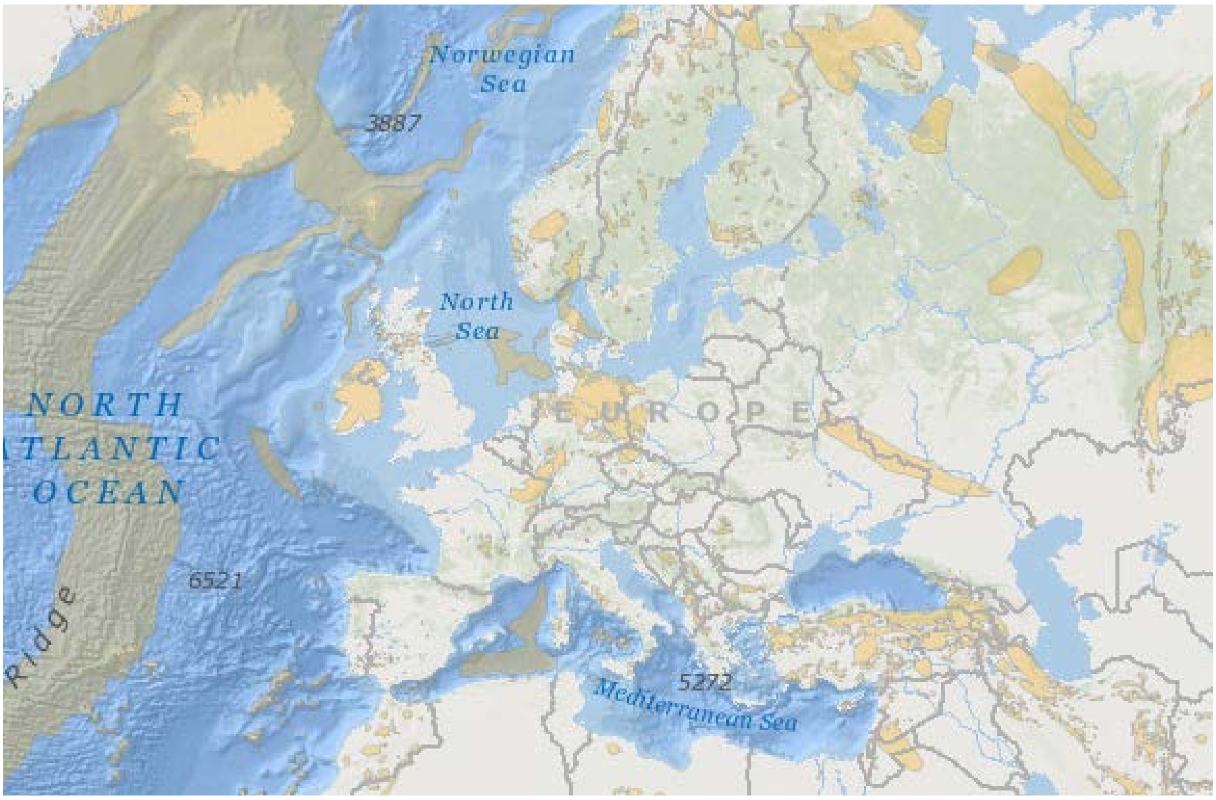


Figure 4.6 The map shows favourable geology (yellow areas) with respect to the CarbFix mineral carbonation method (https://www.carbfix.com/atlas).

4.2 High level mapping in the Baltic Sea region

High level mapping of potential CO_2 storage sites in the Baltic Sea region is shown in Figure 4.7. Natura2000 areas are added to the map in Figure 4.8. The maps are magnified and shown country-wise in Section 12 (Appendix C). A table listing all potential CO_2 storage sites together with their capacity estimates, SRL level and source of information is also given in the Appendix.

Figure 4.7 shows that this region has a diversity of potential storage sites including deep saline aquifers, hydrocarbon fields, and both on- and offshore structures. The corresponding storage capacity identified by CCUS ZEN is listed country wise in Table 4.2.

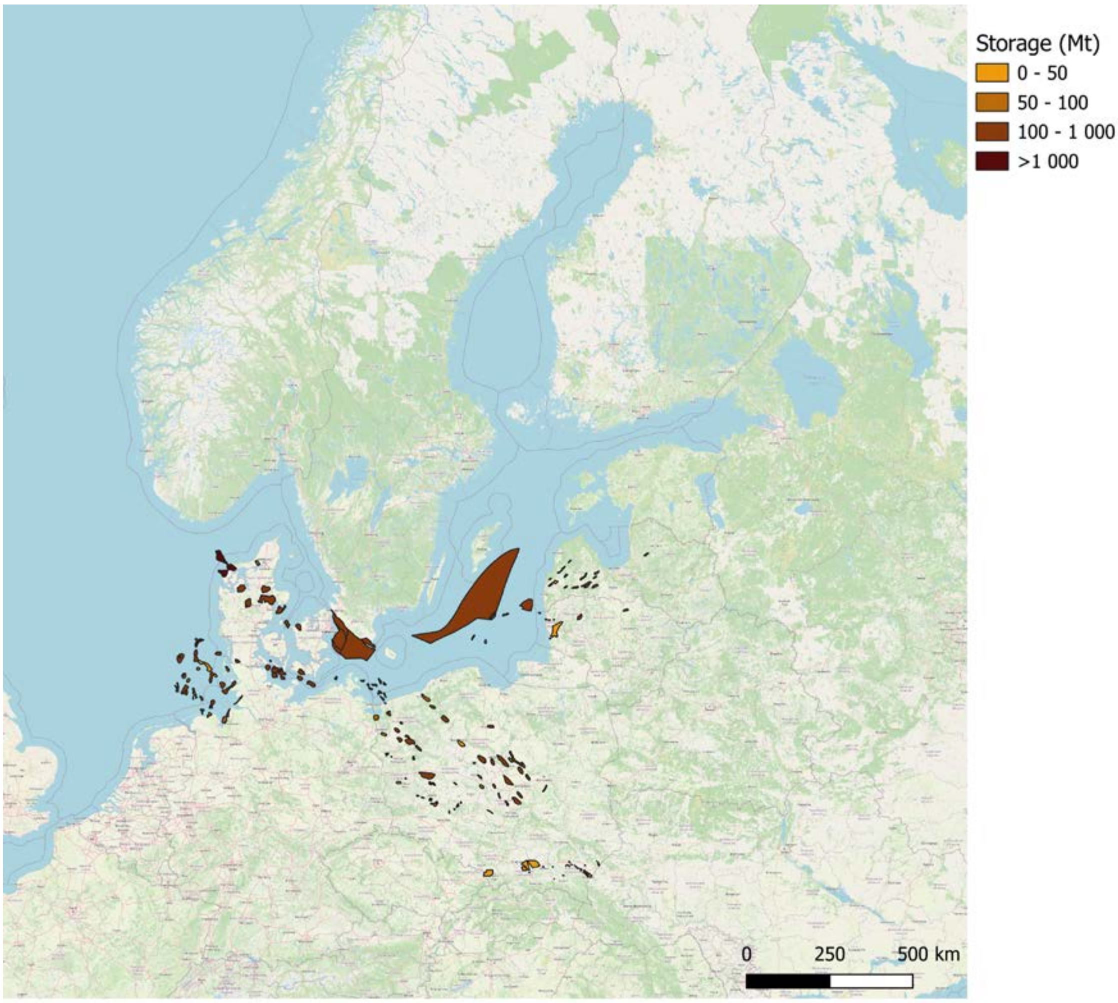


Figure 4.7 **CCUS ZEN Baltic Sea region**: High level mapping of CO_2 storage sites.

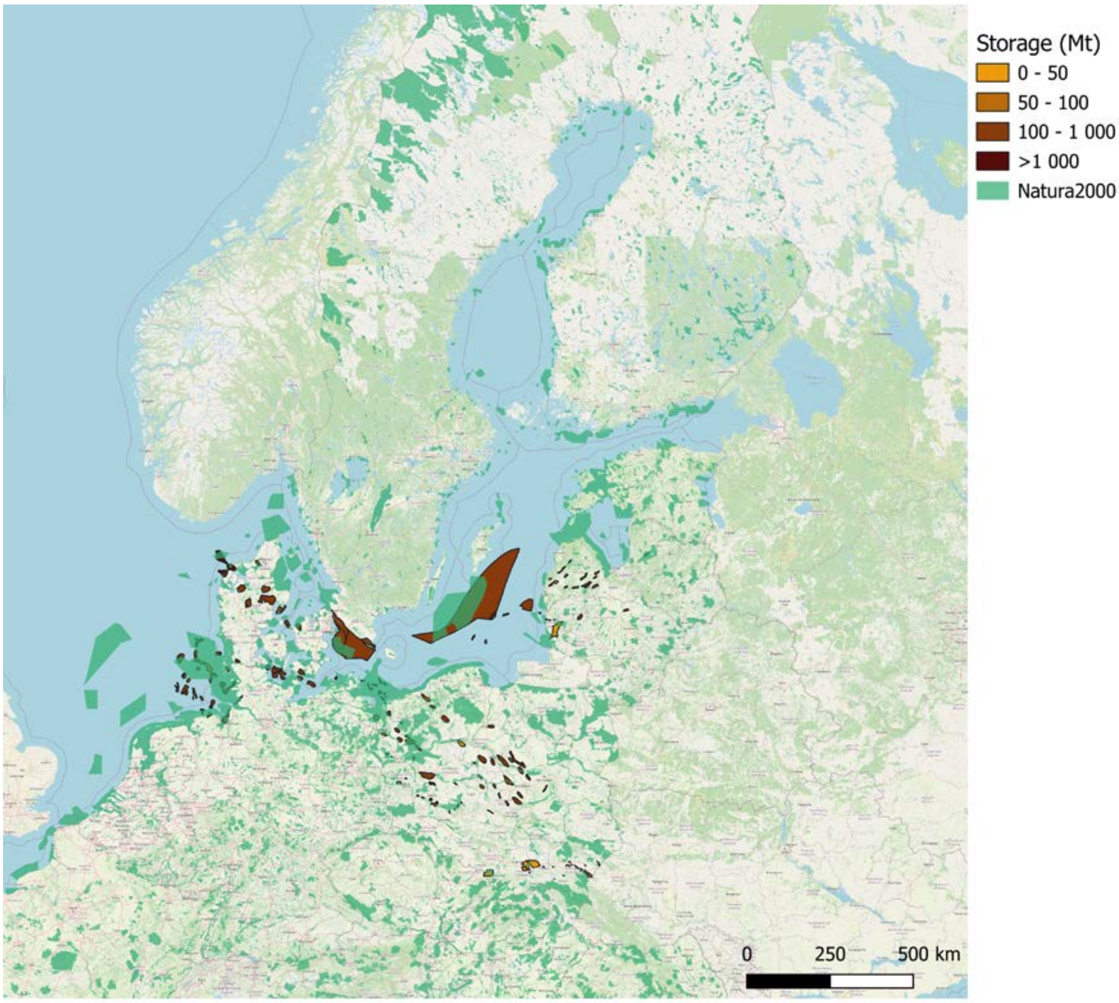


Figure 4.8 **CCUS ZEN Baltic Sea region**: High level mapping of potential CO_2 storage sites and Natura2000 areas (dark green).

Table 4.2 **CCUS ZEN Baltic Sea region**: Potential CO_2 storage sites and corresponding capacities. DSA stands for Deep Saline Aquifer and HC field for Hydrocarbon field.

Country	# of DSA	# HC field	Total capacity (Mt)
Sweden	9	0	3 420
Finland	0	0	0
Denmark	27	Not included	16 042
Estonia	0	0	0
Latvia	17	0	1 172
Lithuania	12	5	299
Poland	55	39	8 885
Germany	34	Not included	3 539
SUM			33 357

4.3 High level mapping in the Mediterranean Sea region

High level mapping of potential CO_2 storage sites in the Mediterranean Sea region is shown in Figure 4.9. In France, only storage structures in the south of the country have been considered. Possible storage structures in Northern and Central France have not been included since the project focuses on the Mediterranean Sea region. For the same reason, only possible storage sites in the eastern part of Spain have been included in the study. The storage capacity identified by CCUS ZEN in this region is listed country wise in Table 4.3.

In Figure 4.10, Natura2000 areas are added to the map in Figure 4.9. The maps are magnified and shown country-wise in Section 13 (Appendix D). A table listing all potential CO_2 storage sites together with their capacity estimates, SRL level and source of information is also given in the Appendix.

Figure 4.9 **CCUS ZEN Mediterranean Sea region**: High level mapping of potential CO_2 storage sites.

Figure 4.10 **CCUS ZEN Mediterranean Sea region**: High level mapping of potential CO_2 storage sites and Natura2000 areas (dark green)

Table 4.3 **CCUS ZEN Mediterranean Sea region**: Potential CO_2 storage sites and corresponding capacities. DSA stands for Deep Saline Aquifer and HC field for Hydrocarbon field.

Country	# of DSA	# HC field	Total capacity (Mt)
Spain	17	Not included	4 816
France	4	20	739
Italy	14	11	4 699
Greece	5	2	3 174
Türkiye	Not evaluated	109	109
SUM			13 537

5 CO_2 transport options and intermediate storage solutions

This chapter summarises existing infrastructure relevant for CO_2-transport with emphasis on pipelines, existing natural gas corridors, ports and waterways. In cases where transport via pipelines or waterways is not considered feasible, other transport options, in particular railways and road (lorries), will be considered. In certain cases, even corridors made for electricity lines may be considered, with the aim of identifying possible routes for laying new CO_2 pipelines over land.

A transport network is needed to connect clusters of emissions sources in a defined geographical area (or large standalone emitters) with identified locations for permanent storage of CO_2 or alternatively industries that can utilize large quantities of CO_2 in their production. In a transport network there may be a need for intermediate storage of CO_2, in the producing end of the chain, in the receiving end of the chain or both. This is relevant when CO_2 is transported in batches, which for instance is the case when using ships for the whole or parts of the transport chain. An example is the Northern Lights project, where a hub is constructed at the West coast of Norway allowing incoming shiploads of CO_2 to be unloaded and eventually stored intermediately before the CO_2 is transported in a pipeline to the permanent storage site offshore.

5.1 Methodology

5.1.1 Sources of information and tools: Transport options

For transportation the mapping tool developed in the CO2LOS project is particularly relevant and is used to identify opportunities related to ships and barges, while the PCI Transparency Platform in combination with the OpenStreetMap is used for pipelines.

The CO2LOS project (2019-2023), led by Brevik Engineering and SINTEF, aims to reduce the cost of the CCUS logistic chain and has developed a tool that shows the limitations and possibilities for the waterways in Northern Europe. The PCI Transparency Platform maps the location of Projects of Common Interest (PCI) which includes projects related to the networks for electricity, gas, cross-border carbon dioxide pipelines and smart grids. The PCI Transparency Platform also provides information about existing ship routes and has therefore been the main source of information for the high-level mapping for CCUS ZEN. Additionally, the European Network of Transmission Systems Operators for Gas (ENTSOG) provides a yearly updated map with an overview of existing gas pipeline infrastructure and projections for future development.

Publicly available data regarding pipeline routes is considered only as indicative. Information on the exact position of pipelines with high accuracy is generally not disclosed by the respective owners. Possible projects which may consider existing pipelines for CO_2 transportation may be impacted by the less precise positioning of the infrastructure in early stages. This may lead to the application of design contingencies.

5.1.2 Sources of information: Intermediate storage solutions

The partners in the project have very good overview of technical solutions for intermediate storage and will, based on their experience, be able to assess both the need for intermediate storage as well as possible solutions in each case. Intermediate storage of LPG is common, and the storage tanks would be similar according to pressure and temperature.

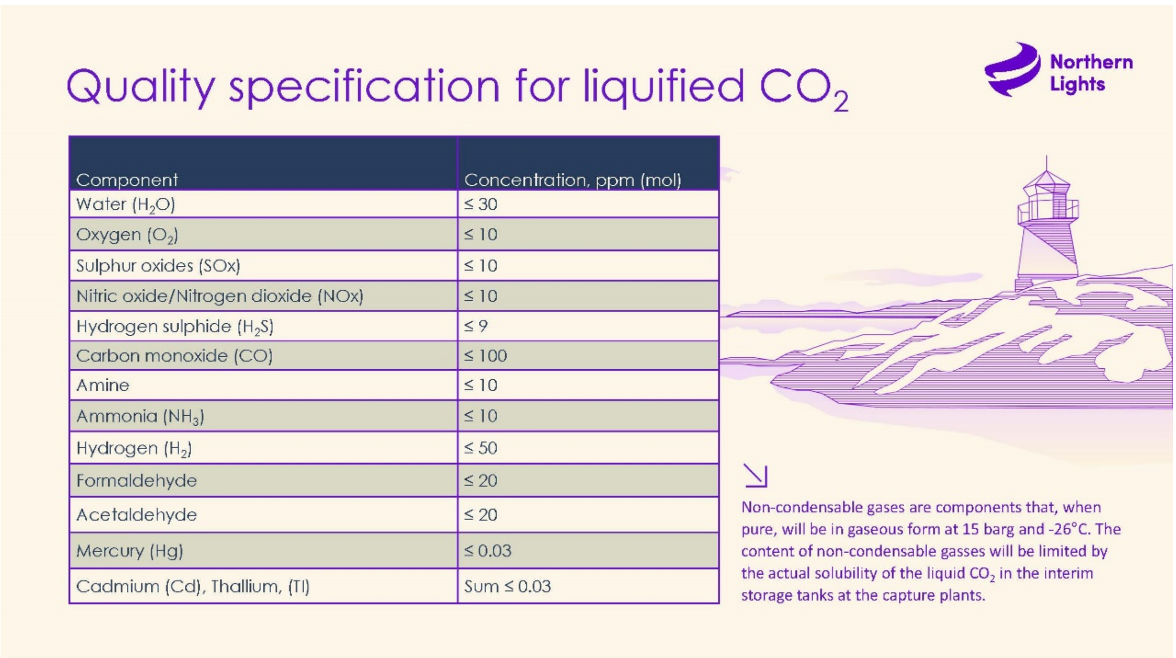
5.2 Liquefaction and purification of CO_2

Without going into details in this high-level report, it should be noted that transportation of medium (or low) pressure CO_2 by ships or barges, and even by road and rail, requires that CO_2 is liquefied. According to Hegerland et al. (2004) who describe an industrial process for liquefaction, CO_2 must be compressed, condensed and depressurized. In addition, inert (non-condensable) gases such as hydrogen, oxygen, nitrogen, and methane, must be separated during the liquefaction process. Water should also be removed to prevent corrosion and formation of hydrates. For certain projects, the CO_2 must comply with defined specifications which may include trace substances as well. An example is given in Figure 5.1 and relates to the Northern Lights project in the North Sea.

5.3 CO_2 transport options

Natural gas pipelines may be converted to CO_2, but such conversion may not be straight forward. This is due to reasons such as choice of phase for CO_2 (gas phase or supercritical), water content and other impurities in the CO_2 stream which have an impact on pressure rating, wall thickness and material of construction requirement for the CO_2 pipeline. Also, the routing of the pipelines should fit the purpose, that is preferably as close as possible to go from large CO_2 sources to a storage facility.

Converting existing **oil pipelines** to CO_2 is possible if the pipeline can handle CO_2 with the specifications given, that is phase conditions, impurities content etc., in very much a similar manner as with natural gas pipelines. Additionally, oil pipelines are expected to be more easily redundant and phased out due to the existing decarbonisation initiatives in Europe which prioritises gas infrastructure. This may result in higher oil pipelines availability for repurposing to CO_2 transportation.


Quality specification for liquified CO_2

Component	Concentration, ppm (mol)
Water (H_2O)	≤ 30
Oxygen (O_2)	≤ 10
Sulphur oxides (SOx)	≤ 10
Nitric oxide/Nitrogen dioxide (NOx)	≤ 10
Hydrogen sulphide (H_2S)	≤ 9
Carbon monoxide (CO)	≤ 100
Amine	≤ 10
Ammonia (NH_3)	≤ 10
Hydrogen (H_2)	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Mercury (Hg)	≤ 0.03
Cadmium (Cd), Thallium, (Tl)	Sum ≤ 0.03

Figure 5.1 CO_2 quality specifications for the Northern Lights project (Northern Lights, 2020)

Requirements for re-use of existing infrastructure may be looked upon in different ways. Re-use of physical pipelines (for instance shifting from natural gas to CO_2) is technically more complicated than simple re-use of existing pipeline corridors for new CO_2 pipelines. In the ACT-project ALIGN-CCUS (Van Os, 2020) a review was made of technical criteria for re-use of offshore oil and gas infrastructure to accelerate deployment and reduce the cost of CCS. The review was done with re-use of infrastructure relevant for CO_2 storage in the North Sea area in mind. The review points to location of infrastructure relevant to sites of known and sufficient CO_2 storage capacity as most important. Also, availability and lifespan of the infrastructure are important parameters. Even though this can only be accurately estimated with data from operators, rough estimates are possible using publicly available information. Part of an assessment of the re-use of existing infrastructure must also consider the possible time-gap between existing use and future use for CO_2 transport. There may also be legal challenges if re-use of existing infrastructure is desirable. Challenges are primarily related to the decommissioning regime for offshore hydrocarbon infrastructure.

Natural gas pipelines may be reused to transport CO_2. But if they are technically not suitable for that, the gas pipelines could potentially be used as an infrastructure to pull-in inside supercritical CO_2 pipelines (which typically have a lower diameter). Additionally, either for oil and gas pipelines or power cables, the corridors defined for such infrastructure may be available for the installation of a new CO_2 pipeline, even if the existing pipeline infrastructure is not suited for CO_2 repurposing.

In the North Sea case, the review concluded that where relevant pipeline infrastructure will still be in production for the foreseeable future, new installations will be necessary for the initial development of CO_2 pipeline infrastructure.

Regarding re-use of existing pipelines onshore, the above criteria are also highly relevant, while legal aspects may be different from what is the case offshore.

Ships may also be new-built or rebuilt. Shipowners have suggested to convert LPG tankers to CO_2 carriers for medium pressure conditions. Medium pressure conditions mean about 15 barg and -28°C as opposed to low pressure @ 7-8 barg and -50°C. Low pressure conditions do have some advantages, but at the time being, medium pressure conditions are the preferred option and will be used for instance in the Northern Lights project. There are also some early-stage projects investigating to transport CO_2 at 35-45 bar. That reduces the cost for liquefaction but increases the wall thickness and thereby also the weight of the tanks.

Already existing infrastructure of ports, jetties, berths, and harbours will be utilized for CO_2 transport if possible.

In principle, apart from the size of tanks and cargo, **transport by road or rail** will not be significantly different than ship transportation. Lorries/trucks and railway containers will also carry liquefied CO_2 under similar conditions as with ships.

5.3.1 Comparison between pipeline and shipping transportation alternatives

There are multiple ways to transport CO_2 which include pipelines, ships, trucks/lorries or railways. All methods are often combined with pre- and/or post-processes such as compression and drying of the CO_2 stream, removal of impurities, liquefaction and intermediate storage solutions. Larger CO_2 quantities, such as usually estimated for a CO_2 cluster require either a pipeline or ships, or a combination of both. This sub-section presents a high-level comparison between the two transportation methods.

The best transportation is often a combination of multiple methods that balances costs with convenience, practicality and compliance with safety, and legal and environmental requirements. Pipelines are commonly the safest and most economical way to transport large quantities of CO_2 over short to medium distances. On the other hand, pipelines are not a temporary flexible infrastructure and must be considered for long-term operations. They require a high initial investment, but reduced OPEX. Re-utilisation of existing infrastructure may, therefore, be a key for such projects. OPEX may also be reduced by combining processes like drying or compression with the emitter's industrial processes which produce heat or cold. Construction of a CO_2 pipeline should consider the environmental impacts and routes might be concerned by deviations of protected areas. Residential or densely populated areas may be a risk factor for the presence of CO_2 pipelines as well. Pipelines can transport CO_2 at gaseous, liquid or supercritical phases. Currently, there are approximately 3 200 kilometres of onshore CO_2 pipeline in the US today. In Norway, one offshore CO_2 pipeline is already installed, and another is under construction at the Northern Light project.

Shipping is a more flexible operation and is viable for longer distances and also for smaller volumes. While the CAPEX costs are lower and the ships can be repurposed after the project closure, the OPEX costs are a main decision driver. Residential areas are not an obstacle in ship traffic and compliance to environmental restrictions is easier. On the other hand, shipping is dependent on the existence of suitable harbours and cannot travel onshore. Shipping logistics commonly require a large intermediate storage and CO_2 can only be transported in liquid phase. Commonly today, 1500 to 3000 ton vessels are used in the food industry, and the transport conditions are 15 barg and -28ºC. It is foreseen that the ship size for CCS project will be larger, but it depends on the logistic chain.

5.4 Intermediate storage solutions

For transport by pipeline, line packing is a possible option for short time (daily and hourly) storage and works by utilizing the compressibility of the gas. The need for intermediate storage of CO_2 is mostly linked to batch-wise transportation, that is transport by ships/barges and/or trucks, railway. For ship-based transport, CO_2 is brought into cryogenic liquid state through a series of cooling and compression steps. Intermediate storage is necessary as a buffer between the continuous process of CO_2 capture and the batch-wise transportation by ships (or trucks, railway). Therefore, the intermediate storage must be sized in accordance with the capacity of the selected batch transportation method. After unloading at a hub, the CO_2 needs once again to be stored intermediately at the hub before further transportation. Offshore unloading may also be an option and is already being explored for example in the Greensand project, in Denmark.

Apart from line packing, temporary (or intermediate) storage technologies include quayside storage in tanks and geological storage. Technologies for geological intermediate (as opposed to permanent) storage of CO_2 include salt caverns, depleted hydrocarbon fields and even saline aquifers.

Ongoing projects today operate or plan to be operated with quayside storage in tanks. Nippon Gases and previously Yara have a decade-long history of transporting CO_2 by ship. This transport also includes quayside storage tanks. The Northern Lights project (Northern Lights FEED Report, 2020) will use standardized ships with a 7 500 m^3 capacity, operating at medium pressure conditions. The 12 cylindrical intermediate tanks will have a total volume of 8 250 m^3, thus allowing a 10% buffer capacity. Tanks will be made of low temperature carbon steel.

Capturing large CO_2 volumes requires significant intermediate storage units and therefore availability of large areas. Emitters may be restrained by the available land either due to footprint, permitting and authorisations or land acquisition. Additionally, high volume capacity tanks (units over 5 000 m^3 can be manufactured today) may pose larger risks in case of leakage or rupture. One mitigation for emitters or clusters located near shore can be the use of intermediate storage in the form of Floating Storage Units (FSU) or Floating Liquefaction and Storage Units (FLSU), offshore. For both alternatives, CO_2 is sent to offshore floating units in liquid phase or gaseous phase for liquefaction respectively. These units can be located nearshore, eliminating the land use disadvantage and mitigating leakage or rupture risks. The CO_2 is then transferred to ships or pipelines for further transportation.

If offloaded directly at an offshore storage location, a floating storage and injection unit (FSI) may become an alternative for intermediate storage and injection of the incoming CO_2. This would allow more flexibility in terms of emitters' location and avoid the requirement of an onshore intermediate terminal leading to permitting and planning constraints. In this option, LCO_2 carriers would directly offload the liquid CO_2 on the FSI which will temporarily store it and then inject it in the geological reservoir located close by, hence minimising the subsea infrastructures and pipelines. The required intermediate storage volume can be designed according to the transportation chain requirements.

5.5 High-level mapping in the Baltic Sea region

5.5.1 Ship transport

The infrastructure needed for ship and barge transport are harbours and terminals. There are ports and infrastructure for ship-based transport in all the countries, and these ports may have extra capacity to include CO_2 transport. The waterways in Europe are classified according to the ship sizes they may operate. The classification is from zero to VII. To determine which port and waterways should be used in the logistic chain, both the capacity and the distance from the source should be considered. For Germany, Poland and Lithuania, we have this overview (Figure 5.2) of the available waterways, regulated rivers and canals. In the Baltic region there are limited waterways available for CO_2 transport compared to the western Europe.

Clusters that export CO_2 through shipping (or other batch transportation method) must have additional specialised items. Offloading from an intermediate storage to a ship requires the use of loading arms or hoses. When the CO_2 is flashed to the shipping tanks, a small percentage of it will boil, which requires its extraction and re-liquefaction. Typically, a vapour return line is required to direct the gaseous CO_2 to the liquefaction unit. A local, small liquefaction unit may also be considered, or onboard liquefaction, if available on the ship.

5.5.2 Railways and roads for CO_2 transportation

Railway and road transportation will typically limit the batch size to comparably much lower volumes than transportation by ship or pipeline. Nonetheless, these methods can provide more flexibility and easy access. Additionally, if the necessary infrastructure is available, railways can be an opportunity for CO_2 transportation use. Train and truck transportation can be sustainably operated with hydrogen, renewable electricity or biofuels. The railway infrastructure in the Baltic region is represented in Figure 5.3.

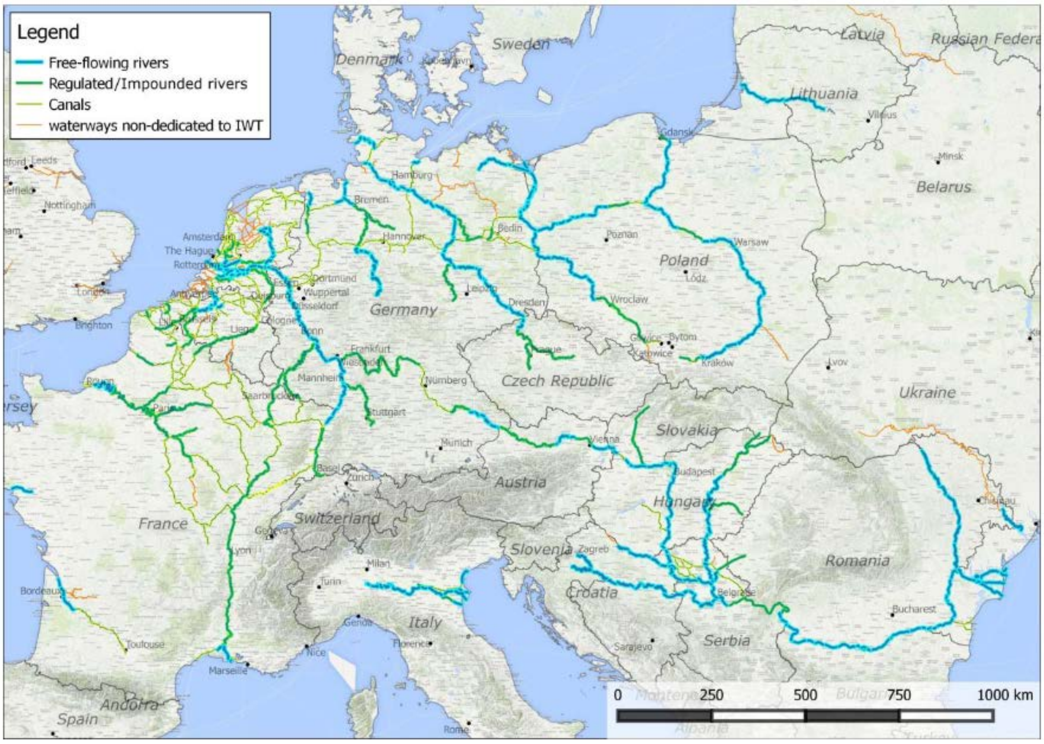


Figure 5.2 Type of inland waterways in Europe (Prominent, 2016).

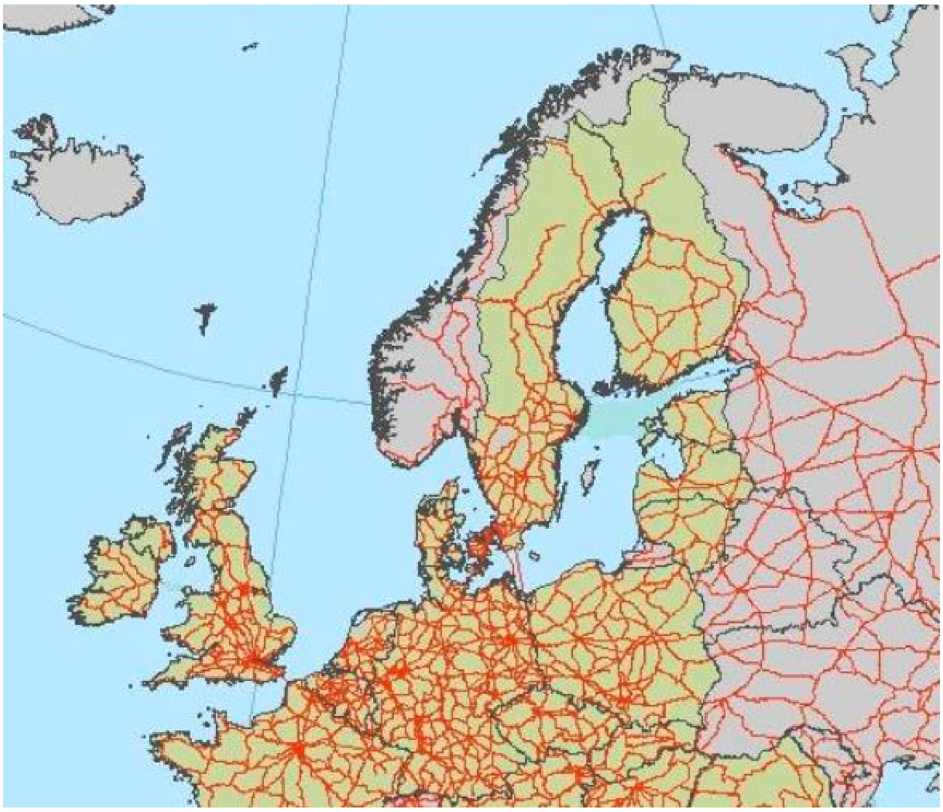


Figure 5.3 Baltic Sea region: Railway infrastructure. (JRC Science and policy reports, 2014)

5.5.3 Natural gas infrastructure

The present chapter describes the existing gas infrastructure displayed in the ENTSOG System Development Map 2020/2021. It was approved on the 1st of December 2021 by the correspondent Transmission System Operators (TSOs).

The map presented in Figure 5.4 shows existing gas pipelines in the Baltic region, either projected (dashed lines) or already built (continuous lines). Thicker lines represent higher diameter pipelines, oppositely to finer lines.

In the future, there may be a competition between CO_2 transportation and natural gas supply. Therefore, in the case of multiple adjacent pipelines and supply redundancy, there will be an opportunity to select one of the pipelines to convey CO_2.

Considering the selected pipelines conditions and capacity, they may be used directly for CO_2 transportation if fit, regarding risk profile and design factors, minimum wall thickness required, wall thickness loss due to corrosion, built or planned constructions in the vicinity or nature and environmental protection areas, for example. Otherwise, the existing routes can be used for new pipelines. The existing pipelines can also be studied for a pull-in of new CO_2 pipelines through, avoiding major costs related to pipeline construction.

More details regarding gas pipelines in the Baltic region can be found in Section 12.2 (Appendix C).

Figure 5.4 Baltic Sea region: Existing gas pipeline infrastructure – 2020/2021 System Development Map (ENTSOG).

5.5.4 Oil infrastructure

In this chapter we provide an overview of existing pipelines and ongoing projects (PCI) for oil infrastructure. The PCI Transparency Platform is the main source of information.

In Figure 5.5, existing oil pipelines projects in the Baltic region are shown. Most infrastructure is onshore, apart from the part of the Danish oil pipeline system that enters the West coast of Jutland with crude oil from the North Sea. No new projects seem to be under development.

5.5.5 Electricity infrastructure

The main features of the electricity grid, selected from the PCI Transparency Platform are presented in this section Figure 5.6 shows the main routes for transmission of electricity in the area. The relevance for transport of CO_2 is that electricity routes in some cases may indicate where eventual new CO_2 pipelines could be located.

5.5.6 CO_2 infrastructure

Planned CO_2 infrastructure is also addressed in the PCI Transparency Platform. The CO2LOS tool can be used to supplement the information related to ships and barges, including in-land waterways.

Planned infrastructure according to the PCI Transparency Platform is shown in Figure 5.7. All the planned infrastructure is ship-based, and at least partly identical to proposals by Northern Lights. CO_2 to be supplied to Northern Lights must comply with the quality specifications given in Figure 5.1.

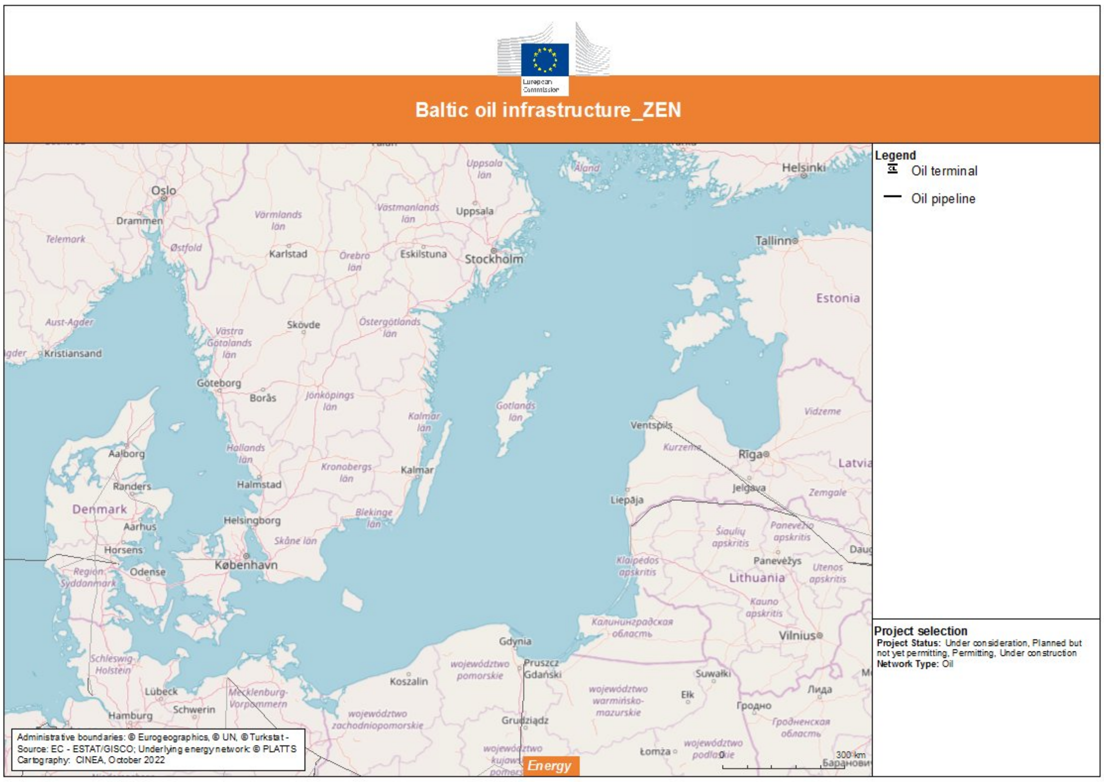


Figure 5.5 Baltic Sea region: Oil pipeline infrastructure (PCI Transparency Platform)

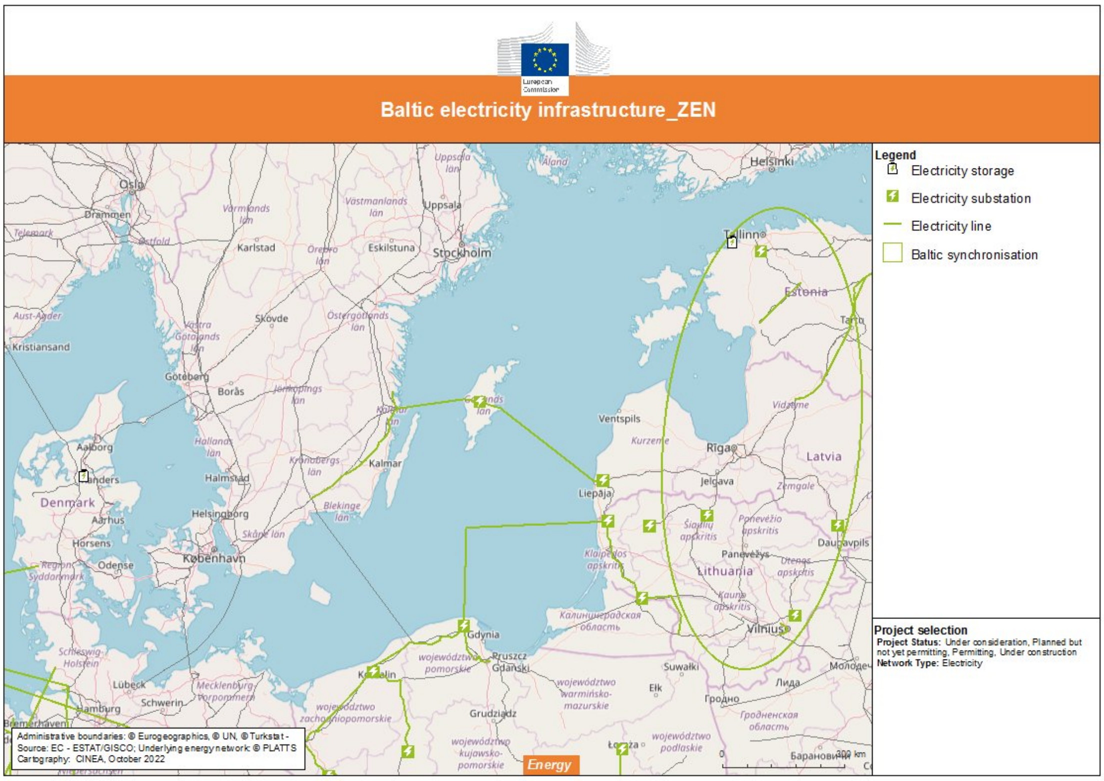


Figure 5.6 Baltic Sea region: Existing main routes for electricity transmission (black) and new and ongoing projects according to the PCI Transparency Platform (green).

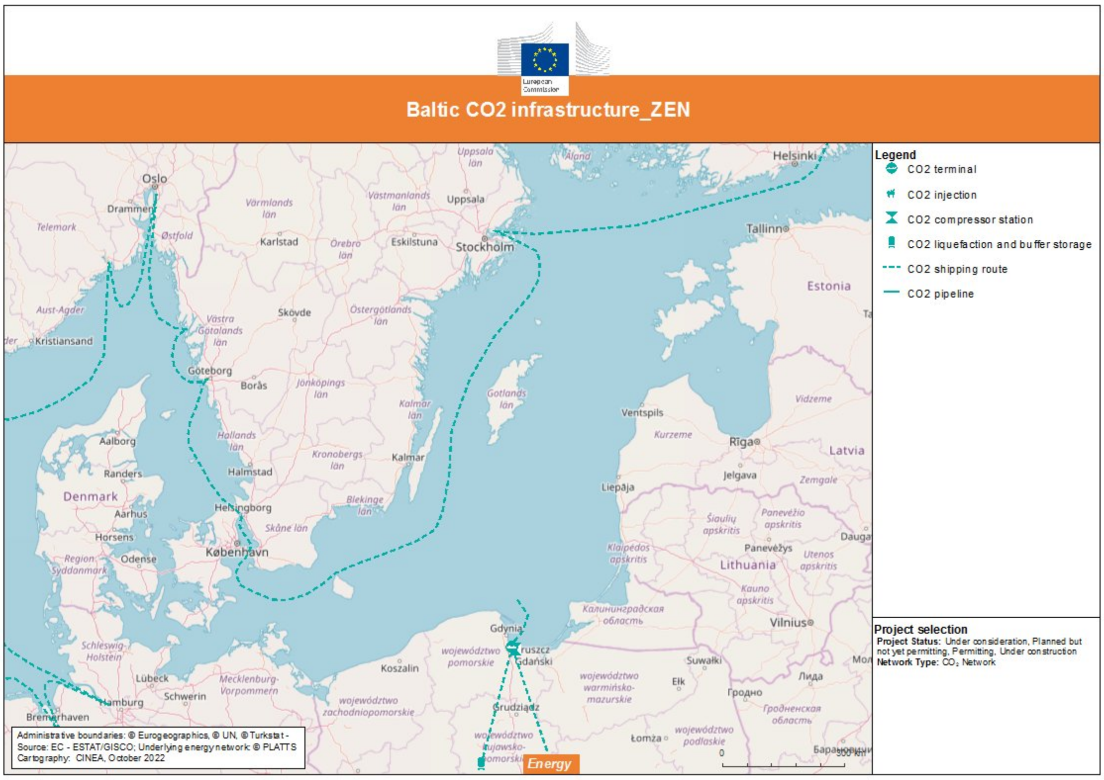


Figure 5.7 Baltic Sea region: Planned infrastructure for CO_2 transport according to the PCI Transparency platform.

5.5.7 Summary of existing and planned infrastructure in the Baltic Sea region

When looking at a map showing the combined existing and planned relevant infrastructure (natural gas, oil, main electricity transmission routes and CO_2), it seems possible to construct or convert a suitable infrastructure for CO_2 transport. Apart from the planned ship-based infrastructure however, none of the other infrastructure is constructed with transport of CO_2 in mind. This picture must therefore be combined with knowledge of where to find sources of CO_2 (CO_2-emitters/CO_2-clusters) and information on possibilities for CO_2 storage sites relevant for these sources. Figure 5.8 shows the total picture.

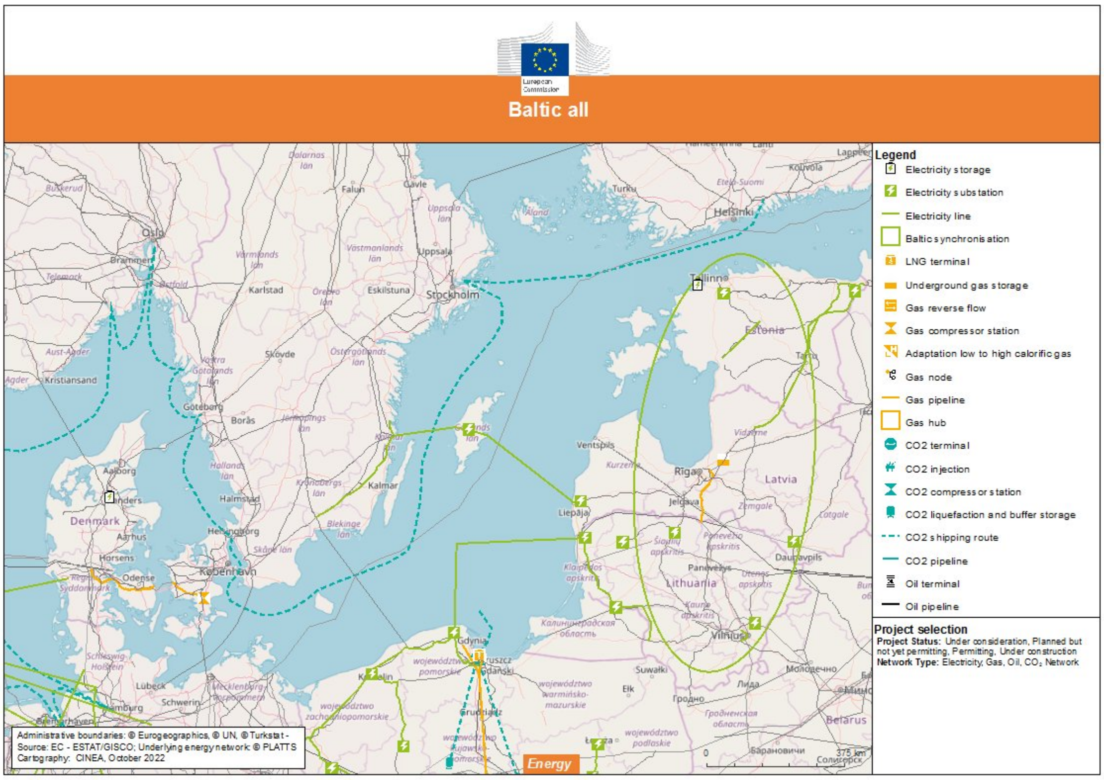


Figure 5.8 Baltic Sea region: Existing and planned infrastructure possibly relevant for CO_2 transport.

5.6 High-level mapping in the Mediterranean Sea region

In this chapter we provide an overview of existing pipelines and ongoing projects (PCI) for natural gas and oil as well as main features of the electricity grid and planned CO_2 infrastructure in the Mediterranean Sea region. The PCI Transparency Platform is the main source of information.

5.6.1 Natural gas infrastructure

As for the Baltic Sea region, available infrastructure for transport of natural gas is assumed to be the most likely candidate for future transport of CO_2, provided such conversion is feasible. As can be seen from Figure 5.9 the natural gas infrastructure is well developed in the region, particularly onshore. New projects are also under way.

There is an extensive natural gas pipeline network in Türkiye. A more detail description of the natural gas pipelines in Türkiye can be seen in Section 13.2 (Appendix D).

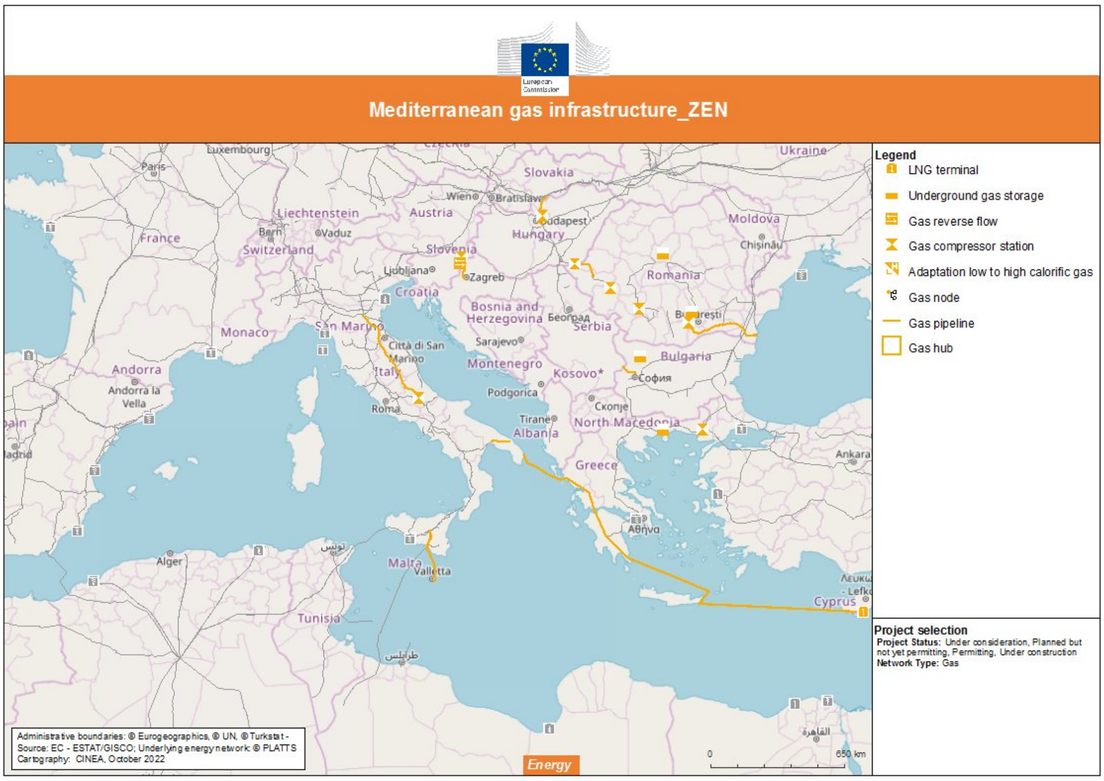


Figure 5.9 Mediterranean Sea region: Existing natural gas infrastructure is shown in black. New projects according to the PCI Transparency Platform are shown in yellow.

5.6.2 Oil infrastructure

In Figure 5.10, existing oil pipelines in the Mediterranean Sea region except Türkiye are shown. Most infrastructure is onshore, and as for the Baltic Sea region, no new oil infrastructure projects are under development according to the PCI transparency platform.

A more detail description of some of the pipelines that are connecting Türkiye to Iraq and Azerbaijan can be found in Section 13.2 (Appendix D).

5.6.3 Electricity infrastructure

Figure 5.11 shows the main routes for transmission of electricity in the area. As for the Baltic Sea region, the relevance for transport of CO_2 is that electricity routes in some cases may indicate where eventual new CO_2 pipelines could be located.

Figure 5.12 shows the electricity infrastructure in Türkiye, operated by the Turkish Electricity Transmission Corporation (TEIAŞ). The transmission network is mainly composed of 380kV and 154kV voltage levels. The 380 kV network is the backbone of the transmission grid, while the 154 kV network is the sub-transmission system.

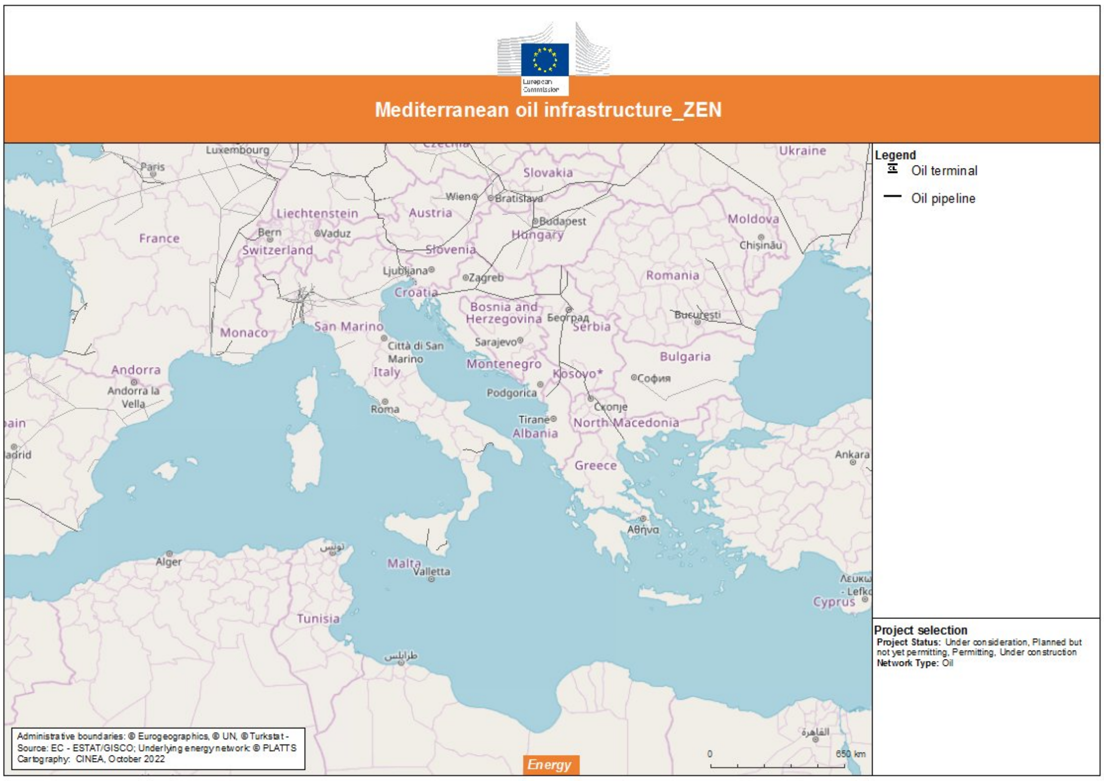


Figure 5.10 Mediterranean Sea region except Türkiye: Existing pipelines for transport of oil.

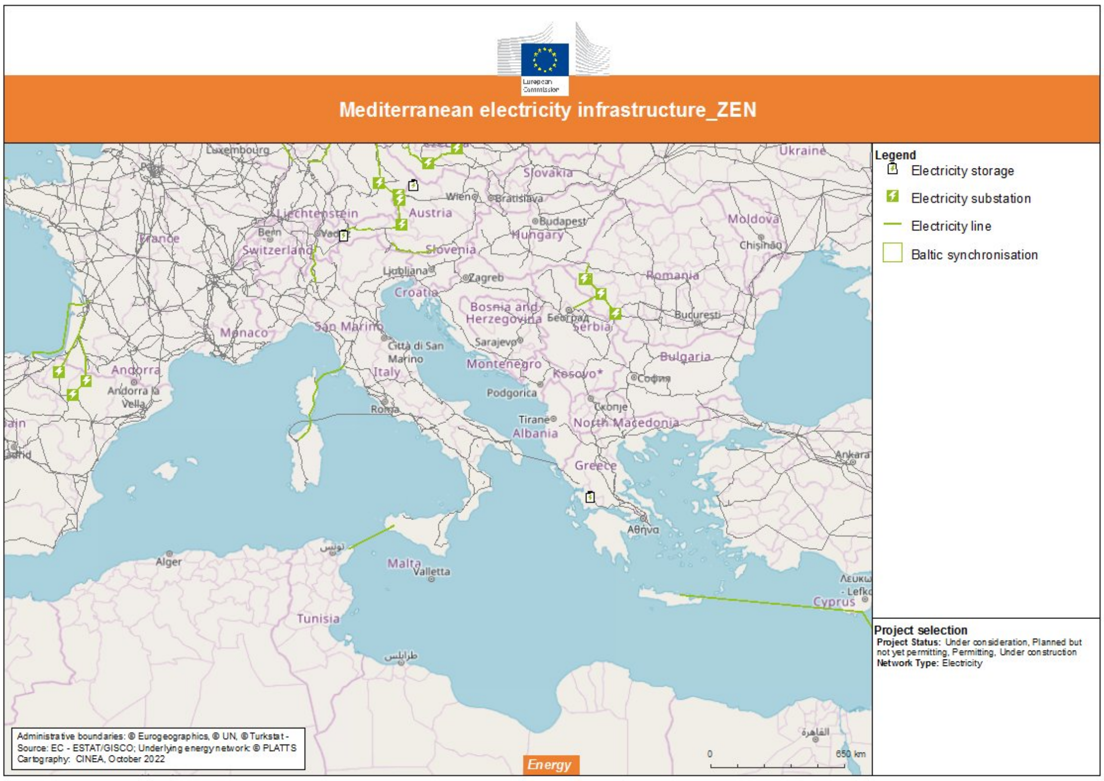


Figure 5.11 Infrastructure for electricity in the Mediterranean Sea region except Türkiye: Existing major transmission line routes are shown in black, while new projects according to the PCI Transparency Platform are shown in green.

Figure 5.12 Türkiye: 380 kV transmission lines (EU-IPA12/CS02 Final report, 2017)

5.6.4 Summary of existing and planned infrastructure

The map in Figure 5.13 shows all existing and planned CO_2-relevant infrastructure in the region. The main part of the infrastructure is onshore, only a few existing or planned natural gas pipelines are available offshore. Also, there are a few existing or planned offshore electricity cables connecting countries in the region. These could possibly indicate where future CO_2 pipelines may be placed.

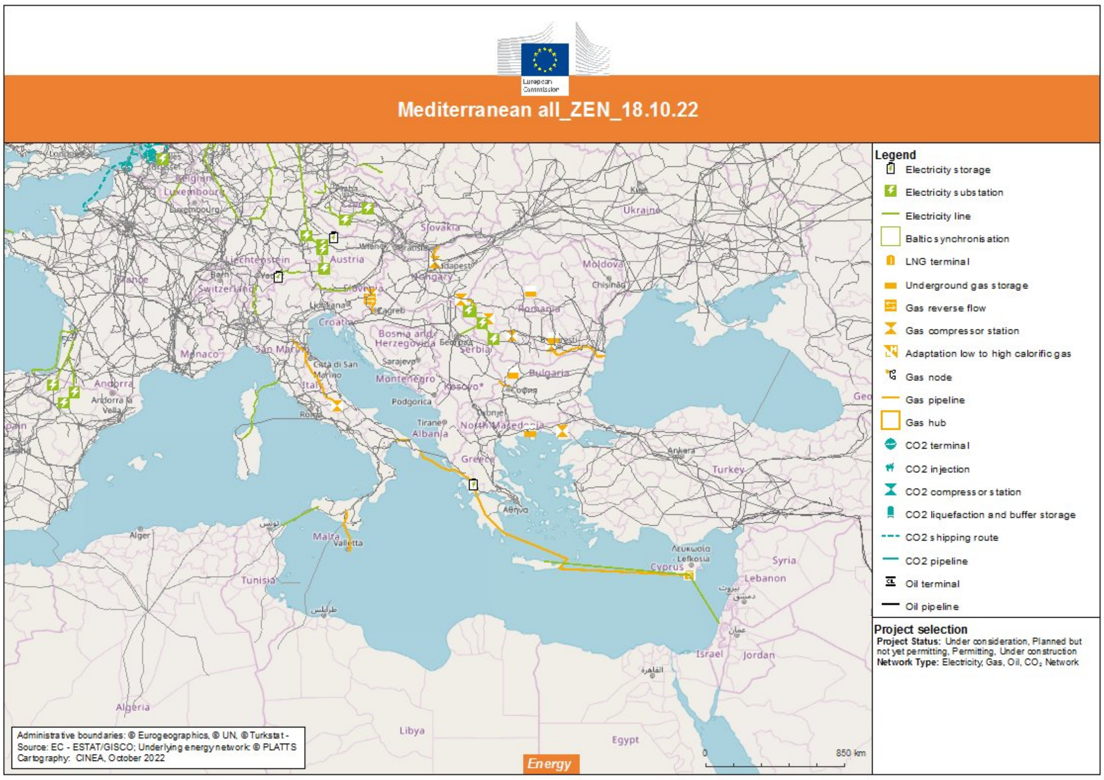


Figure 5.13 Mediterranean Sea region: Existing and planned infrastructure possibly relevant for CO_2 transport.

One main difference between the Baltic and the Mediterranean Sea areas is that no CO_2-infrastructure seems to be planned for the Mediterranean region. As is the case also in the Baltic, the figure above must be combined with information on where to find sources of CO_2 (CO_2-emitters/CO_2-clusters) as well as possibilities for CO_2 storage sites relevant for these sources.

6 CO_2 utilisation

6.1 CO_2 utilisation options

Carbon is essential to life and our society. We are carbon-based lifeforms, and all the products we consume daily are either made from carbon or with carbon. We cannot live nor maintain or improve our standard of living without using carbon. The issue is the source of that carbon.

Fundamentally, global warming can only be solved by the cessation in the use of fossil fuels (Matthews, 2022). About 80% of fossil fuel consumption is directly related to energy production, while the remainder is used as a carbon feedstock for chemicals and materials. While renewable energy sources such as wind and solar energy can displace the use of fossil fuels along the energy vector (commonly referred to as decarbonization), alternative sources of carbon are required for the displacement of fossil fuels to produce chemicals and materials (hence the term defossilization, indicating the use of fossil carbon as feedstock, rather than decarbonization). Defossilization of chemicals and materials can only be achieved using renewable carbon sources, specifically CO_2, biomass and recycled carbon materials, such as plastics (Renewable carbon initiative). The use of renewable carbon sources will lead to the creation of a circular carbon economy.

Carbon Capture and Utilisation (CCU) is therefore a necessary part of the solution to global warming since it leads to decreased use of fossil carbon. The contribution of CCU to climate change mitigation will depend on the CCU pathway (spanning from emission reduction to emission avoidance and to carbon removals in some case). Many products made from CO_2 are not storage solutions, as they have relatively short lifetimes, resulting in the emission of CO_2 to the atmosphere upon end-of-life. However, the fabrication of such products from captured carbon replaces fossil carbon use and thereby prevents the release of new fossil carbon CO_2 at the end-of-life for these products. As well, production methods using captured carbon can often have reduced energy requirements (e.g., mineralisation), which adds extra benefits as a global warming solution since the CO_2 footprint from energy consumption for conventional production is smaller.

Since CO_2 lies in a thermodynamic well, energy is required for its conversion to chemicals and materials. As a simple example, production of fuels from CO_2 requires at least as much energy as that derived from the combustion of fuels. Therefore, the first requirement for CCU as a global warming solution is that CCU technologies must use renewable energy. Use of fossil energy for CCU leads to greater emissions of CO_2 than is used in the production process. The second requirement is that a cradle-to-gate life cycle assessment (LCA) shows that the CO_2-based processes contribute to reducing CO_2 emissions.

CCU represents therefore an array of technologies that capture carbon from industrial emissions or directly from the air and transform it into marketable products like fuels, chemicals and materials. Direct uses of CO_2 are also possible, for instance in greenhouses. A summary of potential use is given in Figure 6.1.

Among the multitude of technologies that CCU encompasses (thermochemical, electrochemical, photocatalytic conversion, mineralisation, etc.) some are at higher Technology Readiness Level (TRL) and close to wide commercialisation while others more at R&D level. Further details and description of CCU technologies are available in various sources like IEA (2019), Chavez (2020), NASEM (2019).

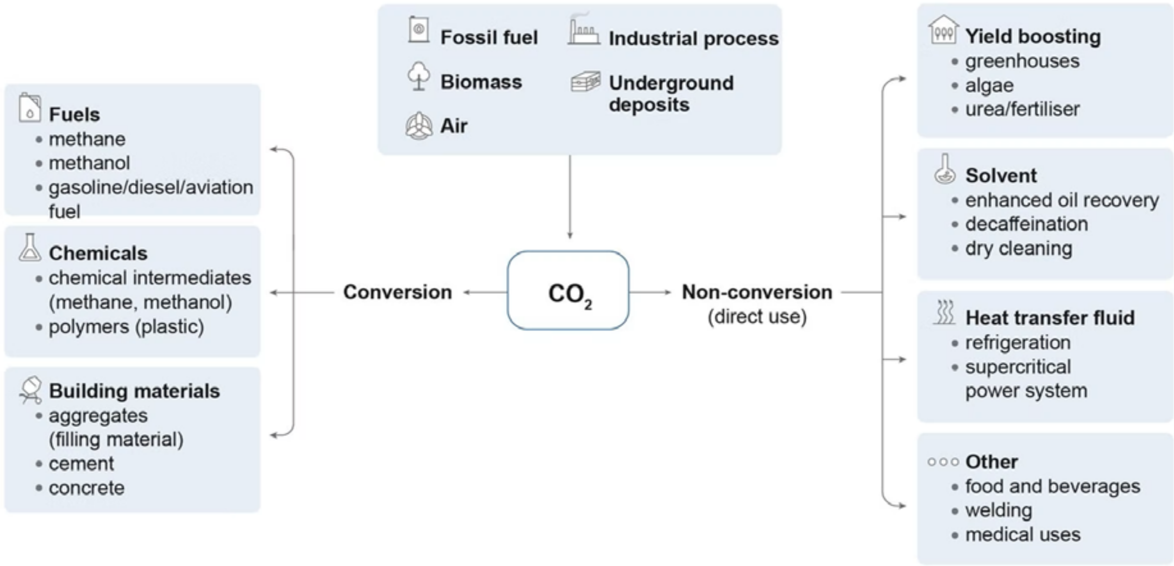


Figure 6.1 Overview of CCU [from IEA, 2019) Putting CO_2 to use: Creating Value from emissions

Accordingly, the climate mitigation impact of CCU technologies can span from contributing to net emission reductions, emission neutral production systems or even carbon removals. This depends on a variety of factors like the origin of CO_2, the type of energy used for the conversion, the type of product and the storage duration, the product replaced, etc. In any case, this impact should be assessed by rigorous life cycle assessments. Table 6.1 below provides an estimation of the utilisation potential for some CCU products.

Table 6.1 Estimates of the future potential for CO2 utilisation (Hepburn et al., 2019)

Pathway	Utilisation potential 2050 (Mt CO_2 per year)
Chemicals	300 - 600
Fuels	1 000 – 4 200
Microalgae	200 – 900
Concrete building materials	1 – 1 400

6.2 Ongoing and upcoming CCU projects

To determine the contribution of CCU in the value chains proposed by CCUS ZEN, the principal information source will be CO_2 Value Europe's database on CCU (Figure 6.2). This database has been developed thanks to previous EU Projects (SCOT, IMPACTS9) and contains approximately 150 on-going or upcoming CCU projects (and more completed) at EU scale and at different TRL levels. It can serve as a mapping tool to be overlaid with the rest of the mapping tools used from CCUS ZEN (CO_2 sources, infrastructure networks, storage sites, etc) and provides important information on the utilisation opportunities in the regions of interest.

All projects are listed in a table below the map and the most important information can be directly visible to the visitor (Figure 6.3).

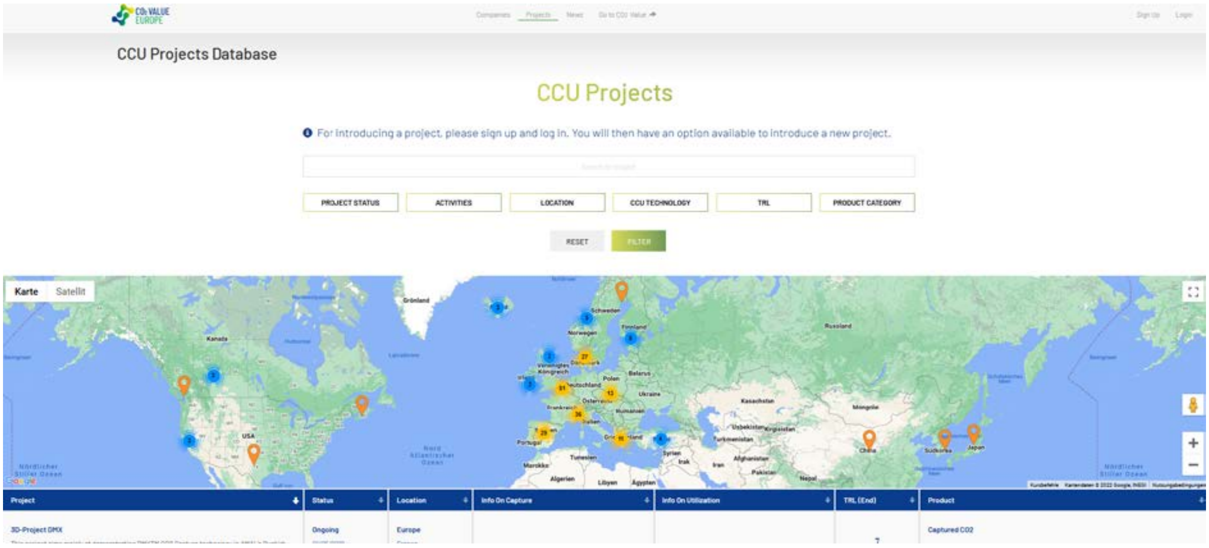


Figure 6.2 CO_2 Value Europe's database on CCU projects: Homepage CO_2 Value Europe's database on CCU

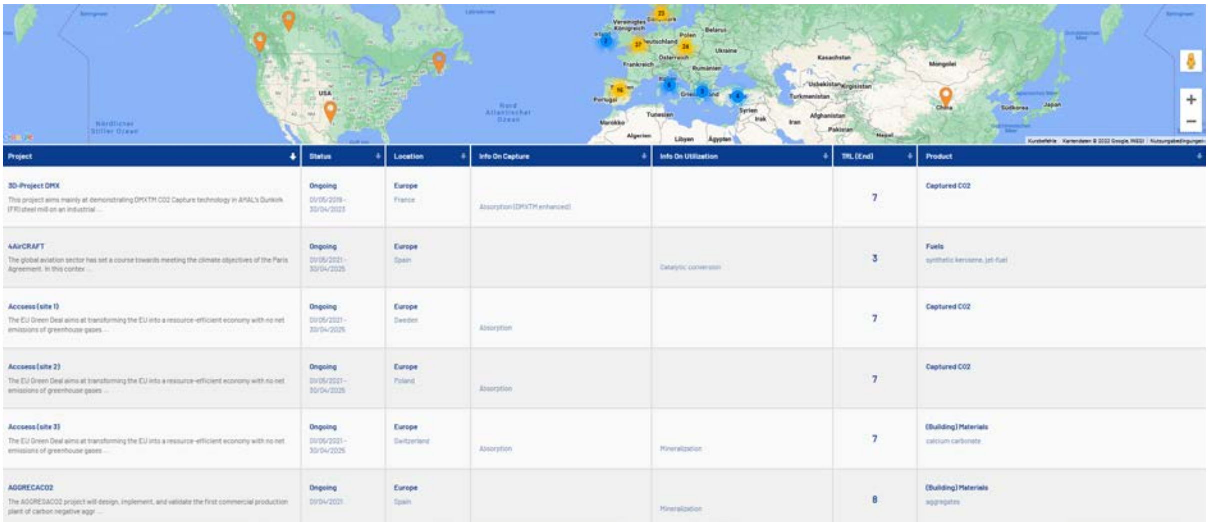


Figure 6.3 CO_2 Value Europe's database on CCU projects: Table view

By clicking on a project of interest, further details (when available) on the specific project are provided (see Figure 6.4):

- A brief description
- The project timeline and status
- The project budget and funding source
- Geographical information
- Technical information
- Partners
- Website

Technical information includes (whenever available) the type of activity, CO_2 source, TRL, plant stage, specific capture and utilisation technology, rates of CO_2 capture/utilisation, product volumes and specific product.

A variety of technologies have been listed when completing information about a project. Capture includes technologies from point sources or directly from the air such as solvent-based absorption, calcium looping, ionic liquid absorption, metalo-organic framework adsorption, SEWGS, membrane separation, oxy-fuel combustion, cryogenic technology, etc.

Utilisation includes biological conversion, thermochemical conversion, electrochemical conversion, photocatalytic conversion, mineralisation, Fischer-Tropsch synthesis, reverse water gas shift, etc.

The database gives the opportunity to filter information based on free keywords or fixed filters like Project status, Activities, Location, CCU technology, TRL and Product category.

Importantly the information on the database is publicly accessible and everyone can introduce a new project, which, after proofing and validation, can appear in the database. Throughout CCUS ZEN, the database will be further updated, corrected and improved.

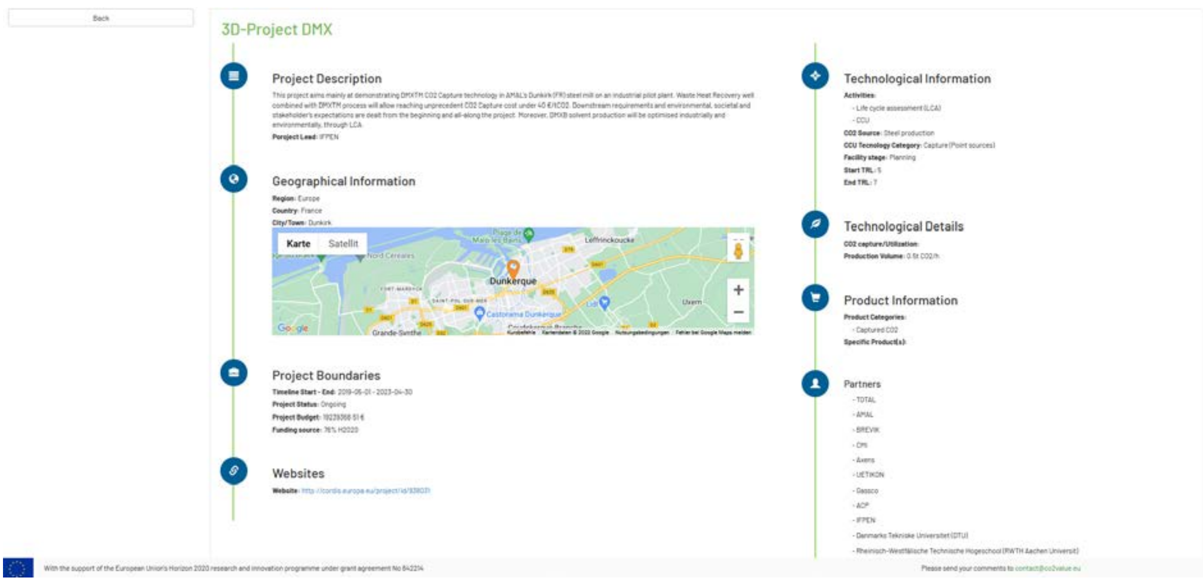


Figure 6.4 CO_2 Value Europe's database on CCU: Project detail

Figure 6.5 provides a snapshot of on-going and upcoming projects in the Baltic Sea region and Table 6.2 some indicative examples of the type and size of those projects. Most of the projects listed are expected to become operational within the next 4-5 years.

In analogy to the Baltic Sea region, Figure 6.6 and Table 6.3 provides a snapshot of on-going and upcoming projects in the Mediterranean Sea region and some details of their type and size, respectively.

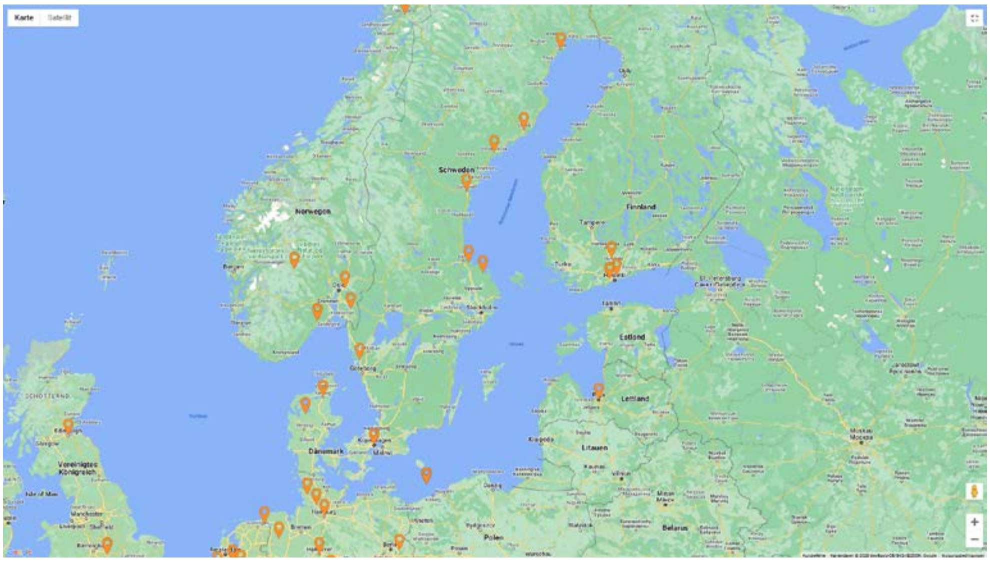


Figure 6.5 CO_2 Value Europe's database on CCU: Snapshot of the Baltic Sea region

Table 6.2 Brief description of on-going or upcoming CCU projects in the Baltic Sea region.

Project	Location	Brief description
INITIATE	Lulea, Sweden	Valorization of steelmaking off-gases for the production of urea. Separation of CO_2 with sorption enhanced water gas shift reaction. Demonstration at TRL 7
Carbon2x	Riimäki, Finland	Pilot demonstrations of the valorization of emissions from waste incineration for methane and specialty chemicals production
Forest CUMP	Espoo, Finland	Valorization of forestry and waste incineration emissions to produce polyolefins through Fischer-Tropsch synthesis.
ACCSESS	Skutskär, Sweden	Demonstration at TRL 7 of a solvent based, enzymatically enhanced capture process for paper mill emissions.
CO2Carbon	Riga, Latvia	Pilot demonstration of CO_2 conversion to carbon nanomaterials and graphite (approx. 2.7 t/a product capacity)
WestKüste100, Carbon2Business	Lägerdorf / Heide, Germany	Linked projects demonstrating at TRL 8 the chain of oxy-fuel combustion in cement production combined with methanol production to final kerosene for the Hamburg airport
Green fuels for Denmark	Copenhagen, Denmark	Large scale demonstration of biogenic CO_2 conversion into green fuels like methanol and kerosene (approximately 100 MW electrolysis and 50 kt/a fuel capacity by 2025)
HySkies	Forsmark, Sweden	Large scale demonstration of the valorization of biogenic emissions from waste incineration to ethanol and subsequently jet fuel (approx. 200 MW electrolysis and 82 kt/a fuel capacity)
CONSENCUS	Aalborg, Denmark	Validation at TRL 7 of the capture and conversion of cement emissions to formic acid (approx. 100 kg/h capture capacity)
FlagshipONE	Örnsköldsvik, Sweden	Large scale demonstration of methanol production from biogenic emissions of a WtE plant (approx. 45 kt/a methanol capacity by 2024)
MariSynFuel	Bremerhaven, Germany	Demonstration of methanol production for direct use as marine fuel in a retrofitted ship vessel (approx.. 0.5t/d fuel capacity
Project AIR	Stenungsund, Sweden	Large scale demonstration of the production of methanol from chemical refinery emissions (approx. 200 kt/a methanol at full capacity by 2027)

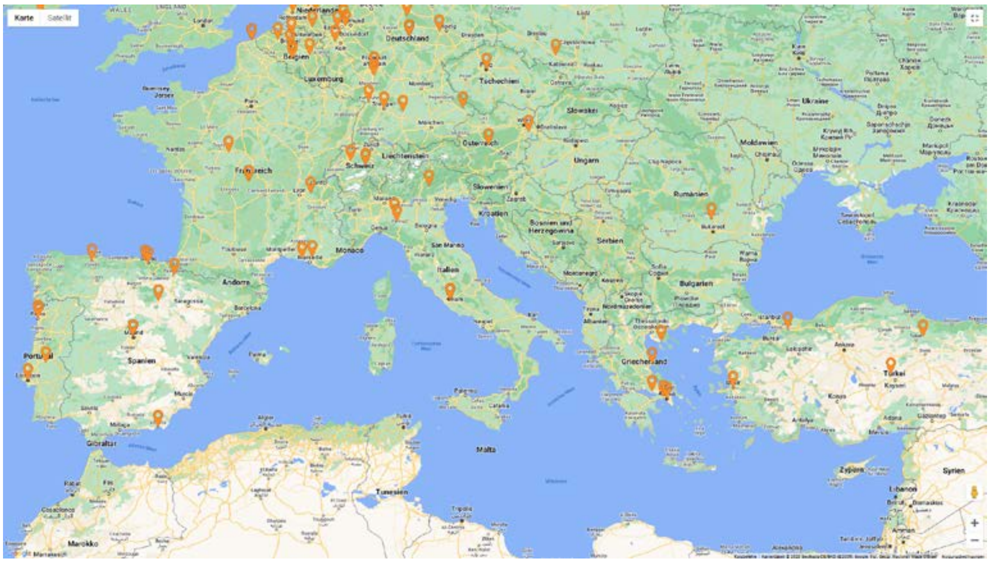


Figure 6.6 CO_2 Value Europe's database on CCU: Snapshot of the Mediterranean Sea region

Table 6.3 Brief description of on-going or upcoming CCU projects in the Mediterranean Sea region.

Project	Location	Brief description
ECCO2	Almeria, Spain	Demonstration of solvent-based capture of emissions from cement production (approximately 10% of emissions by 2024)
SolDac	Barcelona, Spain	Demonstration at TRL4 of an integrated system for DAC and photo-electrochemical conversion to ethylene
Jupiter1000	Marseille, France	Demonstration at TRL 7 of synthetic methane production (approx. 25 m^3/h capacity)
Hynovera	Meyreuil, France	Demonstration at TRL 8 of synthetic fuel production from biogenic emissions (approx. 100 MW electrolytic capacity and 200 t/d fuel capacity by 2027)
Herccules	Vernasca, Italy Elefsina, Greece	Demonstration at TRL7 of CO_2 capture and mineralisation process to produce cementitious material (approx. 1000h testing)
CONSENCUS	Yerakini, Greece	Validation at TRL 7 of the capture and conversion of cement emissions to formic acid (approx. 100 kg/h capture capacity)
HiRECORD	Thisvi & Volos, Greece	Demonstration at TRL 7 of a solvent-based capture technology for the quicklime and power production industry (approx. 10 t/d capture capacity)
COZMOS	Kocaeli, Türkiye	Demonstration at TRL 5 of catalytic conversion of industrial emissions to methanol and C3 products
CO2Fokus	Izmir, Türkiye	Demonstration at TRL 6 of catalytic conversion of industrial emissions to DME
Repsol e-fuel	Bilbao, Spain	Demonstration at TRL 7 of catalytic conversion of CO_2 for synthetic fuel production (approx. 2100 t/y fuel capacity)

Apart from mapping CCU projects, a further element to determine the role of CCU in the selected CCUS value chain within CCUS ZEN is the number of active CCU stakeholders, for example providers of capture and conversion technology. Although CCU technology providers can provide their technology at different locations, it is still useful to see the spread and the existence of local actors in the areas of interest, as this might be a factor to decide over the one or the other technology to implement. This element is covered by an extension of the CO_2 Value Europe database to include technology providers alongside the existing section with projects. This part of the database is under construction with a beta version being ready (see Figures 6.7 and 6.8) but not yet public.

In analogy to the projects section, the companies section contains a map with a tabled view of the most important characteristics of the technology provider, i.e. name, type, location, info on capture, info on utilisation, product category and specific product.

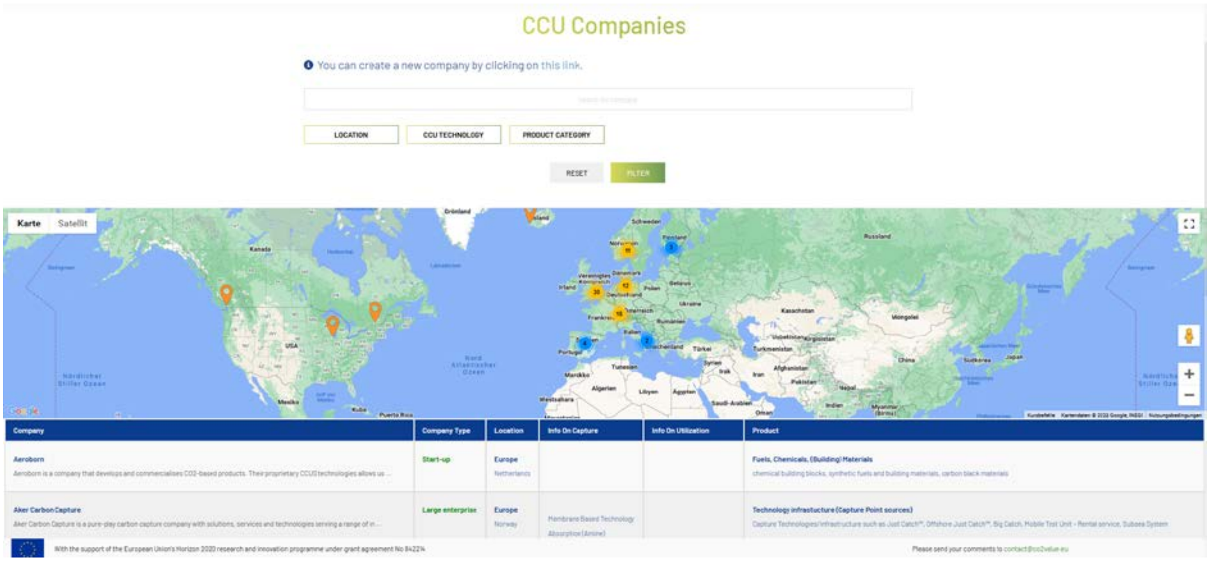


Figure 6.7 CO_2 Value Europe's database on CCU companies

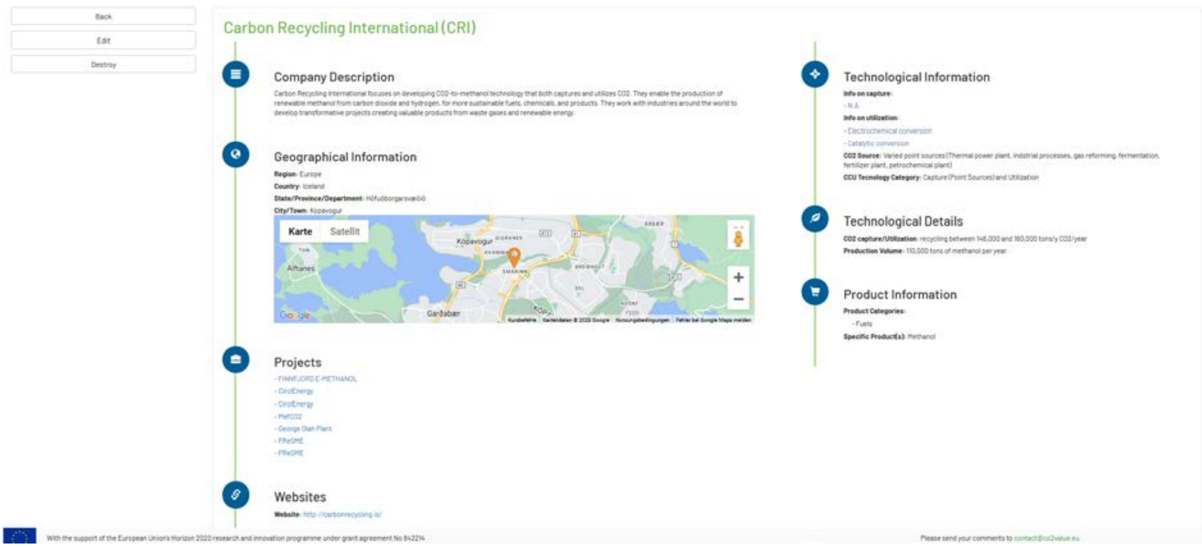


Figure 6.8 CO_2 Value Europe's database on CCU companies: company detail

By clicking on a given company, the visitor is able to see further details about the company, similar to the projects section, i.e. technological details, product information, website, projects (with link to the projects listed in the project section). Also here, the visitor can introduce a new company that will, after validation, appear in the database.

Table 6.4 provides an indicative overview of CCU technology providers with headquarters within the regions of interest.

Many CCU applications require renewable energy. It is therefore interesting to correspond the high-level mapping of CCU projects in the regions of interest to existing mapping instruments for renewable energy generation. For instance the Energy and Industry Geography Lab (EIGL) is mapping, among other information, renewable energy potential (biomass, solar, wind) but also future clean energy projects (including hydrogen backbone, new transmission infrastructure, sectoral projects, etc.). Figures 6.9 to 6.12 provide images of the renewable energy potential and the future hydrogen backbone elements in the Baltic and Mediterranean regions, respectively.

We can deduce that both the hydrogen backbone and the renewable energy potential in the regions is favourable enough to support the development of CCU value chains in the regions of interest. It is furthermore expected that the hydrogen value chain will be considerably expanded in the short term as a result of 76 projects of transnational character that have been accepted by the IPCEI scheme and which include also companies from the Mediterranean and Baltic regions.

Table 6.4 CCU technology providers in the Baltic and Mediterranean Sea regions.

Company	Country	Description
DACMa GmBH	Germany	DAC development
REintegrate	Denmark	E-fuel producer
Arcadia efuel	Denmark	E-fuel project developer
Topsoe	Denmark	E-fuel producer
Soletair Power	Finland	DAC development
P2X Solutions	Finland	Hydrogen and e-methane producer
Hydrocell Oy	Finland	DAC development
UP Catalyst	Estonia	Carbon nanomaterials producer
Liquid Wind	Sweden	E-Methanol project developer
IC2R	Italy	Catalytic conversion to chemicals
Hysytech	Italy	Engineering for H_2 and CCU
Revcoo	France	Capture development
Axens	France	Capture and conversion developer
Polymem	France	Membrane development
Dioxycle	France	Catalytic conversion to chemicals
Monolithos	Greece	Catalyst development

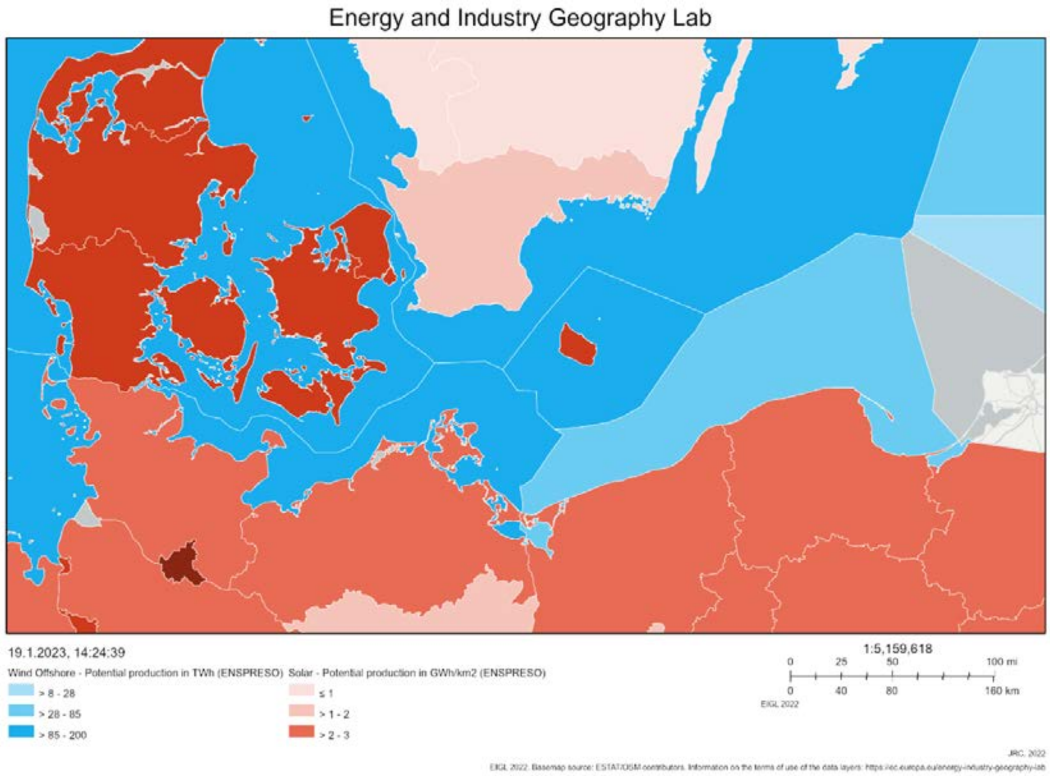


Figure 6.9 Baltic Sea region: Excerpt of wind and solar energy potential (EIGL)

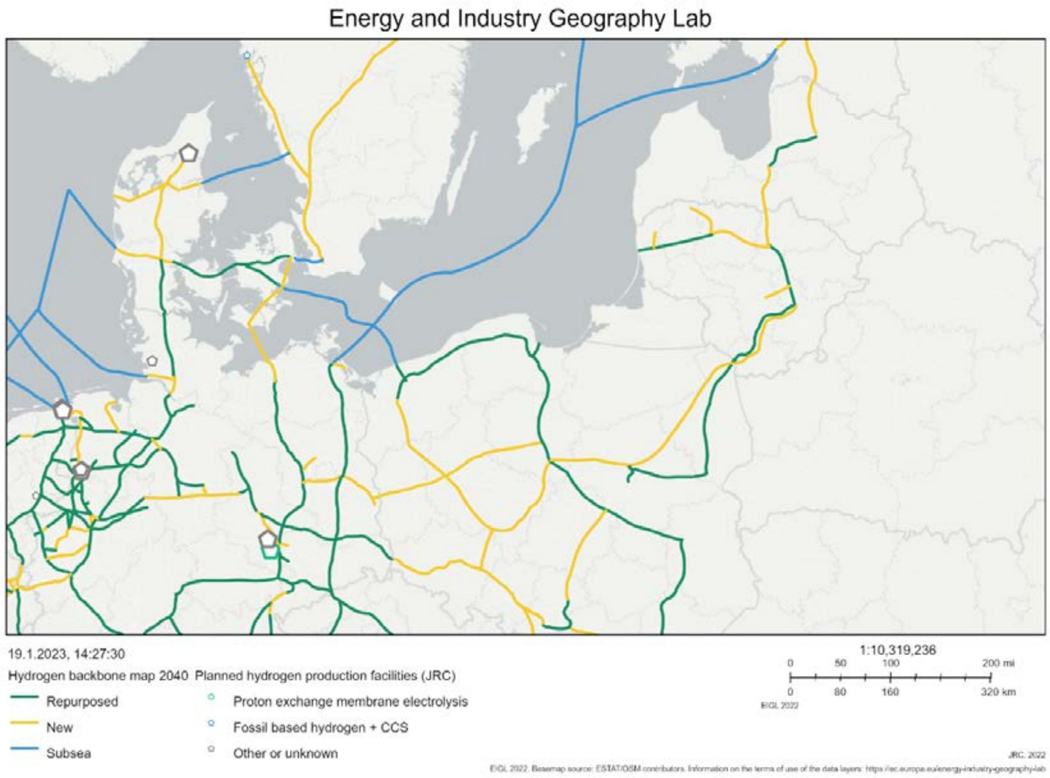


Figure 6.10 Baltic Sea region: Excerpt of hydrogen backbone plans (EIGL)

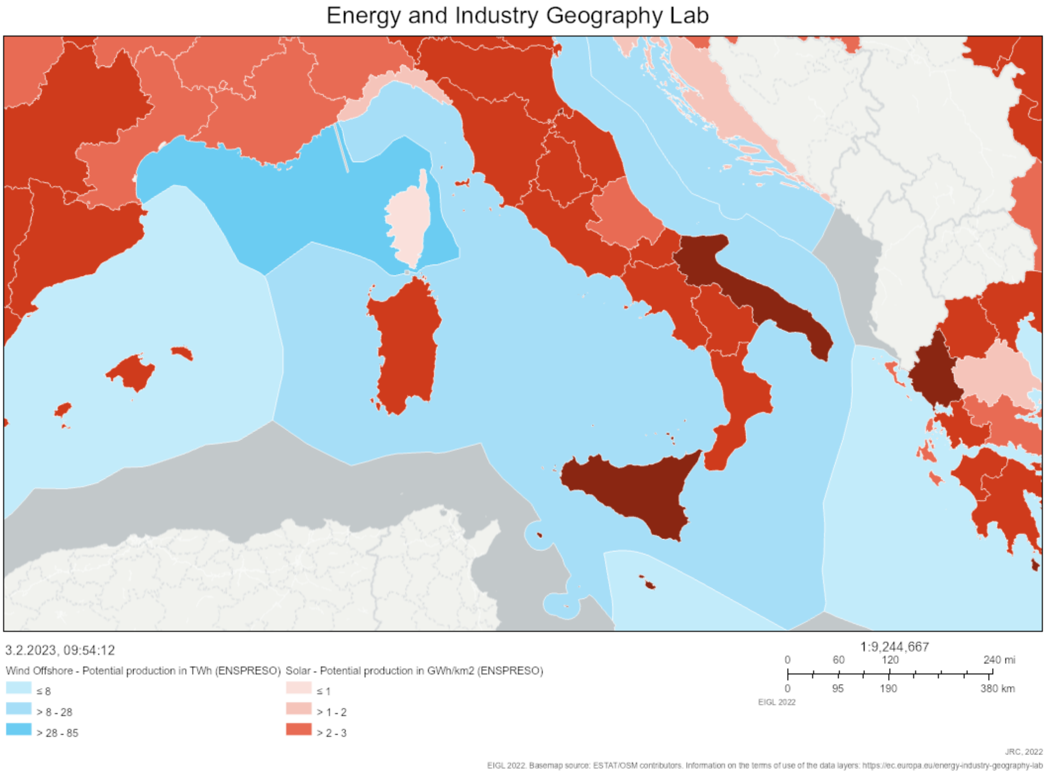


Figure 6.11 Mediterranean Sea region: Excerpt of wind and solar energy potential (EIGL)

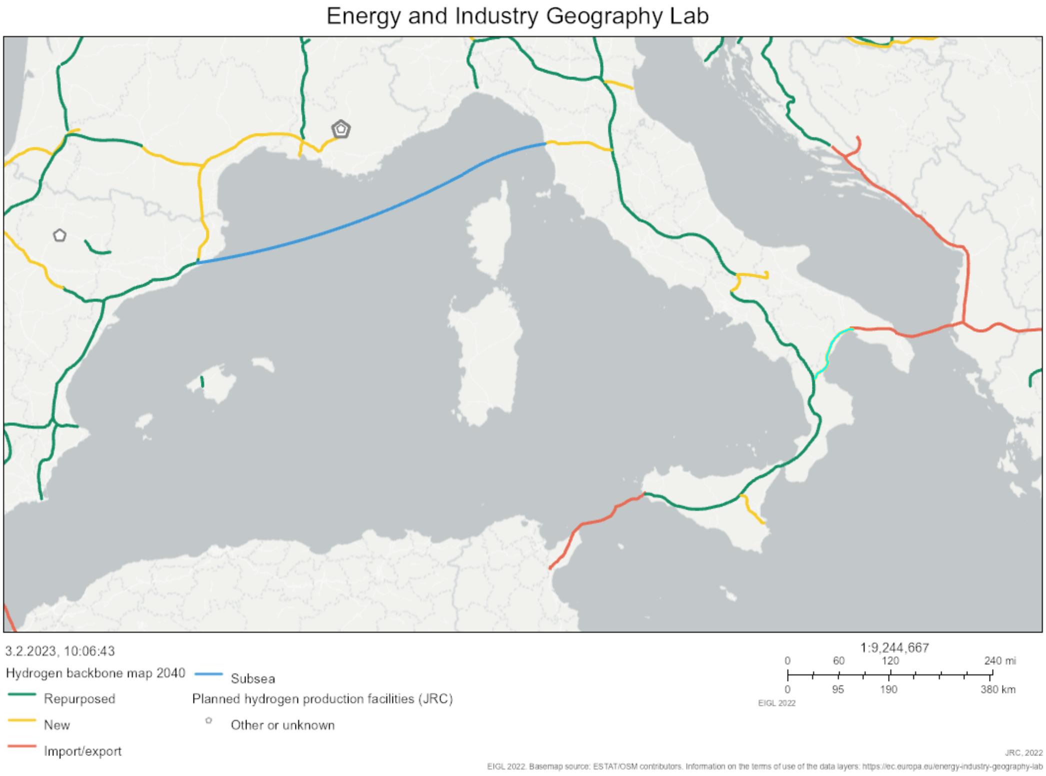


Figure 6.12 Mediterranean Sea region: Excerpt of hydrogen backbone plans (EIGL)

7 Conclusion

High-level mapping of CO_2 emission sources and potential CO_2 storage sites has been performed for the Baltic Sea and Mediterranean Sea regions defined by CCUS ZEN. Excel-templates with attributes characterising the emission sources and storage sites were made and populated for all countries covered by the CCUS ZEN regions and imported into QGIS for visualisation. Regional results are shown in Figure 7.1 and Figure 7.2 for the Baltic Sea and the Mediterranean Sea, respectively.

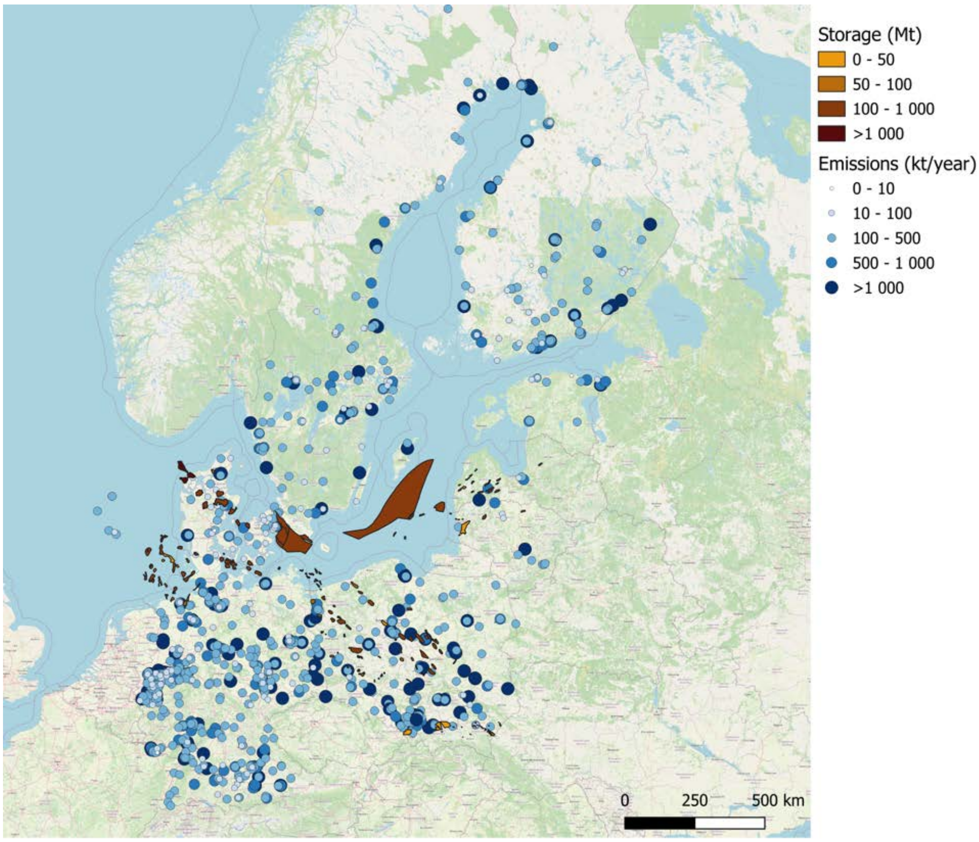


Figure 7.1 Baltic Sea region: CO_2 emission sources and potential CO_2 storage sites.

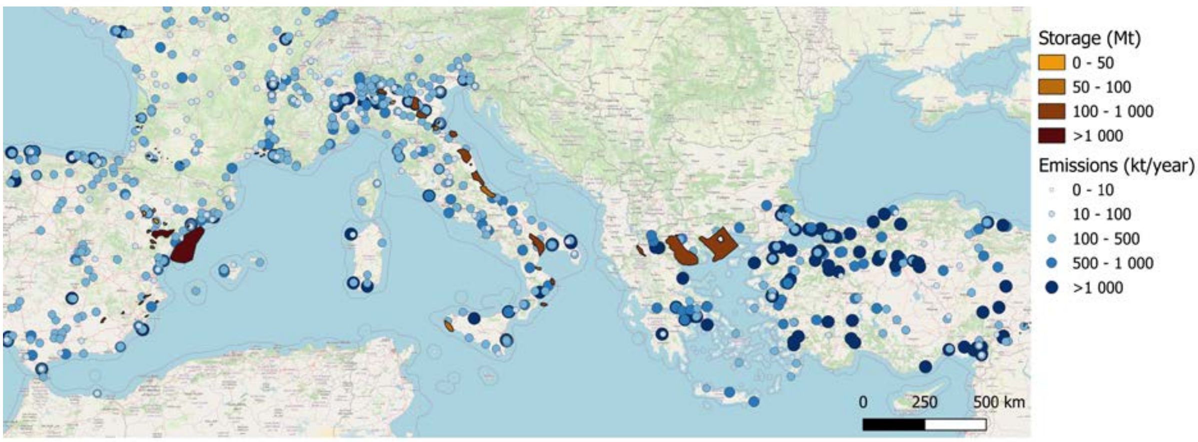


Figure 7.2 Mediterranean Sea region: CO_2 emission sources and potential CO_2 storage sites.

In addition, a high-level mapping of possible CO_2 transport options and intermediate storage solutions in the two CCUS ZEN regions has been performed. This includes existing oil and gas pipelines, ship transport, railways and roads, and corridors with high voltage lines.

Finally, CO_2 utilisation options and the CCU database developed by CO_2 Value Europe were described.

Based on the high-level mapping of CO_2 emission sources, possible transport options and potential storage sites, the four most promising CCS value chains in each of the two CCUS ZEN regions will be identified for further analyses in the project. In these analyses, based on the CO_2 utilisation database, existing and future industry using CO_2 as feedstock will be added.

8 Acknowledgement

CCUS ZEN is grateful for the contribution given by the networking partners BGR (Federal Institute of Geosciences and Natural Resources, Germany), SGU (Geological Survey of Sweden) and IGME (Geological and Mining Institute of Spain, Spanish National Research Council) to the mapping of potential storage sites in their respective countries. We are also grateful to CERTH (Centre for research and technology Hellas) for their contribution to the capacity estimates for storage sites in Greece.

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10 Appendix A: CCUS ZEN CO_2 emission template

CCUS ZEN has defined a CO_2 emission template with the attributes listed in Table 10.1 below. The template is an Excel-file and a file for each country in the project has been created. The Excel-files have further been imported into QGIS for visualisation.

Table 10.1 CCUS ZEN CO_2 emission source template: List and description of attributes. The grey line is automatically filled.

Attribute	Unit	Description
EMITTER_ID		Unique CCUS ZEN identifier for the emitting facility
FACILITY_NAME		Name of facility, which is used to distinguish different facilities from the same company
FACILITY_ID		The facility identifier assigned by ENDRAVA
COMPANY_NAME		Name of company that is responsible for emission
REGION		Name of the region: Baltic Sea or Mediterranean Sea
COUNTRY		Name of country where the facility is located
COUNTRY_CODE		ISO country code
LATITUDE		Latitude geographic coordinates (WGS84)
LONGITUDE		Longitude geographic coordinates (WGS84)
STATE		Name of state where the facility is located
INDUSTRY_SECTOR		Adapt from second level of NACE hierarchy
TOTAL_CO_2_EMISSIONS	ton/year	Total CO_2 emissions, including both fossil and biogenic
FOSSIL_CO_2_EMISSIONS	ton/year	Fossil CO_2 emissions
BIOGENIC_CO_2_EMISSIONS	ton/year	Biogenic CO_2 emissions
YEAR_EMISSIONS		Year to which the CO_2 emissions relate
SHUT_YEAR		The year the emission source closed or is projected to close
EMISSION TREND		Trend in emission the last five years
INFORMATION_SOURCE		Primary source(s) of information
REMARKS		Any other relevant information

STATE

State, county, municipality or region of where the facility is located. To illustrate, the state where the facility "ESP_7427" is located is provided as "Las Palmas".

INDUSTRY_SECTOR

The attribute refers to the industries or sectors that the emitting facilities belong to. A classification with nineteen categories of industries was used in CCUS_ZEN template, see Table 10.2. The "Other" category represents the industry or sectors which do not fall into the rest of eighteen categories implemented in CCUS_ZEN template. To illustrate, the sectors "manufacturing, vehicles and machinery", "manufacturing, metal products", "non-metallic minerals, lime and plaster" or "non-metallic minerals, ceramics" that are provided by ENDRAVA are classified as "Other" in the CCUS_ZEN template. The corresponding clarifications have been made under the "REMARKS" attribute in template.

Table 10.2 Industry categories used by CCUS ZEN

Power	Chemicals (other)	Fermentation
Ammonia	Refineries	Energy from waste
Cement	Oil & gas Processing	Anaerobic digestion
Ethylene	Paper and pulp	Water/sewage treatment
Ethylene Oxide	Non-iron metals	Other
Hydrogen	Glass	
Iron & Steel	Food & drink	

TOTAL_CO2_EMISSIONS

FOSSIL_CO2_EMISSIONS

BIOGENIC_CO2_EMISSIONS

How the CO_2 emissions were obtained are described in Section 3.1.2 for Türkiye and in Section 3.1.1 for the other countries in the two CCUS ZEN regions.

EMISSION TREND

Indicates each facility's CO_2 emission trends, which are classified as "falling", "growing" or "stable" based on the facility's latest CO_2 emission compared with the same facility's average of CO_2 emissions over last five years (Table 10.3 and Table 10.4).

Table 10.3 The determination strategy used for facilities' CO2 emission trends

Condition		Emission trend
If the latest total CO_2 emission of facility	> facility's last 5 years' average CO_2 emissions	"Growing"
	< facility's last 5 years' average CO_2 emissions	"Falling"
	= facility's last 5 years' average CO_2 emissions	"Stable"

Table 10.4 Example data of different facilities in Spain identified with different emission trends

Facility_ID	Latest total CO_2 emissions (ton)	Average of last 5 years' CO_2 emissions (ton)	Emission trend
ESP_8930	5 262 000	5 046 000	"Growing"
ESP_8521	5 176 000	5 769 000	"Falling"
ESP_400257	530 000	530 000	"Stable"

SHUT_YEAR

Indicates the year when the emission source is closed or is projected to close. This information was provided for one facility in Estonia.

INFORMATION_SOURCE

Provides primary source(s) of information if changes or additional information to the data downloaded from CaptureMap have been added.

11 Appendix B: CCUS ZEN CO_2 storage template

CCUS ZEN has defined a CO_2 storage template with the attributes listed in Table 11.1 to Table 11.5 below. The template is an Excel-file and a file for each country in the project has been created. The Excel-files have further been imported into QGIS for visualisation.

Table 11.1 CCUS ZEN CO_2 storage template: Sheet = Storage Unit. The grey lines are automatically filled. The light orange ones are filled with values selected from a list. White lines are manually filled.

Attribute	Unit	Description
STORAGE_ID		Unique identifier for this storage unit.
REGION		Name of the region: Baltic Sea or Mediterranean Sea
COUNTRY		Name of country
COUNTRY_CODE		ISO country code (two first letters in capital)
STORAGE TYPE		Deep Saline aquifer (DSA) or Hydrocarbon Field (HC)
FORMATION		Name of storage formation
STORAGE_UNIT		Name of storage unit
DAUGHTER_UNIT		Name of daughter unit, usually a well-defined structure with closure
PROSPECT_UNIT		Name of prospect unit
FIELD_HC_CONTENT		Hydrocarbon type: oil, gas, condensate. Only for hydrocarbon fields
FIELD_STATUS		Only for hydrocarbon fields: Producing, Suspended, Abandoned.
FIELD_CLOSURE		Expected date of closure for a producing HC field
DATE_ENTERED		Date of data entry
ON_OFF_SHORE		Onshore or offshore or onshore-offshore
DATA_SOURCE		Reference to data source

STORAGE_ID

Each storage structure is identified by an auto generated code com posed by the letter S for storage, the structure country code and a number. For example, a storage structure in France would be S_FR1.

STORAGE TYPE

Deep Saline Aquifer is a saline aquifer below 800 m to ensure that the CO_2 is in dense phase when stored in the structure. No conflict with freshwater use (drinking water and/or agriculture) has been identified.

STORAGE_UNIT, DAUGHTER_UNIT and **PROSPECT_UNIT**

The attributes are described in Section 4.1.1

DATA_SOURCE

Data source for the shape file.

Table 11.2 CCUS ZEN CO_2 storage template: Sheet = Reservoir. The grey lines are automatically filled. The light orange ones are filled with values selected from a list. White lines are manually filled.

Attribute	Unit	Description
STORAGE_ID		Unique identifier for this storage unit
STORAGE_NAME		Name of the storage, daughter or prospect unit
STORAGE_LEVEL		Storage unit, daughter unit or prospect unit
LITHOLOGY		Lithology of the reservoir
AREA_EXPECTED	km^2	Representative area, expected
AREA_NET_TO_GROSS	%	Expected net to gross for storage area
DEPTH_TO_TOP	M	Average depth to top of unit or at representative borehole. Maybe needed for cost estimates: approximate depth of injection wells.
THICKNESS	M	Representative thickness, expected gross thickness
POROSITY_TYPE		Indicate if primary or secondary porosity type.
POROSITY_EXPECTED	%	Representative porosity, expected
PERMEABILITY	mD	Representative permeability, expected
COMPRESSIBILITY	1/MPa	Representative bulk compressibility
TEMPERATURE	°C	Representative temperature
PRESSURE	MPa	Representative pressure
CO2_DENSITY	kg/m^3	Representative CO_2 density, expected
DATA_SOURCE		References to literature from where data are extracted
REMARKS		Any other relevant information

Table 11.3 CCUS ZEN CO_2 storage template: Sheet = Seal. The grey lines are automatically filled. The light orange ones are filled with values selected from a list. White lines are manually filled.

Attribute	Unit	Description
STORAGE_ID		Unique identifier for this storage unit.
STORAGE_NAME		Name of the storage, daughter or prospect unit
STORAGE_LEVEL		Storage unit, daughter unit or prospect unit
SEAL		Name of the primary seal, the main seal providing containment to the storage site
SEAL_LITHOLOGY		Representative lithology
SEAL_THICKNESS	m	Thickness of the primary seal (SEAL attribute)
SECONDARY_SEALS		Number of secondary seals
DATA_SOURCE		References to literature from where data are extracted
REMARKS		Any other relevant information

SEAL

Low permeability units in the stratigraphy above the storage reservoir

SECONDARY_SEALS

Low permeability units in the stratigraphy above the primary seal that provide secondary containment if the primary seal fails

SEAL

Low permeability units in the stratigraphy above the storage reservoir

SECONDARY_SEALS

Low permeability units in the stratigraphy above the primary seal that provide secondary containment if the primary seal fails

Table 11.4 CCUS ZEN CO_2 storage template: Sheet = Capacity. Mt stands for million ton CO_2. The grey lines are automatically filled. The light orange ones are filled with values selected from a list. White lines are manually filled.

Attribute	Unit	Description
STORAGE_ID		Unique identifier for this storage unit.
STORAGE_NAME		Name of the storage, daughter or prospect unit
STORAGE_LEVEL		Storage unit, daughter unit or prospect unit
BOUNDARY_CONDITION		Boundary condition of the prospect: Open, closed, semi-closed, unknown
SEFF_CLASS		Storage Efficiency class: Global, Regional, Local. Only for saline aquifers
SEFF_ESTIMATE	%	Storage Efficiency Factor. Only for saline aquifers
CAPACITY_MEAN	Mt	Previous expected storage capacity of unit
CAPACITY_MIN_P90	Mt	Previous expected minimum storage capacity of unit
CAPACITY_P50	Mt	Previous expected P50 storage capacity of unit
CAPACITY_MAX_P10	Mt	Previous expected maximum storage capacity of unit
CAPACITY_ESTIMATION_ CALCULATION		Calculations from: Analytical equation, modelling or injection test
CAL_METHODOLOGY		Methodologies applied in capacity and injectivity estimates
DATA_SOURCE		References to literature from where data are extracted
REMARKS		Any other relevant information

SEFF_ESTIMATE

The attribute is described in Section 4.1.2

Table 11.5 CCUS ZEN CO_2 storage template: Sheet = Maturity. The grey lines are automatically filled. The light orange ones are filled with values selected from a list. White lines are manually filled.

Attribute	Unit	Description
STORAGE_ID		Unique identifier for this storage unit.
STORAGE_NAME		Name of the storage, daughter or prospect unit
STORAGE_LEVEL		Storage unit, daughter unit or prospect unit
PROJECTED_YEAR		Projected year of operation start, depending on maturity and Storage Readiness Level (SRL)
STORAGE_ READINESS_ LEVEL		Storage Readiness Level (SRL): 1 - 9 (based on Akhurst et al. 2021)
SEISMIC_SURVEY		Have information from seismic survey
WELLS		Number of wells
ACCESIBLE/ ABANDONED		Number of accessible and abandoned wells
MODELLING		Information from modelling
BASE_LINE_DATA		Carrying out monitoring
INJECTION_TESTS		Carrying out injection test
SURFACE_ISSUES		Characteristics of the surface that can difficult the storage.
REMARKS		Any other relevant information

STORAGE_READINESS_LEVEL

The attribute is described in Section 4.1.3

12 Appendix C: Baltic Sea region

The Baltic Sea region defined in CCUS ZEN covers Denmark including its inland waters and the easternmost of Northern Sea, Sweden, Finland, Germany, Estonia, Latvia, Lithuania, Poland and the Baltic Sea (Figure 12.1). In this section, CO_2 emissions and potential geological CO_2 storage sites of the Baltic Sea region are presented country wise. Possible transport options in the region are, in addition, presented.

12.1 Country wise CO_2 emissions and potential storage sites

The emissions and potential CO_2 storage sites are shown on maps and listed in tables. The emissions are grouped by industry sector in the tables, with the distinction between facilities which emit more than 100 000 tons per year, and the ones below 100 000 tons per year. Note that the emissions below 100 000 tons per year are far from complete, see Section 3.1.1 for details.

As the number of geological storage sites are limited, all are listed with their main attributes including storage type (deep saline aquifer or hydrocarbon field), whether they are located on-shore, off-shore or both, unit type and capacity. For definition of the attributes, see Section 11 (Appendix B). The storage capacity is estimated in the previous projects and publications listed in Table 12.1.

Figure 12.1 The CCUS ZEN Baltic Sea region: Denmark including its inland waters and the easternmost of Northern Sea, Sweden, Finland, Germany, Estonia, Latvia, Lithuania, Poland and the Baltic Sea.

Table 12.1. **List of the sources for the capacity estimations** for the potential CO_2 storage sites identified by CCUS ZEN in the Baltic Sea region. # refers to the reference number used in the subsequent tables for geological storage sites.

#	Reference
1	Hjelm, L., Anthonsen, K.L., Dideriksen, K., Nielsen, C.M., Nielsen, L.H. & Mathiesen, A. (2020). Evaluation of the CO_2 storage potential in Denmark. Capture, Storage and Use of CO_2 (CCUS). Danmarks og Grønlands Geologiske Undersøgelse (GEUS) Rapport 2020/46.
2	Anthonsen, K.L., Bernstone, C. and Feldrappe, H. (2014). Screening for CO_2 storage sites in Southeast North Sea and Southwest Baltic Sea. Energy Procedia 63 (2014) 5083 – 5092.
3	Mortensen, G.M. and Sopher, D. (2021). Rapportering av regeringsuppdrag. Geologisk lagring av koldioxid i Sverige och i grannländer - status och utveckling. In Swedish. https://resource.sgu.se/dokument/publikation/rr/rr202104rapport/RR2104.pdf
4	Šliaupiene R. (2014). Prospects of CO_2 Geological storage in the Baltic Sedimentary Basin. PhD thesis, in Lithuanian. 170 pp.
5	Shogenov, K., Shogenova, A., Vizika-Kavvadias, O. (2013). Petrophysical properties and capacity of prospective for CO_2 geological storage Baltic offshore and onshore structures. In: Energy Procedia. (5036−5045). Elsevier. DOI: 10.1016/j.egypro.2013.06.417.
6	Shogenov, K., Shogenova, A., Vizika-Kavvadias, O. (2013). Potential structures for CO_2 geological storage in the Baltic Sea: case study offshore Latvia. Bulletin of the Geological Society of Finland, 85 (1), 65−81.
7	Shogenova, A., Sliaupa, S., Vaher, R., Shogenov, K., Pomeranceva, R. (2009). The Baltic Basin: structure, properties of reservoir rocks and capacity for geological storage of CO_2. Estonian Journal of Earth Sciences, 58 (4), 259−267.
8	Simmer K, (2018). Estonian-Latvian Transboundary Carbon Dioxide Capture, Transport and Storage (CCS) Scenario for the Cement Industry. Master Thesis. Tallinn University of Technology; 2018:1-48.
9	Poulsen, N., Holloway, S., Neele, F., Smith, N.A. and Kirk, K. (2014). CO2STOP Final Report. Assessment of CO_2 storage potential in Europe. https://energy.ec.europa.eu/publications/assessment-co2-storage-potential-europe-co2stop_en
10	Šliaupienė R. and Šliaupa S. (2011). Prospects for CO_2 geological storage in deep saline aquifers of Lithuania and adjacent territories. Geologija. 2011. Vol. 53. No. 3(75). P. 121–133.
11	Wójcicki A., Nagy S., Lubaś J., Chećko J., Tarkowski R. (2014). Assessment of formations and structures suitable for safe CO_2 storage (in Poland) including the monitoring plans (https://skladowanie.pgi.gov.pl/twiki/pub/CO2/WebHome/seq-summ.pdf) and updates by Wójcicki, A. (2023).
12	Wójcicki, A. (2023). Pers. com. Calculations based on the pore volume published in Anthonsen et al. (2014) and using the CSFL methodology with SEF = 20% which is comparable to other German and Polish site calculations.

12.1.1 Denmark

CO_2 emission sources and potential CO_2 storage sites in Denmark is shown in Figure 12.2. The emissions per industry sector are summarised in Table 12.2. Natura2000 areas are shown together with the potential storage sites in Figure 12.3.

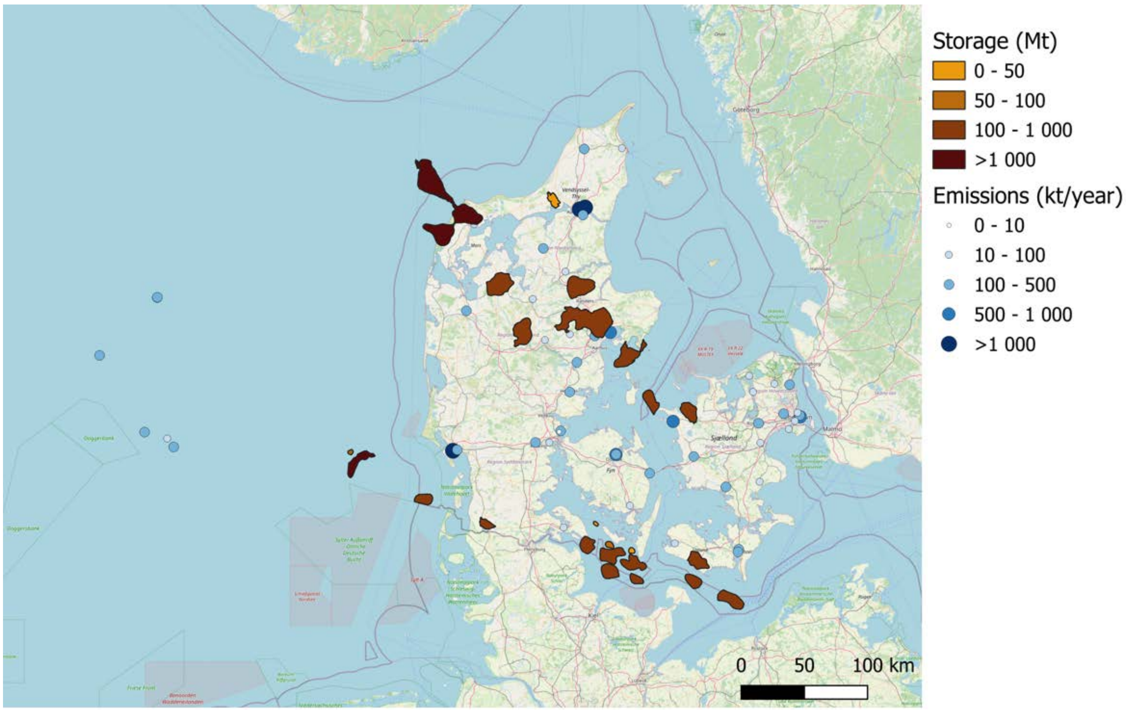

Figure 12.2 Denmark: CO_2 emission sources and potential CO_2 storage sites.

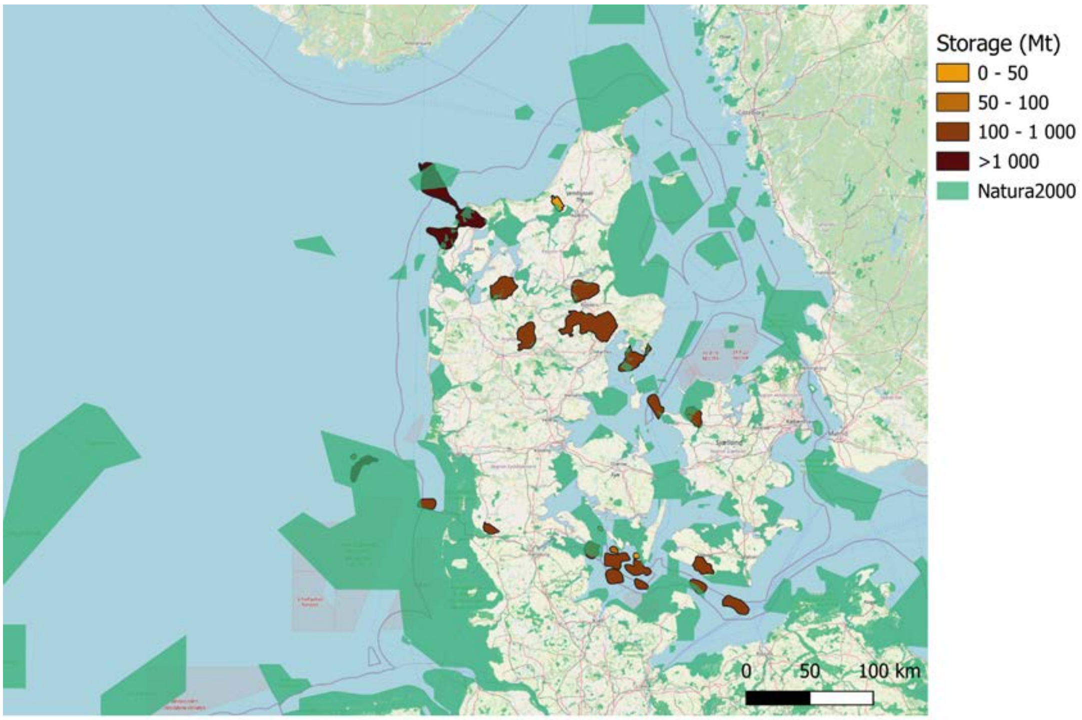

Figure 12.3 Denmark: Potential CO_2 storage sites and Natura2000 areas.

Table 12.2. **Denmark: Emissions per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kt/year		Facilities with CO_2 emissions above 100 kt/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Energy from waste	7	530	18	3 671
Power	8	466	4	3 720
Cement	0	0	1	2 248
Refineries	0	0	2	961
Oil and gas processing	1	98	5	850
Other	1	23	2	279
Food and drink	2	77	1	105
Iron and Steel	1	80	0	0
Paper and pulp	1	35	0	0
Chemicals (other)	1	33	0	0
Sum	**22**	**1 342**	**33**	**11 834**

Table 12.3. **Denmark: Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 12.1 with capacity calculations.

Storage name	Storage type	On-shore / off-shore	Unit type	SRL level	Capacity [Mt]	Ref.
Hanstholm_S	Deep Saline Aquifer	Offshore	Daughter Unit	2	3 463	1
Thisted	Deep Saline Aquifer	Onshore	Daughter Unit	2	2 415	1
Legind	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	1 622	1
SNS-2	Deep Saline Aquifer	Offshore	Daughter Unit	2	1 458	2
Hanstholm_G	Deep Saline Aquifer	Offshore	Daughter Unit	4	1 341	1
Voldum	Deep Saline Aquifer	Onshore	Daughter Unit	2	851	1
Gassum	Deep Saline Aquifer	Onshore	Daughter Unit	2	586	1
Røsnæs	Deep Saline Aquifer	Offshore	Daughter Unit	2	429	1
Rødby	Deep Saline Aquifer	Onshore	Daughter Unit	2	342	1
Skive	Deep Saline Aquifer	Onshore	Daughter Unit	2	335	1
WBS-4	Deep Saline Aquifer	Offshore	Daughter Unit	2	328	2
Helgenæs	Deep Saline Aquifer	Offshore	Daughter Unit	2	307	1
Havnsø	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	4	305	1
WBS-2	Deep Saline Aquifer	Offshore	Daughter Unit	2	305	2
Thorning	Deep Saline Aquifer	Offshore	Daughter Unit	2	297	1
WBS-6	Deep Saline Aquifer	Offshore	Daughter Unit	2	263	2
WBS-1	Deep Saline Aquifer	Offshore	Daughter Unit	2	245	2
Tønder	Deep Saline Aquifer	Onshore	Daughter Unit	2	239	1
WBS-10	Deep Saline Aquifer	Offshore	Daughter Unit	2	215	2
WBS-8	Deep Saline Aquifer	Offshore	Daughter Unit	2	187	2
WBS-5	Deep Saline Aquifer	Offshore	Daughter Unit	2	149	2
SNS-1	Deep Saline Aquifer	Offshore	Daughter Unit	2	135	2
SNS-3	Deep Saline Aquifer	Offshore	Daughter Unit	2	98	2
WBS-7	Deep Saline Aquifer	Offshore	Daughter Unit	2	51	2
Vedsted	Deep Saline Aquifer	Onshore	Daughter Unit	4	37	1
WBS-3	Deep Saline Aquifer	Offshore	Daughter Unit	2	26	2
WBS-9	Deep Saline Aquifer	Offshore	Daughter Unit	2	14	2
Sum CCUS ZEN storage capacity in Denmark					**16 042 Mt**	

12.1.2 Sweden

CO_2 emission sources and potential CO_2 storage sites in Sweden is shown in Figure 12.4. The emissions per industry sector are summarised in Table 12.4, while the potential storage sites are listed

Table 12.5. Natura2000 areas are shown together with the potential storage sites in Figure 12.5.

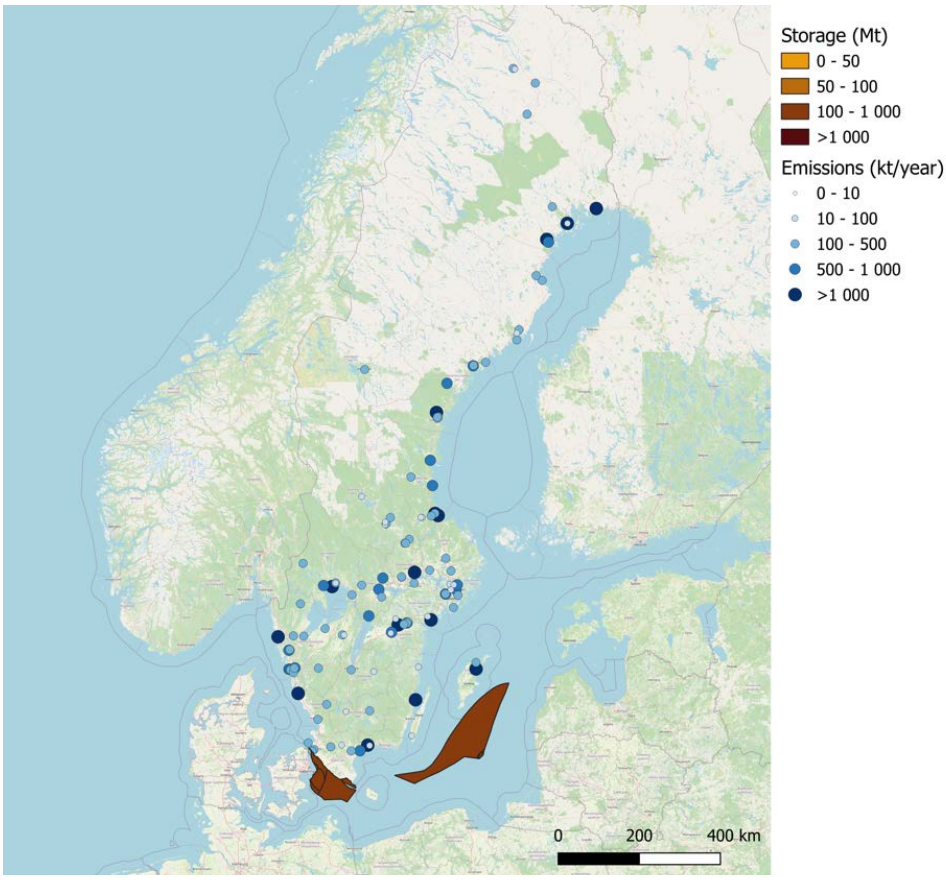

Figure 12.4 Sweden: CO_2 emission sources and potential CO_2 storage sites.

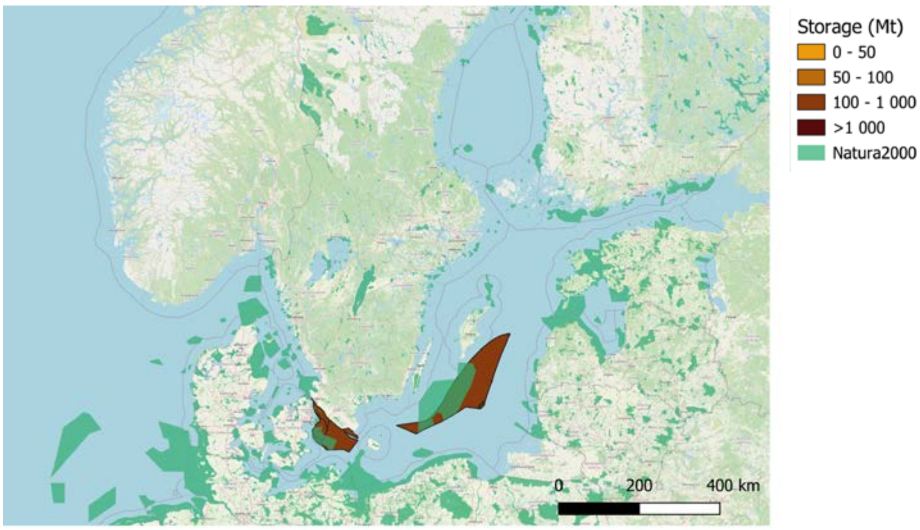

Figure 12.5 Sweden: Potential CO_2 storage sites and Natura2000 areas.

Table 12.4. **Sweden: Emissions per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kt/year		Facilities with CO_2 emissions above 100 kt/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Paper and pulp	0	0	28	25 278
Power	9	488	28	7 637
Energy from waste	11	902	16	5 548
Iron & Steel	1	89	8	6 014
Refineries	0	0	4	2 535
Cement	1	66	2	2 030
Chemicals (other)	1	94	3	926
Non-iron metals	1	65	3	622
Other	1	38	3	446
Sum	**25**	**1 742**	**95**	**51 036**

Table 12.5. **Sweden: Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 12.1 with capacity calculations.

Storage name	Storage type	On-shore / off-shore	Unit type	SRL level	Capacity [Mt]	Ref.
Faludden Storage Unit	Deep Saline Aquifer	Offshore	Storage Unit	2	745	3
Viklau Storage Unit	Deep Saline Aquifer	Offshore	Storage Unit	2	553	3
Höganäs-Rya Storage Unit	Deep Saline Aquifer	Onshore-Offshore	Storage Unit	2	543	3
Arnager Greensand Storage Unit	Deep Saline Aquifer	Onshore-Offshore	Storage Unit	2	521	3
När Storage Units	Deep Saline Aquifer	Offshore	Storage Unit	2	426	3
Lower Cretaceous Sands Storage Unit A	Deep Saline Aquifer	Onshore-Offshore	Storage Unit	2	330	3
Bunter Storage Unit	Deep Saline Aquifer	Onshore-Offshore	Storage Unit	2	165	3
Lower Cretaceous Sands Storage Unit B	Deep Saline Aquifer	Onshore-Offshore	Storage Unit	2	115	3
Dalders Structure	Deep Saline Aquifer	Offshore	Daughter Unit	2	22	3
Sum CCUS ZEN storage capacity in Sweden					**3 420 Mt**	

12.1.3 Finland

CO_2 emission sources in Finland is shown in Figure 12.6 and summarised in Table 12.6. No potential CO_2 storage sites have been identified for Finland as the bedrock is mainly composed of crystalline and low porosity rocks.

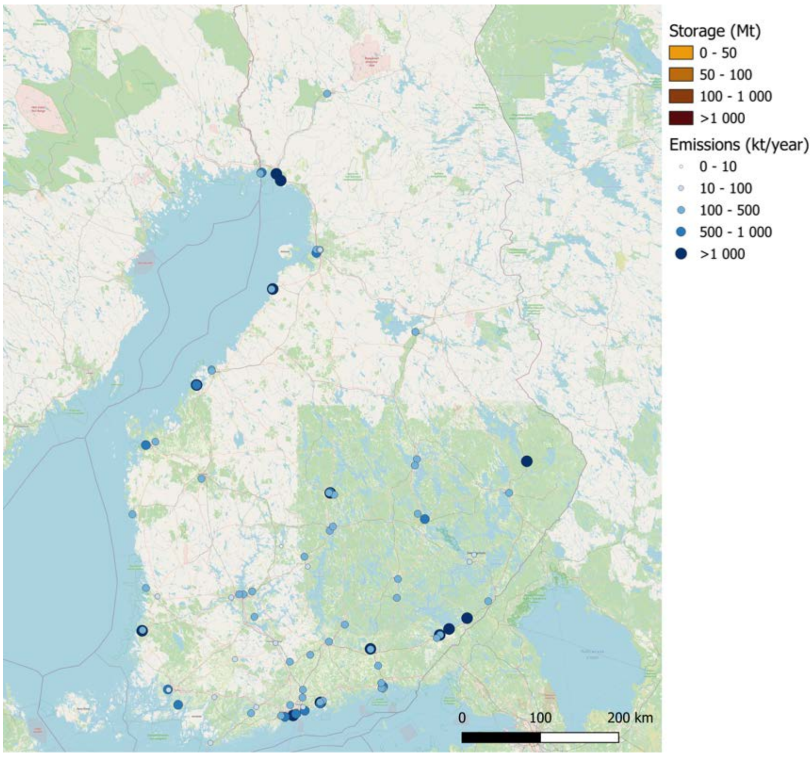

Figure 12.6 Finland: CO_2 emission sources. There are no storage sites in Finland.

Table 12.6. **Finland: Emissions per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kt/year		Facilities with CO_2 emissions above 100 kt/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Paper and pulp	1	54	23	23 022
Power	10	41	36	12 714
Iron and Steel	0	0	2	4 970
Refineries	1	50	1	2 360
Cement	0	0	2	907
Other	2	138	3	666
Energy from waste	0	0	5	707
Chemicals (other)	0	0	2	687
Sum	**14**	**652**	**74**	**46 033**

12.1.4 Germany

CO_2 emission sources and potential CO_2 storage sites in Germany is shown in Figure 12.7. The emissions per industry sector are summarised in Table 12.7, while the potential storage sites are listed Table 12.8. Natura2000 areas are shown together with the potential storage sites in Figure 12.8.

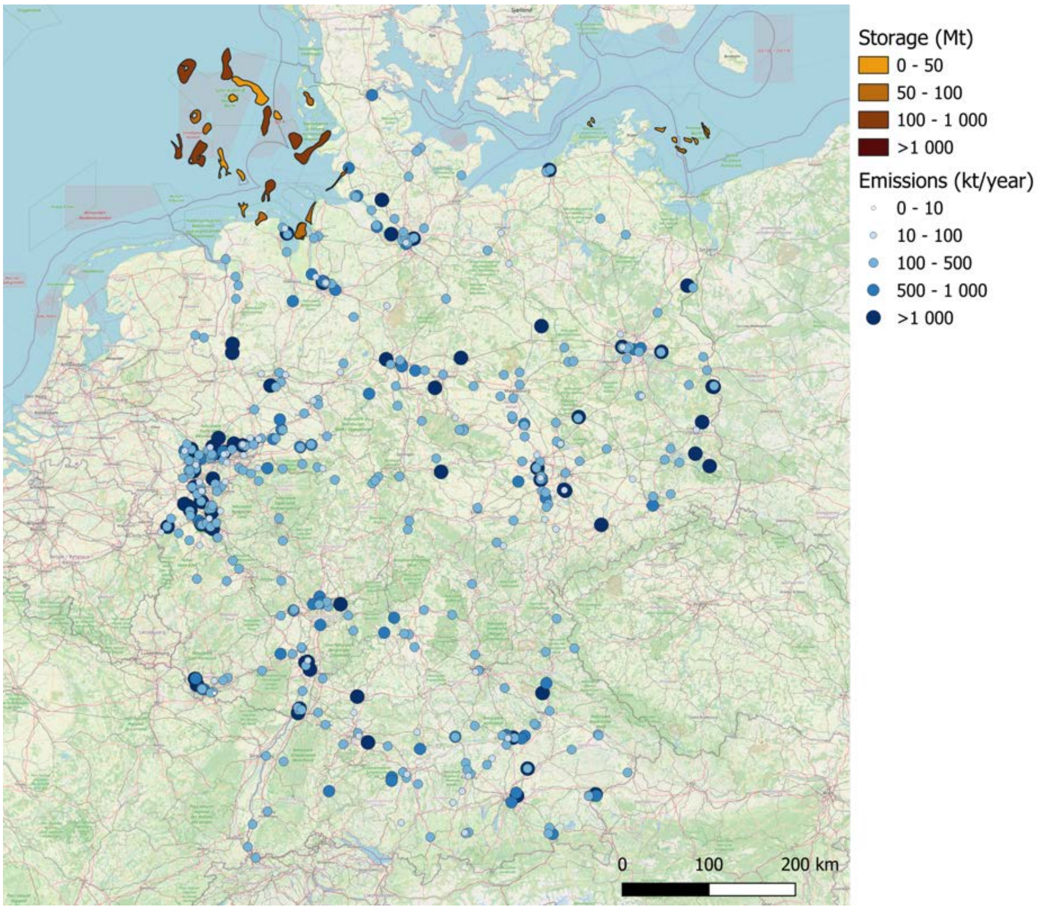

Figure 12.7 Germany: CO_2 emission sources and potential CO_2 storage sites.

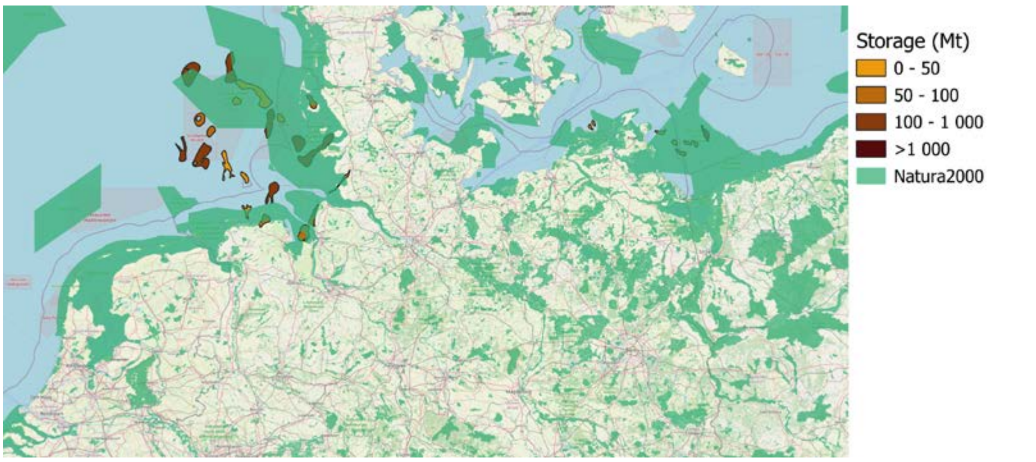

Figure 12.8 Germany: Potential CO_2 storage sites and Natura2000 areas.

Table 12.7. **Germany**: **Emissions per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kt/year		Facilities with CO_2 emissions above 100 kt/year	
	Number of facilities	CO_2 emissions [kt/year]	Number of facilities	CO_2 emissions [kt/year]
Power	26	1 393	127	210 351
Iron & Steel	5	362	21	32 773
Energy from waste	6	562	72	22 152
Refineries	1	62	16	21 134
Cement	0	0	30	20 700
Other	1	53	46	18 226
Chemicals (other)	6	438	30	12 431
Ethylene Oxide	0	0	2	9 768
Paper and pulp	7	452	21	7 301
Ammonia	0	0	2	3 279
Non-iron metals	0	0	8	1 778
Food & drink	1	69	11	1 690
Glass	2	166	10	1 455
Hydrogen	0	0	4	1 222
Ethylene	0	0	1	898
Oil & gas Processing	3	164	4	682
Sum	**58**	**3 721**	**405**	**365 840**

Table 12.8. **Germany**: **Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 12.1 with capacity calculations.

Storage name	Storage type	On-shore / off-shore	Unit type	SRL level	Capacity [Mt]	Ref.
Middle Buntsandstein Daughter Unit 2	Deep Saline Aquifer	Offshore	Daughter Unit	2	729	9
Middle Buntsandstein Daughter Unit 12	Deep Saline Aquifer	Offshore	Daughter Unit	2	517	9
Middle Buntsandstein Daughter Unit 9	Deep Saline Aquifer	Offshore	Daughter Unit	2	252	9
Middle Buntsandstein Daughter Unit 5	Deep Saline Aquifer	Offshore	Daughter Unit	2	159	9
Middle Buntsandstein Daughter Unit 7	Deep Saline Aquifer	Offshore	Daughter Unit	2	144	9
Middle Buntsandstein Daughter Unit 17	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	140	9
Middle Buntsandstein Daughter Unit 15	Deep Saline Aquifer	Offshore	Daughter Unit	2	135	9
Middle Buntsandstein Daughter Unit 13	Deep Saline Aquifer	Offshore	Daughter Unit	2	103	9
Middle Buntsandstein Daughter Unit 8	Deep Saline Aquifer	Offshore	Daughter Unit	2	101	9
Keuper Daughter Unit 1	Deep Saline Aquifer	Offshore	Daughter Unit	2	101	9
Middle Buntsandstein Daughter Unit 11	Deep Saline Aquifer	Offshore	Daughter Unit	2	88	9
Middle Buntsandstein Daughter Unit 16	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	75	9
Middle Buntsandstein Daughter Unit 1	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	67	9
Keuper Daughter Unit 3	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	65	9
Mbu_27_GER_K	Deep Saline Aquifer	Offshore	Daughter Unit	2	64	2
Middle Buntsandstein Daughter Unit 10	Deep Saline Aquifer	Offshore	Daughter Unit	2	59	9
Middle Buntsandstein Daughter Unit 19	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	59	9
Mbu_25_GER_K	Deep Saline Aquifer	Offshore	Daughter Unit	2	59	2
Middle Buntsandstein Daughter Unit 18	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	58	9
Mbu_12_GER_H	Deep Saline Aquifer	Offshore	Daughter Unit	2	53	2

Middle Jurassic Daughter Unit 2	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	52	9
J_03_GER_H	Deep Saline Aquifer	Offshore	Daughter Unit	2	50	2
Middle Buntsandstein Daughter Unit 3	Deep Saline Aquifer	Offshore	Daughter Unit	2	49	9
Middle Buntsandstein Daughter Unit 14	Deep Saline Aquifer	Onshore-Offshore	Daughter Unit	2	47	9
Middle Jurassic Daughter Unit 1	Deep Saline Aquifer	Offshore	Daughter Unit	2	47	9
J_02_GER_H	Deep Saline Aquifer	Offshore	Daughter Unit	2	46	2
Middle Buntsandstein Daughter Unit 4	Deep Saline Aquifer	Offshore	Daughter Unit	2	43	9
Middle Buntsandstein Daughter Unit 6	Deep Saline Aquifer	Offshore	Daughter Unit	2	43	9
Keuper Daughter Unit 2	Deep Saline Aquifer	Offshore	Daughter Unit	2	42	9
Mbu_24_GER_H	Deep Saline Aquifer	Offshore	Daughter Unit	2	28	2
J_01_GER_H	Deep Saline Aquifer	Offshore	Daughter Unit	2	27	2
Mbu_21_GER_H	Deep Saline Aquifer	Offshore	Daughter Unit	2	24	2
Uke_02_GER_F	Deep Saline Aquifer	Offshore	Daughter Unit	2	10	2
Uke_04_GER_F	Deep Saline Aquifer	Offshore	Daughter Unit	2	3	2
Sum CCUS ZEN storage capacity in Germany					**3 539 Mt**	

12.1.5 Estonia

CO_2 emission sources in Estonia is shown in Figure 12.9. According to available studies CO_2 geological storage capacity in saline aquifers and depleted hydrocarbon fields is practically absent in Estonia.

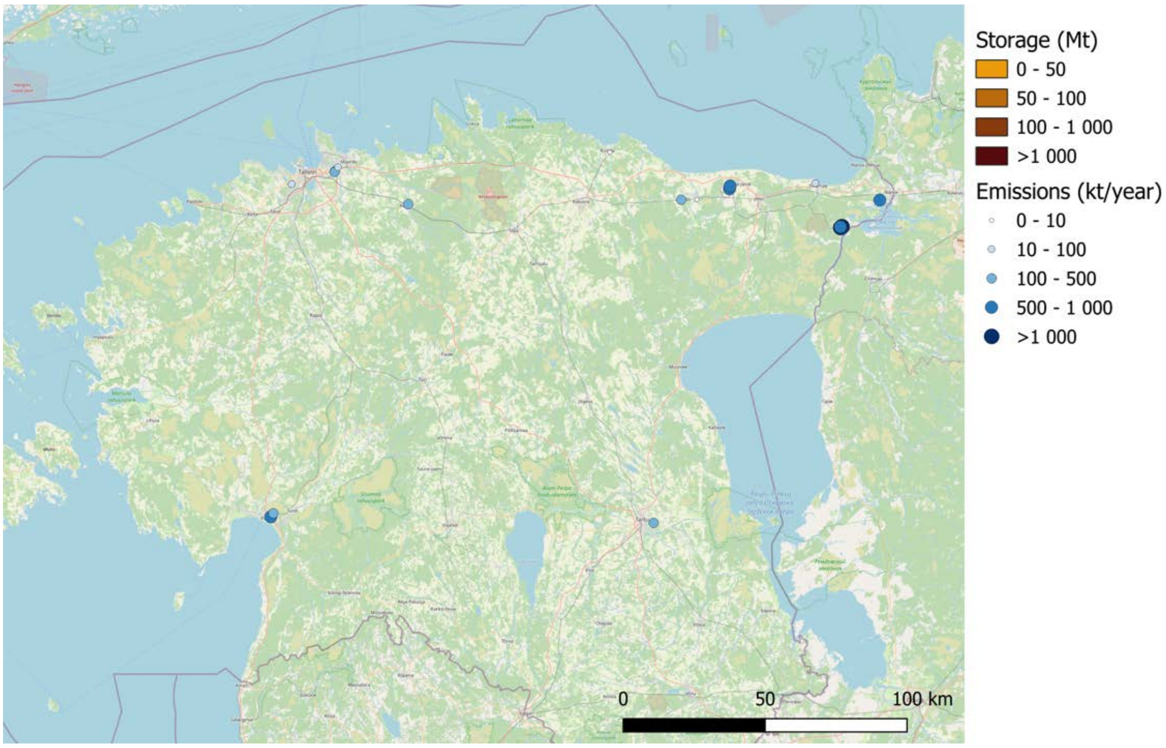

Figure 12.9 **Estonia**: CO_2 emission sources.

Table 12.9. **Estonia**: **Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Power	2	139	13	8 643
Refineries	2	139	2	1 486
Paper and pulp	1	0	2	815
Chemical (other)	0	0	1	159
Energy from waste	1	97	0	0
Sum	**5**	**236**	**13**	**8 643**

12.1.6 Latvia

CO_2 emission sources and potential CO_2 storage sites in Latvia are shown in Figure 12.10. The emissions per industry sector are summarised in Table 12.10, while the potential storage sites are listed Table 12.11. Natura2000 areas are shown together with the potential storage sites in Figure 12.11.

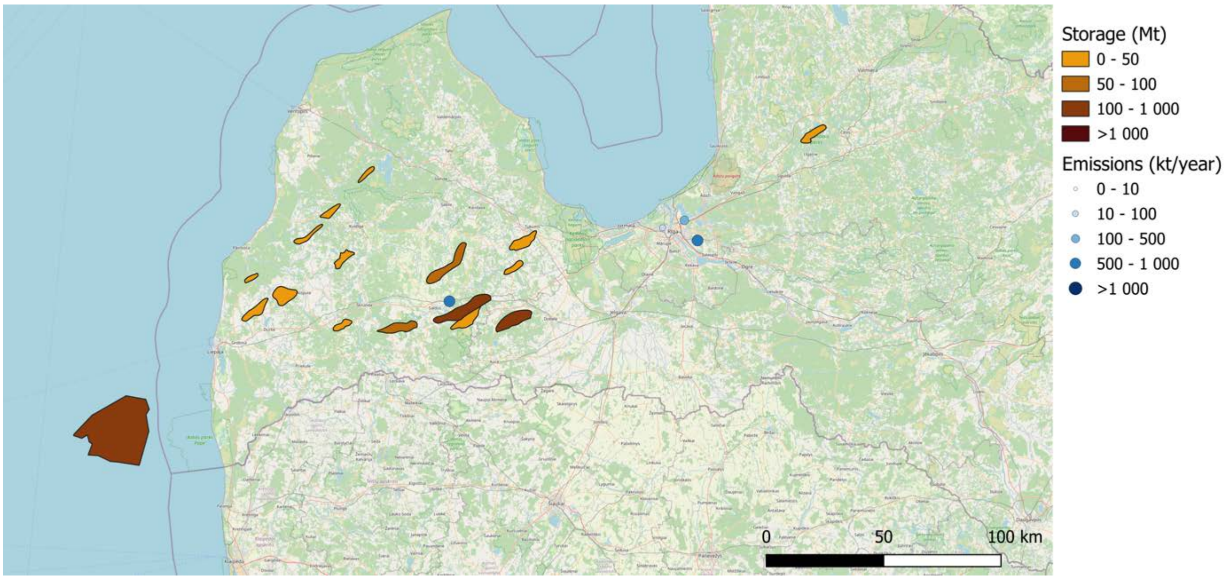

Figure 12.10 **Latvia**: CO_2 emission sources and potential CO_2 storage sites.

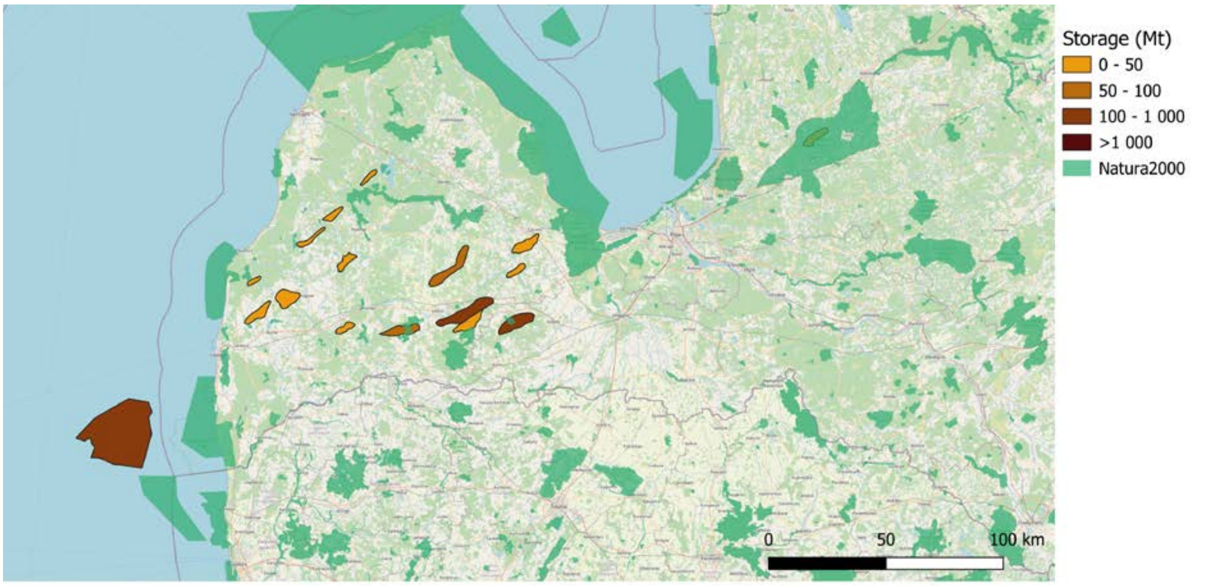

Figure 12.11 **Latvia**: Potential CO_2 storage sites and Natura2000 areas.

Table 12.10. **Latvia**: **Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kt/year		Facilities with CO_2 emissions above 100 kt/year	
	Number of facilities	CO_2 emissions [kt/year]	Number of facilities	CO_2 emissions [kt/year]
Power	1	100	2	902
Cement	0	0	1	752
Sum	**1**	**100**	**3**	**1 654**

Table 12.11. **Latvia**: **Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 12.1 with capacity calculations.

Storage name	Storage type	On-shore / off-shore	Unit type	SRL level	Capacity [Mt]	Ref.
E6	Deep Saline Aquifer	Offshore	Daughter Unit	4	396	6
North Blidene	Deep Saline Aquifer	Onshore	Daughter Unit	3	267	8
Dobele	Deep Saline Aquifer	Onshore	Daughter Unit	4	106	5
South Kandava	Deep Saline Aquifer	Onshore	Daughter Unit	3	95	5
Luku-Duku	Deep Saline Aquifer	Onshore	Daughter Unit	2	68	4
Liepaja	Deep Saline Aquifer	Onshore	Daughter Unit	2	37	4
Blidene	Deep Saline Aquifer	Onshore	Daughter Unit	3	30	8
Snepele	Deep Saline Aquifer	Onshore	Daughter Unit	2	29	4
North Ligatne	Deep Saline Aquifer	Onshore	Daughter Unit	2	23	7
Degole	Deep Saline Aquifer	Onshore	Daughter Unit	2	21	4
Kalvene	Deep Saline Aquifer	Onshore	Daughter Unit	2	20	4
Viesatu	Deep Saline Aquifer	Onshore	Daughter Unit	2	20	4
Aizpute	Deep Saline Aquifer	Onshore	Daughter Unit	2	18	4
North Kuldiga	Deep Saline Aquifer	Onshore	Daughter Unit	2	14	4
Edole	Deep Saline Aquifer	Onshore	Daughter Unit	2	11	4
Vergale	Deep Saline Aquifer	Onshore	Daughter Unit	2	9	4
Usma	Deep Saline Aquifer	Onshore	Daughter Unit	2	8	4
Sum CCUS ZEN storage capacity in Latvia					**1 172 Mt**	

12.1.7 Lithuania

CO_2 emission sources and potential CO_2 storage sites in Latvia are shown in Figure 12.12. The emissions per industry sector are summarised in Table 12.12, while the potential storage sites are listed Table 12.13. Natura2000 areas are shown together with the potential storage sites in Figure 12.12.

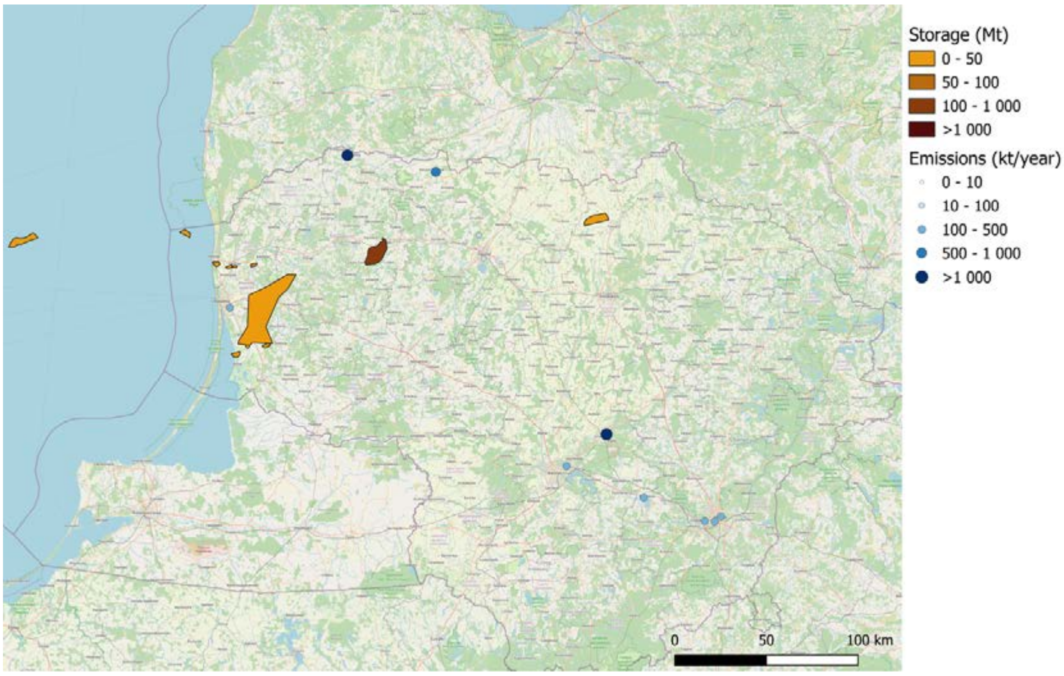

Figure 12.12 **Lithuania**: CO_2 emission sources and potential CO_2 storage sites.

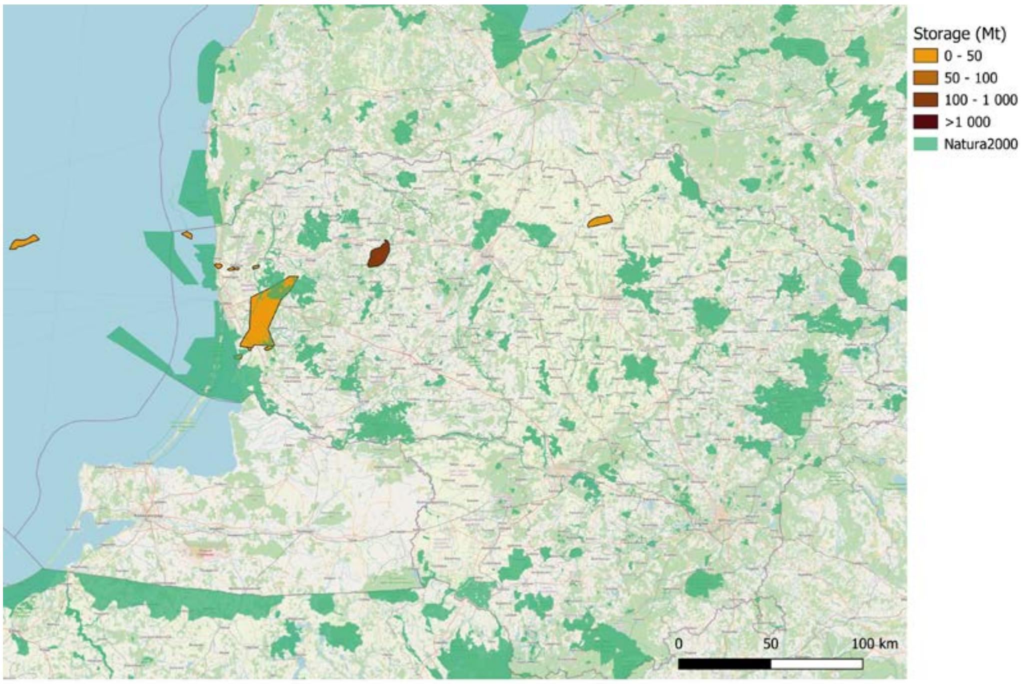

Figure 12.13 **Lithuania**: Potential CO_2 storage sites and Natura2000 areas.

Table 12.12. **Lithuania**: **Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Chemicals (other)	0	0	1	2 034
Refineries	0	0	1	1 502
Cement	0	0	1	997
Energy from waste	1	79	4	606
Power	1	20	2	449
Sum	**2**	**99**	**9**	**5 687**

Table 12.13. **Lithuania**: **Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 12.1 with capacity calculations.

Storage name	Storage type	On-shore / off-shore	Unit type	SRL level	Capacity [Mt]	Ref.
Syderiai	Deep Saline Aquifer	Onshore	Daughter Unit	2	116.7	10
Gargždai	Deep Saline Aquifer	Onshore	Daughter Unit	2	100.0	10
E7	Deep Saline Aquifer	Offshore	Daughter Unit	2	34.0	6
Vaskai	Deep Saline Aquifer	Onshore	Daughter Unit	2	29.7	10
D11	Deep Saline Aquifer	Offshore	Daughter Unit	2	11.3	10
South Siupariai	Hydrocarbon Field	Onshore	Daughter Unit	3	1.5	9
Genciai	Hydrocarbon Field	Onshore	Daughter Unit	3	1.2	9
Vilkyciai	Hydrocarbon Field	Onshore	Daughter Unit	3	1.1	9
Vezaiciai	Hydrocarbon Field	Onshore	Daughter Unit	3	0.6	9
Girkaliai	Hydrocarbon Field	Onshore	Daughter Unit	3	0.5	9
Siupariai	Hydrocarbon Field	Onshore	Daughter Unit	3	0.4	9
Diegliai	Hydrocarbon Field	Onshore	Daughter Unit	3	0.4	9
Sakuciai	Hydrocarbon Field	Onshore	Daughter Unit	3	0.4	9
Kretinga	Hydrocarbon Field	Onshore	Daughter Unit	3	0.3	9
Nausodis	Hydrocarbon Field	Onshore	Daughter Unit	3	0.3	9
Pociai	Hydrocarbon Field	Onshore	Daughter Unit	3	0.3	9
Ablinga	Hydrocarbon Field	Onshore	Daughter Unit	3	0.1	9
Sum CCUS ZEN storage capacity in Lithuania					**299 Mt**	

12.1.8 Poland

CO_2 emission sources and potential CO_2 storage sites in Poland is shown in Figure 12.14. The emissions per industry sector are summarised in Table 12.14, while the potential storage sites are listed Table 12.15. Natura2000 areas are shown together with the potential storage sites in Figure 12.15.

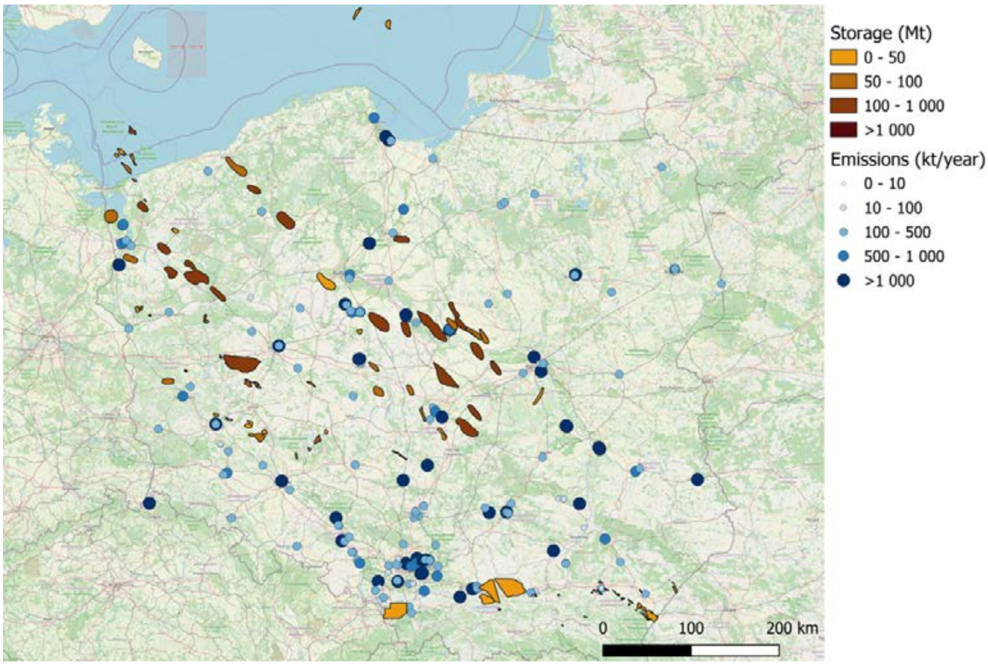

Figure 12.14 **Poland**: CO_2 emission sources and potential CO_2 storage sites.

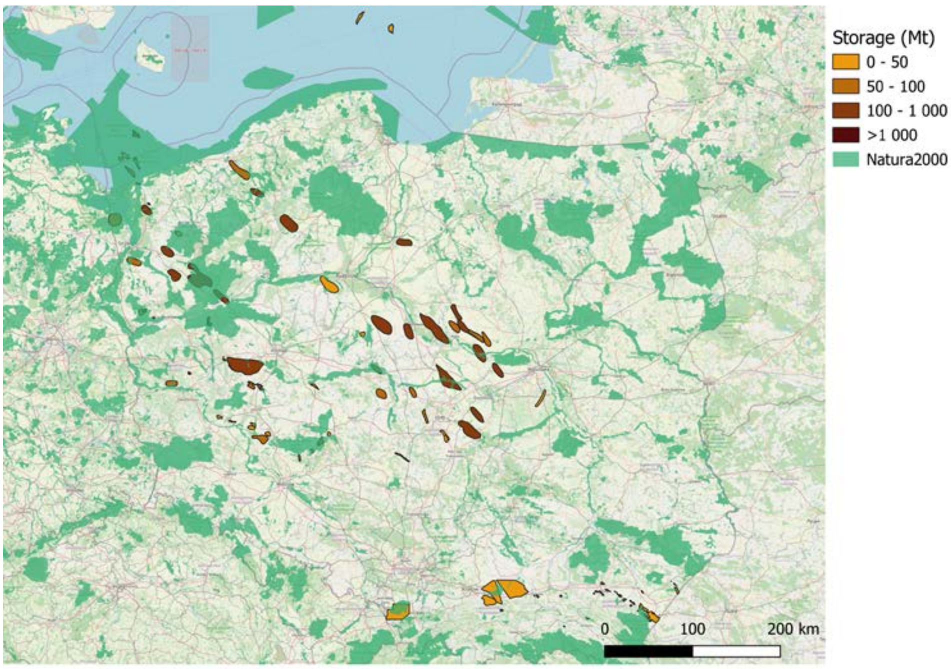

Figure 12.15 **Poland**: Potential CO_2 storage sites and Natura2000 areas.

Table 12.14. **Poland: Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kt/year		Facilities with CO_2 emissions above 100 kt/year	
	Number of facilities	CO_2 emissions [kt/year]	Number of facilities	CO_2 emissions [kt/year]
Power	19	913	83	143 272
Cement	0	0	9	11 723
Chemicals (other)	1	68	15	9 289
Paper and pulp	0	0	9	6 229
Iron & Steel	4	245	6	4 233
Refineries	0	0	3	4 283
Non-iron metals	1	93	6	2 173
Food & drink	2	186	9	2 033
Other	1	45	9	2 024
Ammonia	0	0	2	1 615
Energy from waste	1	31	8	1 143
Glass	1	87	4	806
Fermentation	0	0	1	333
Sum	**30**	**1668**	**164**	**189 159**

Table 12.15. **Poland: Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 12.1 with capacity calculations.

Storage name	Storage type	Onshore / offshore	Unit type	SRL level	Capacity [Mt]	Ref.
Gostynin	Deep Saline Aquifer	Onshore	Daughter Unit	2	514	11
Suliszewo	Deep Saline Aquifer	Onshore	Daughter Unit	2	509	11
Przemyśl	Hydrocarbon Field	Onshore	Daughter Unit	3	370	11
Wojszyce	Deep Saline Aquifer	Onshore	Daughter Unit	3	342	11
Wyszogród	Deep Saline Aquifer	Onshore	Daughter Unit	2	315	11
Konary J	Deep Saline Aquifer	Onshore	Daughter Unit	2	282	11
Jeżów T	Deep Saline Aquifer	Onshore	Daughter Unit	2	277	11
Rokita	Deep Saline Aquifer	Onshore	Daughter Unit	2	264	11
Debrzno	Deep Saline Aquifer	Onshore	Daughter Unit	2	246	11
Huta Szklana	Deep Saline Aquifer	Onshore	Daughter Unit	2	224	11
Sochaczew J	Deep Saline Aquifer	Onshore	Daughter Unit	2	222	11
Sierpc K	Deep Saline Aquifer	Onshore	Daughter Unit	2	212	11

Sochaczew K	Deep Saline Aquifer	Onshore	Daughter Unit	2	206	11
Choszczno	Deep Saline Aquifer	Onshore	Daughter Unit	2	205	11
Wierzchowo	Deep Saline Aquifer	Onshore	Daughter Unit	2	194	11
Bielsk-Bodzanów	Deep Saline Aquifer	Onshore	Daughter Unit	2	194	11
Konary T	Deep Saline Aquifer	Onshore	Daughter Unit	2	182	11
Jeżów J	Deep Saline Aquifer	Onshore	Daughter Unit	2	166	11
Niecka Poznańska (G-U-B-P)	Deep Saline Aquifer	Onshore	Daughter Unit	2	165	11
Grudziądz	Deep Saline Aquifer	Onshore	Daughter Unit	2	157	11
Sierpc J	Deep Saline Aquifer	Onshore	Daughter Unit	2	152	11
Kamionki J	Deep Saline Aquifer	Onshore	Daughter Unit	2	149	11
Żuchlów	Hydrocarbon Field	Onshore	Daughter Unit	3	138	11
Marianowo J&T	Deep Saline Aquifer	Onshore	Daughter Unit	3	129	11
Załęcze	Hydrocarbon Field	Onshore	Daughter Unit	3	117	11
Budziszewice-Zaosie	Deep Saline Aquifer	Onshore	Daughter Unit	2	107	11
J_15_POL_K	Deep Saline Aquifer	Offshore	Daughter Unit	2	102	12
Kamionki K	Deep Saline Aquifer	Onshore	Daughter Unit	2	99	11
Chabowo J&T	Deep Saline Aquifer	Onshore	Daughter Unit	2	99	11
Koszalin	Deep Saline Aquifer	Onshore	Daughter Unit	2	98	11
Brońsko	Hydrocarbon Field	Onshore	Daughter Unit	3	91	11
Bogdaj-Uciechów	Hydrocarbon Field	Onshore	Daughter Unit	3	88	11
Radnica	Deep Saline Aquifer	Onshore	Daughter Unit	2	87	11
Dzierżanowo	Deep Saline Aquifer	Onshore	Daughter Unit	2	84	11
Lutomiersk	Deep Saline Aquifer	Onshore	Daughter Unit	2	78	11
Trześniew	Deep Saline Aquifer	Onshore	Daughter Unit	2	78	11
Kliczków J	Deep Saline Aquifer	Onshore	Daughter Unit	2	77	11
Bodzanów	Deep Saline Aquifer	Onshore	Daughter Unit	2	77	11
Kowalowo	Deep Saline Aquifer	Onshore	Daughter Unit	2	76	11
Husów-Albigowa-Krasne	Hydrocarbon Field	Onshore	Daughter Unit	3	63	11
Bielsk	Deep Saline Aquifer	Onshore	Daughter Unit	2	63	11
Trzebież	Deep Saline Aquifer	Onshore	Daughter Unit	2	61	11

Turek	Deep Saline Aquifer	Onshore	Daughter Unit	2	61	11
Wartkowice	Deep Saline Aquifer	Onshore	Daughter Unit	2	53	11
MBu_28_POL_K	Deep Saline Aquifer	Offshore	Daughter Unit	2	52	12
J_06_POL_H	Deep Saline Aquifer	Offshore	Daughter Unit	2	48	12
Szubin	Deep Saline Aquifer	Onshore	Daughter Unit	2	47	11
Tuszyn	Deep Saline Aquifer	Onshore	Daughter Unit	2	41	11
J_14_POL_K	Deep Saline Aquifer	Offshore	Daughter Unit	2	39	12
MBu_23_POL_K	Deep Saline Aquifer	Offshore	Daughter Unit	2	36	12
Jarosław	Hydrocarbon Field	Onshore	Daughter Unit	3	36	11
Kościan S	Hydrocarbon Field	Onshore	Daughter Unit	3	35	11
BMB	Hydrocarbon Field	Onshore	Daughter Unit	3	30	11
Paproć	Hydrocarbon Field	Onshore	Daughter Unit	3	27	11
MBu_19_POL_K	Deep Saline Aquifer	Offshore	Daughter Unit	2	27	12
Strzelno	Deep Saline Aquifer	Onshore	Daughter Unit	2	25	11
Oświno J	Deep Saline Aquifer	Onshore	Daughter Unit	2	23	11
Wilków	Hydrocarbon Field	Onshore	Daughter Unit	3	23	11
Tarchały (d.g.+cz.s.)	Hydrocarbon Field	Onshore	Daughter Unit	3	20	11
Tuszyn	Deep Saline Aquifer	Onshore	Daughter Unit	2	19	11
Radlin	Hydrocarbon Field	Onshore	Daughter Unit	3	17	11
Tarnów (miocen)	Hydrocarbon Field	Onshore	Daughter Unit	3	15	11
Zat Gdowska	Deep Saline Aquifer	Onshore	Daughter Unit	2	15	11
Jodłówka	Hydrocarbon Field	Onshore	Daughter Unit	3	14	11
Kielanówka-Rzeszów	Hydrocarbon Field	Onshore	Daughter Unit	3	14	11
Skoczów-Czechowice	Deep Saline Aquifer	Onshore	Daughter Unit	2	14	11
Oświno K	Deep Saline Aquifer	Onshore	Daughter Unit	2	13	11
Zalesie	Hydrocarbon Field	Onshore	Daughter Unit	3	13	11
Grobla	Deep Saline Aquifer	Onshore	Daughter Unit	2	13	11
Pilzno Południe	Hydrocarbon Field	Onshore	Daughter Unit	3	12	11
Pruchnik-Pantalowice	Hydrocarbon Field	Onshore	Daughter Unit	3	12	11
Żyrów	Deep Saline Aquifer	Onshore	Daughter Unit	2	11	11
B 3	Hydrocarbon Field	Offshore	Daughter Unit	3	11	11
Grochowice	Hydrocarbon Field	Onshore	Daughter Unit	3	11	11

Jasionka	Hydrocarbon Field	Onshore	Daughter Unit	3	11	11
Czeszów	Hydrocarbon Field	Onshore	Daughter Unit	3	10	11
Lubiatów	Hydrocarbon Field	Onshore	Daughter Unit	3	10	11
Paproć W	Hydrocarbon Field	Onshore	Daughter Unit	3	10	11
Grodzisk_Wlkp.	Hydrocarbon Field	Onshore	Daughter Unit	3	9	11
Lubaczów (J)	Hydrocarbon Field	Onshore	Daughter Unit	3	9	11
B 8	Hydrocarbon Field	Offshore	Daughter Unit	3	8	11
Brzostowo	Hydrocarbon Field	Onshore	Daughter Unit	3	8	11
Góra	Hydrocarbon Field	Onshore	Daughter Unit	3	8	11
Łąkta	Hydrocarbon Field	Onshore	Daughter Unit	3	6	11
Niepołomice	Deep Saline Aquifer	Onshore	Daughter Unit	1	6	11
Węglówka	Hydrocarbon Field	Onshore	Daughter Unit	3	4	11
Kamień Pomorski	Hydrocarbon Field	Onshore-Offshore	Daughter Unit	3	3	11
Buk	Hydrocarbon Field	Onshore	Daughter Unit	3	1	11
Dzieduszyce	Hydrocarbon Field	Onshore	Daughter Unit	3	1	11
Osobnica	Hydrocarbon Field	Onshore	Daughter Unit	3	1	11
Radoszyn	Hydrocarbon Field	Onshore	Daughter Unit	3	1	11
Wysoka Kamieńska	Hydrocarbon Field	Onshore	Daughter Unit	3	1	11
Nosówka	Hydrocarbon Field	Onshore	Daughter Unit	3	0.5	11
Sum CCUS ZEN storage capacity in Poland					**8 885 Mt**	

12.2 Transport options

This section describes identified infrastructures that may be relevant for CO_2 transport in the Baltic Sea region.

12.2.1 Natural gas infrastructure

The following existing gas pipelines may be relevant for CO_2 transport:

Imatra-Mäntsälä1 and Imatra-Mäntsälä2

The two pipelines are located in Finland, as shown in Figure 12.16 and are owned and operated by GasGrid Finland Oy. The total length is 207.5 km with a diameter of 24”. This connection route is also being studied for hydrogen transportation under the Gasgrid Finland and Nordion Energi of Sweden collaboration project, titled "Nordic Hydrogen Route".

Nord Stream 1 and 2

The Nord Stream pipelines cross the Baltic Sea from Russia to Germany, for 1230 km. With a diameter of 48” and design pressure of 150/200 bar, one of the pipelines may be a good candidate for CO_2 transportation. The ownership of the pipelines is (on parent company level) Gazprom’s. Nord Stream 1 operation started in 2011, while Nord Stream 2 built in 2022 has not operated yet. Figure 12.17 highlights the Nord Stream connection.

South Arne - Nybro pipeline

Figure 12.18 presents the pipeline connection between South Arne (Syd-Arne) oil and gas field to the city of Nybro in Denmark with approximately 256 km. This is a 24” pipeline built in 1998 with a design pressure of 150 bar. A section of this connection is parallel to the Baltic Pipe gas pipeline. The South Arne – Nybro connection is already being studied for the carbon storage project Bifrost. The Bifrost project objective is to study the possibility of CO_2 storage in the depleted Harald gas fields, making the South Arne - Nybro pipeline a key infrastructure for the enterprise.

Figure 12.16 Identification of pipeline alternatives for CO_2 transport in the Baltic Sea region: The Finland - Imatra-Mäntsälä pipeline.

Figure 12.17 Identification of pipeline alternatives for CO_2 transport in the Baltic Sea region: The Germany - Russia - Nord Stream pipeline.

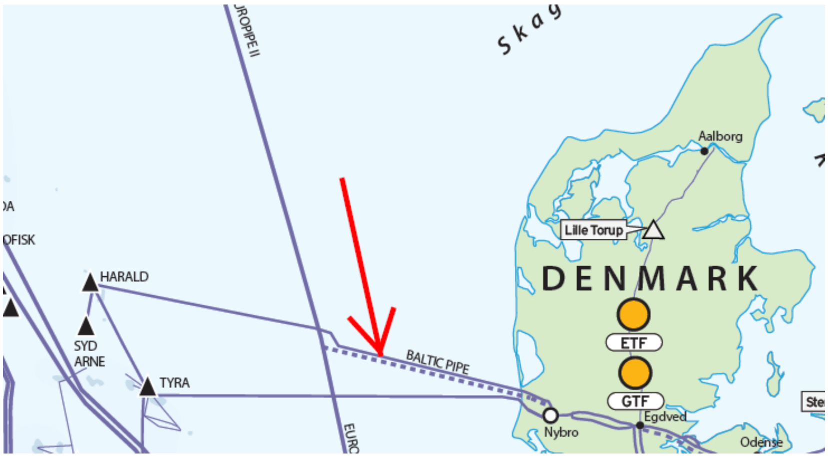

Figure 12.18 Identification of pipeline alternatives for CO_2 transport in the Baltic Sea region: The Denmark - South Arne - Nybro pipeline.

DEUDAN gas pipeline

The DEUDAN gas pipeline represented in Figure 12.19 connects Germany and Denmark through Jutland. It is a 24” pipeline with design pressure of 80/100 bar approximately. The pipeline is 111 km long and is owned by Gasunie and Open Grid Europe (parent companies). The pipeline operation started in 1982 and was expanded in 1996. This connection has been studied for hydrogen transportation as well. It is the first pipeline in Germany to carry a green hydrogen and natural gas blend.

Figure 12.19 Identification of pipeline alternatives for CO_2 transport in the Baltic Sea region. To the left: The Denmark - Germany - DEUDAN gas pipeline. To the right: The Germany – EUGAL and OPAL pipelines.

EUGAL and OPAL pipelines

Both pipelines, shown in Figure 12.19 are approximately 480 km with a diameter of 56”. OPAL started operating in 2011 while EUGAL was built to support the expected gas income from Nord Stream 2. Since Nord Stream 2 is not operating, there may be a possibility of using the EUGAL pipeline for CO_2 transportation. The pipeline is designed for a pressure of 100 bar.

Czech Republic-Slovakia pipelines

The pipelines shown in Figure 12.20 may be selected as well to collect CO_2 from Slovakia and Czech Republic to the EUGAL pipeline. The EUGAL pipeline would, in this scenario, transport the CO_2 to the Baltic region. The pipelines have a diameter of 48” and are designed for a pressure of 80 bar.

Additionally, we provide an overview of existing pipelines and ongoing projects (PCI) for natural gas infrastructure. The PCI Transparency Platform is the main source of information. The CO2LOS tool can be used to supplement the information related to ships and barges, including in-land waterways.

The main difference between the PCI Transparency Platform and the ENTSOG System Development Map is the fact that the first maps exclusively infrastructures classified as Projects of Common Interest, while the second has a broader scope. On the other hand, and oppositely to ENTSOG, the PCI Transparency Platform maps not only the gas infrastructure but oil, CO_2 and electricity infrastructure.

Natural gas infrastructure (PCI)

As shown in Figure 12.21, there are natural gas pipelines in operation in Denmark, Germany, Latvia and Lithuania. The most prominent feature in the map is the mentioned Nord Stream pipeline. This pipeline is no longer transporting natural gas from Russia to Germany and is closed indefinitely. New projects are planned in Denmark, Poland and Latvia.

Figure 12.20 Identification of pipeline alternatives for CO_2 transport in the Baltic Sea region: Czech Republic-Slovakia pipelines.

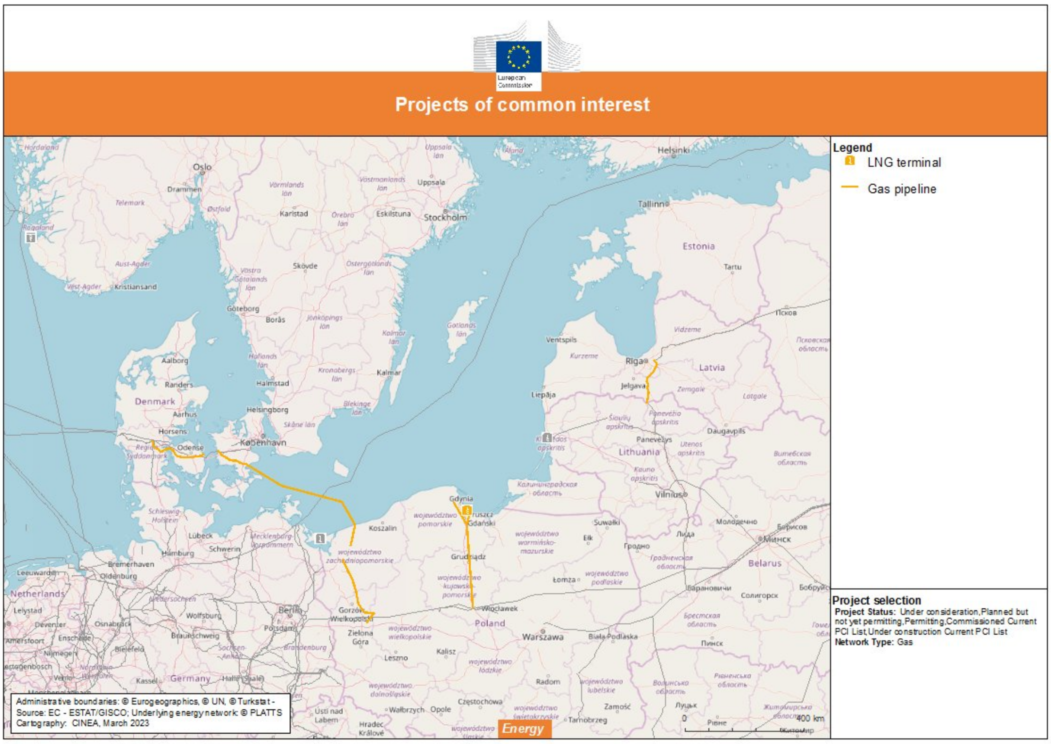

Figure 12.21 Baltic Sea region: Existing gas pipeline infrastructure is shown in black, while PCI projects under consideration are shown in yellow.

12.2.2 Oil infrastructure

A selection of the main oil pipelines for repurposing to CO_2 transportation in the Baltic region is shown below:

LatRosTrans pipeline

The LatRosTrans pipeline represented in Figure 12.22. Its length is approximately 340 km and consists of a section of the 54-year-old oil pipeline connecting multiple countries in Eastern Europe and Russia. Its diameter is approximately 24”. The pipeline was already studied for a gas pipeline conversion. A similar study may be conducted for CO_2 transportation.

Figure 12.22 Identification of pipeline alternatives for CO_2 transport in the Baltic Sea region: The Latvia - LatRosTrans pipeline.

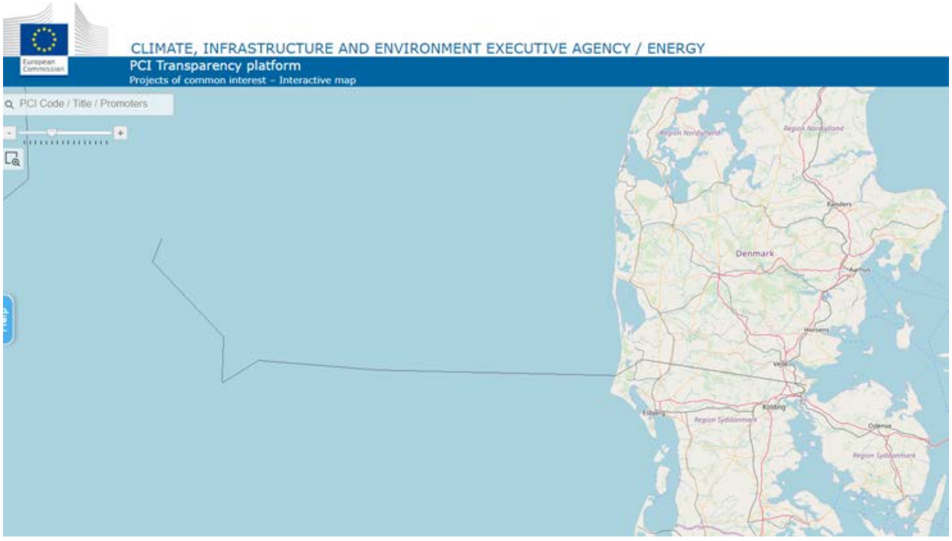

Figure 12.23 Identification of pipeline alternatives for CO_2 transport in the Baltic Sea region: The Denmark - Gorm Fredericia Oil Pipeline.

Gorm Fredericia Oil pipeline

The Gorm Fredericia Oil pipeline is an onshore and offshore pipeline of 20”, which runs from the Danish North Sea to the city of Fredericia for 330 km. This pipeline is also parallel to the South Arne - Nybro pipeline (Figure 12.23) and may be used as well to transport CO_2 to offshore storage locations such as depleted oil and gas fields.

13 Appendix D: Mediterranean Sea region

The Mediterranean Sea region defined in CCUS ZEN covers France, Spain, Italy, Greece, Türkiye and the Mediterranean Sea (Figure 13.1). In this section, CO_2 emissions and potential geological CO_2 storage sites of the Mediterranean Sea region are presented country wise. Note that only storage sites in south of France and in the eastern part of Spain have been included, as the project focus on the Mediterranean Sea region. Possible transport options in Türkiye are, in addition, presented.

13.1 Country wise CO_2 emissions and potential storage sites

The emissions and potential CO_2 storage sites are shown on maps and listed in tables. The emissions are grouped by industry sector in the tables, with the distinction between facilities which emit more than 100 000 tons per year, and the ones below 100 000 tons per year. Note that the emissions below 100 000 tons per year are far from complete, see Section 3.1 for details.

As the number of geological storage sites are limited, all are listed with their main attributes including storage type (deep saline aquifer or hydrocarbon field), whether they are located on-shore, off-shore or both, unit type and capacity. For definition of the attributes, see Appendix B. The storage capacity is estimated in the previous projects and publications listed in Table 13.1.

Figure 13.1 The CCUS ZEN Mediterranean Sea region: France, Spain, Italy, Greece, Türkiye and the Mediterranean Sea.

Table 13.1. **List of the sources for the capacity estimations** for the potential CO_2 storage sites identified by CCUS ZEN in the Baltic Sea region. # refers to the reference number used in the subsequent tables for geological storage sites.

#	Reference
9	Poulsen, N., Holloway, S., Neele, F., Smith, N.A. and Kirk, K. (2014). CO2STOP Final Report. Assessment of CO_2 storage potential in Europe-GEUS Rapport 2014-56. https://energy.ec.europa.eu/publications/assessment-co2-storage-potential-europe-co2stop_en
13	Veloso, F. M. L. (2021). Maturity level and confidence of storage capacities estimates in the promising regions. EU H2020 STRATEGY CCUS Project 837754, Report, pp 125.
14	Vangkilde-Pedersen, T., Anthonsen, K., Smith, N., Kirk, K., N, F., Van der Meer, B., Le Gallo, Y., Bossie-Codreanu, D., Wojcicki, A., Le Nindre, Y., Hendricks, C., Dalhoff, F., Christensen, N. (2009). Assessing European capacity for geological storage of carbon dioxide – the EU GeoCapacity project, Energy Procedia 1 (2009) 2663-2670.
15	Koukouzas, N., Tyrologou, P., Karapanos, D., Carneiro, J., Pereira, P., de Mesquita Lobo Veloso, F., Koutsovitis, P., Karkalis, C., Manoukain, E. and Karametou, R. (2021). Carbon Capture, Utilisation and Storage as a Defense Tool against Climate Change: Current Developments in West Macedonia (Greece), Energies 2021 Vol. 14 Issue 11 Pages 3321, DOI: 10.3390/en14113321
16	Bas, D. and Akpulat, O. (2019). Technical Assistance for Developed Analytical Basis for Formulating Strategies and Actions Towards Low Carbon Development – Turkey capacity Report. EuropeAid/136032/IH/SER/TR.

13.1.1 France

CO_2 emission sources and potential CO_2 storage sites in France are shown in Figure 13.2. Note that only storage structures in the south of France have been considered as CCUS ZEN focus on the Mediterranean Sea region. The emissions per industry sector are summarised in Table 13.2, while the potential storage sites are listed Table 13.3. Natura2000 areas are shown together with the potential storage sites in Figure 13.3.

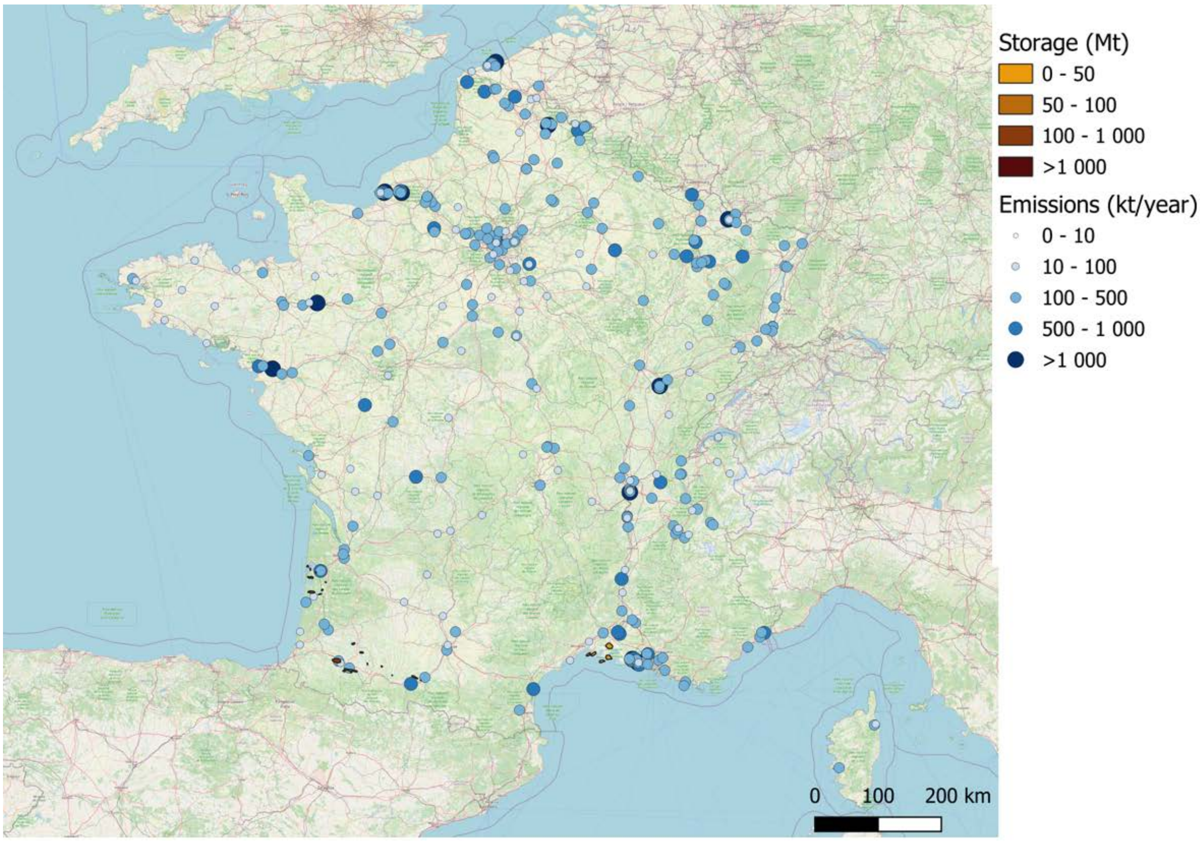

Figure 13.2 **France**: CO_2 emission sources and potential storage sites in the south part of the country.

Figure 13.3 **South of France**: Potential CO_2 storage sites and Natura2000 areas.

Table 13.2. **France: Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Power	13	696	48	24 610
Energy from waste	50	4 098	83	13 203
Iron & Steel	2	172	6	15 178
Chemicals (other)	2	111	22	11 212
Cement	1	50	21	9 453
Refineries	2	137	7	7 054
Other	5	352	22	6 075
Paper and pulp	1	85	15	5 588
Food & drink	4	295	13	2 684
Non-iron metals	1	17	8	1 883
Ammonia	0	0	3	1 490
Glass	5	406	6	842
Hydrogen	0	0	3	536
Oil & gas Processing	1	27	1	187
Sum	**87**	**6 446**	**258**	**99 995**

Table 13.3. **France: Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 13.1 with capacity calculations.

Storage name	Storage type	On-shore/ off-shore	Unit type	SRL level	Capacity [Mt]	Ref.
Lacq	Hydrocarbon Field	Onshore	Storage Unit	3	367	14
Parentis	Hydrocarbon Field	Onshore	Storage Unit	3	126	14
Cazaux	Hydrocarbon Field	Onshore	Storage Unit	3	52	14
Structure de Mas-de-Madame	Deep Saline Aquifer	Onshore	Prospect Unit	2	37	13
Haut d'Abaron	Deep Saline Aquifer	Onshore	Prospect Unit	2	34	13
Vic Bilh	Hydrocarbon Field	Onshore	Storage Unit	3	24	14
Les arbousiers	Hydrocarbon Field	Onshore	Storage Unit	3	17	14
Lagrave	Hydrocarbon Field	Onshore	Storage Unit	3	16	14
Structure de Saintes-Maries-de-la-Mer	Deep Saline Aquifer	Onshore	Prospect Unit	2	14	13
Pecorade	Hydrocarbon Field	Onshore	Storage Unit	3	13	14
Mothes	Hydrocarbon Field	Onshore	Storage Unit	3	9	14
St Marcet Proupiary	Hydrocarbon Field	Onshore	Storage Unit	3	6	14
Meillon 1	Hydrocarbon Field	Onshore	Storage Unit	3	5	14
Les pins	Hydrocarbon Field	Onshore	Storage Unit	3	3	14
Lucats-Cabeil 2	Hydrocarbon Field	Onshore	Storage Unit	3	3	14
Lameac	Hydrocarbon Field	Onshore	Storage Unit	3	2	14
Meillon 2	Hydrocarbon Field	Onshore	Storage Unit	3	2	14
Courbey	Hydrocarbon Field	Onshore	Storage Unit	3	2	14
Lucats-Cabeil 1	Hydrocarbon Field	Onshore	Storage Unit	3	2	14
Lugos	Hydrocarbon Field	Onshore	Storage Unit	3	1	14
Tamaris	Hydrocarbon Field	Onshore	Storage Unit	3	1	14
Structure de Cicendele	Deep Saline Aquifer	Onshore	Prospect Unit	2	1	13
Bonrepos montastruc	Hydrocarbon Field	Onshore	Storage Unit	3	1	14
Auzas	Hydrocarbon Field	Onshore	Storage Unit	3	1	14
Sum CCUS ZEN storage capacity in the south part of France					**739 Mt**	

13.1.2 Spain

CO_2 emission sources and potential CO_2 storage sites in Spain is shown in Figure 13.4. Note that only the storage sites in the eastern part of Spain have been considered, as CCUS ZEN focus on the Mediterranean Sea region. The emissions per industry sector are summarised in Table 13.4, while the potential storage sites are listed Table 13.5. Natura2000 areas are shown together with the potential storage sites in Figure 13.5.

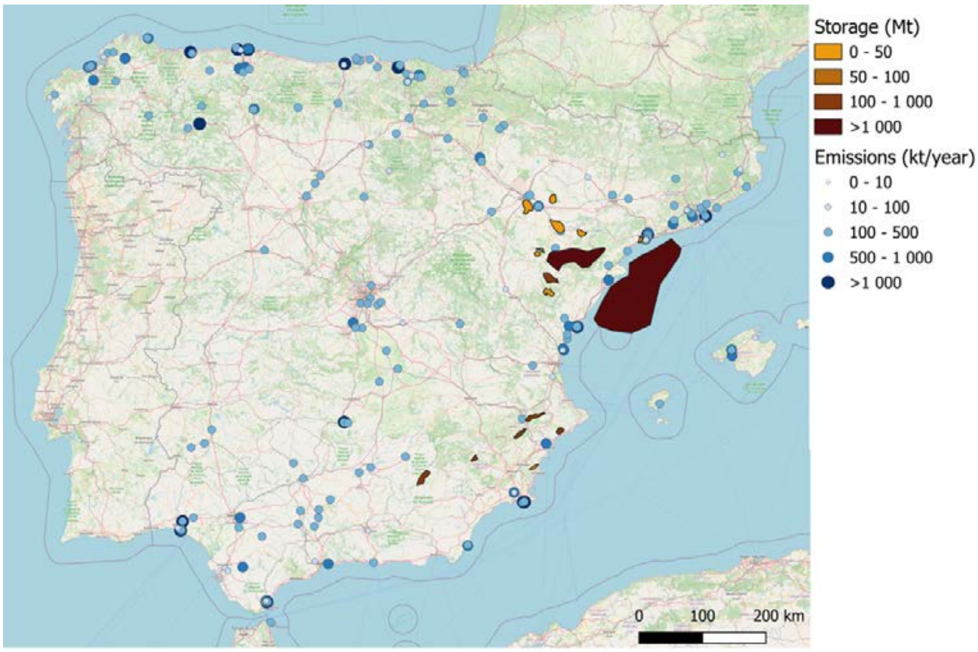

Figure 13.4 **Spain**: CO_2 emission sources and potential CO_2 storage sites.

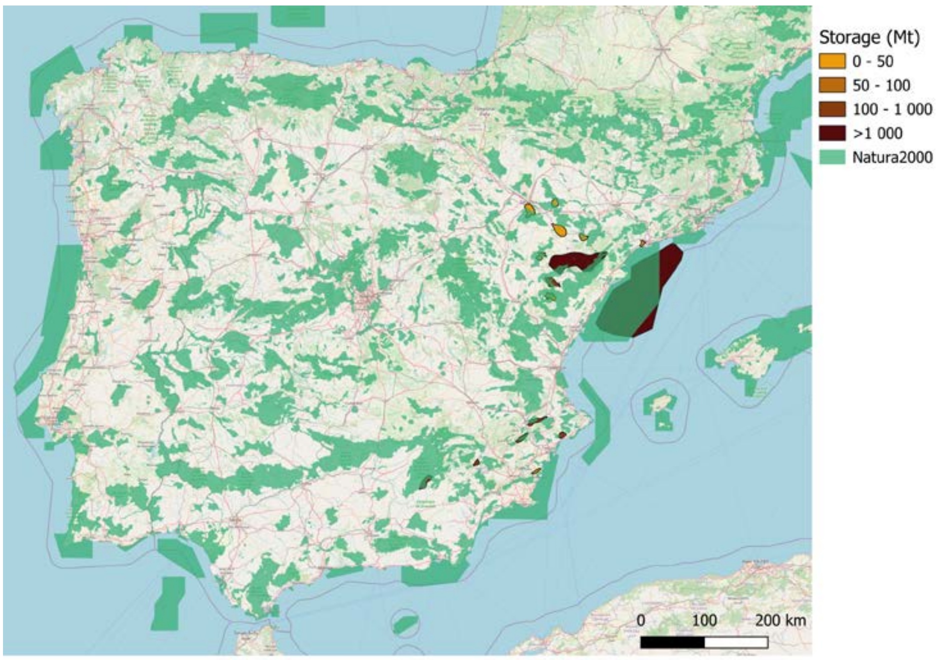

Figure 13.5 **Eastern part of Spain**: Potential CO_2 storage sites and Natura2000 areas.

Table 13.4. **Spain: Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Power	11	579	85	39 536
Cement	2	89	27	13 339
Refineries	1	32	8	12 682
Iron & Steel	1	93	8	6 413
Chemicals (other)	4	298	18	5 544
Paper and pulp	3	189	12	3 301
Other	2	193	12	2 521
Non-iron metals	2	108	6	2 392
Energy from waste	2	151	11	2 057
Food & drink	3	265	4	1 013
Glass	3	284	5	590
Ammonia	0	0	2	739
Hydrogen	0	0	1	348
Sum	**34**	**2 281**	**199**	**90 475**

Table 13.5. **Spain: Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 13.1 with capacity calculations.

Storage name	Storage type	Onshore / offshore	Unit type	SRL level	Capacity [Mt]	Ref.
Ebro Offshore	Deep Saline Aquifer	Offshore	Storage Unit	2	1 785	14
Zona Enlace-Bunt	Deep Saline Aquifer	Onshore	Storage Unit	2	1 213	9
Sierra Seca	Deep Saline Aquifer	Onshore	Storage Unit	2	487	9
Murcia B-1	Deep Saline Aquifer	Onshore	Storage Unit	2	414	9
Macaroba	Deep Saline Aquifer	Onshore	Storage Unit	2	225	9
Sierra de Benejama (Dogger)	Deep Saline Aquifer	Onshore	Storage Unit	2	191	9
Sierra de Salinas (Dogger)	Deep Saline Aquifer	Onshore	Storage Unit	2	180	9
Maestrazgo-3	Deep Saline Aquifer	Onshore	Daughter Unit	3	103	13
Caspe Mayals	Deep Saline Aquifer	Onshore	Daughter Unit	3	42	13
Obón-Oliete A	Deep Saline Aquifer	Onshore	Storage Unit	2	42	9
Lopin	Deep Saline Aquifer	Onshore	Daughter Unit	3	29	13
Obón-Oliete B	Deep Saline Aquifer	Onshore	Storage Unit	2	25	9
Monegrillo	Deep Saline Aquifer	Onshore	Daughter Unit	3	25	13
Maestrazgo-2	Deep Saline Aquifer	Onshore	Daughter Unit	3	22	9
Reus	Deep Saline Aquifer	Onshore	Daughter Unit	3	21	13
Maestrazgo-1	Deep Saline Aquifer	Onshore	Daughter Unit	3	13	9
Benejuzar-Rojales	Deep Saline Aquifer	Onshore	Storage Unit	2	0.4	9
Sum CCUS ZEN storage capacity in the eastern part of Spain					**4 816 Mt**	

13.1.3 Italy

CO_2 emission sources and potential CO_2 storage sites in Italy is shown in Figure 13.6. The emissions per industry sector are summarised in Table 13.4, while the potential storage sites are listed Table 13.7. Natura2000 areas are shown together with the potential storage sites in Figure 13.7

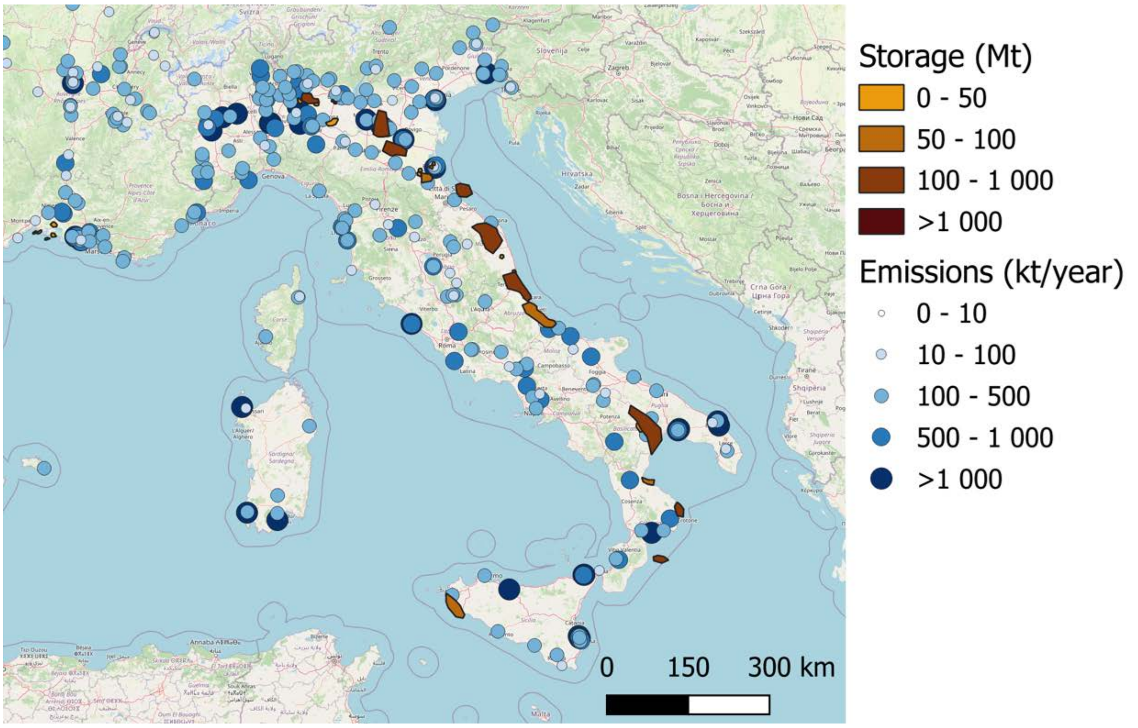

Figure 13.6 **Italy**: CO_2 emission sources and potential CO_2 storage sites.

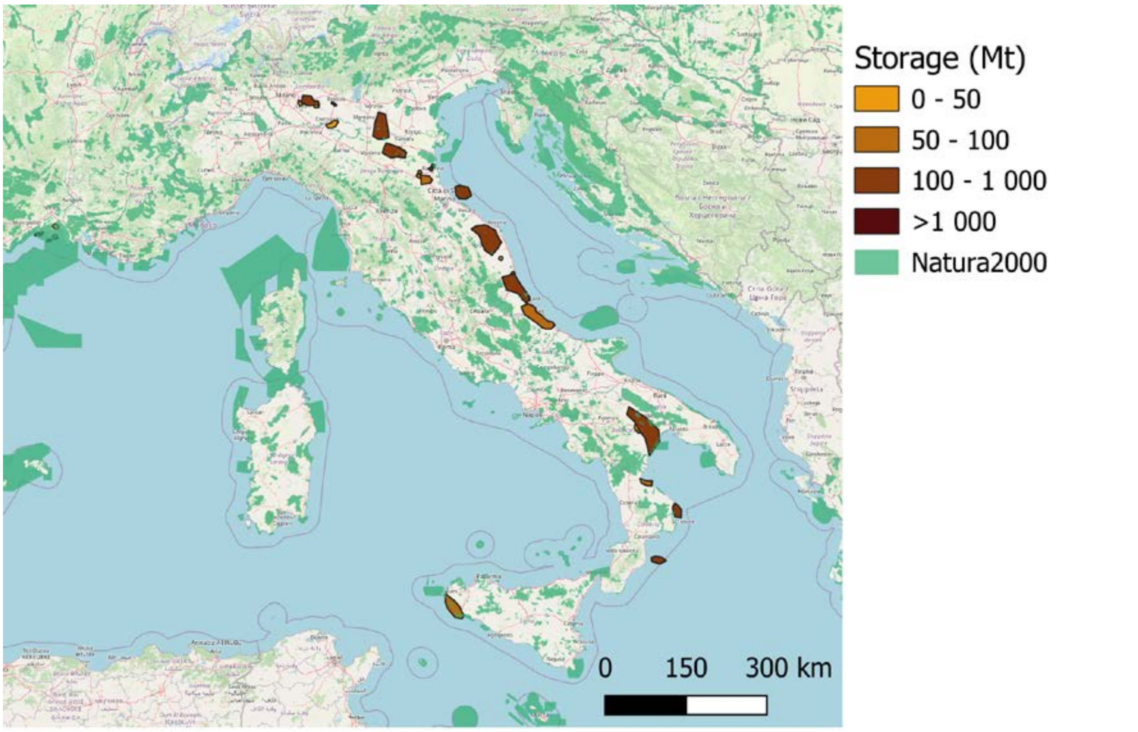

Figure 13.7 **Italy**: Potential CO_2 storage sites and Natura2000 areas.

Table 13.6. **Italy: Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Power	9	579	80	68 679
Refineries	0	0	14	17 626
Cement	4	138	30	12 727
Iron & Steel	3	143	9	7 227
Energy from waste	6	537	31	5 612
Chemicals (other)	1	18	11	3 598
Other	2	154	8	1 483
Paper and pulp	2	171	5	771
Glass	1	85	7	776
Food & drink	0	0	4	753
Ammonia	0	0	1	647
Oil & gas Processing	2	133	1	135
Non-iron metals	0	0	1	259
Hydrogen	0	0	1	125
Water/sewage treatment	0	0	1	119
Sum	**30**	**1 958**	**204**	**120 538**

Table 13.7. **Italy: Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 13.1 with capacity calculations.

Storage name	Storage type	Onshore / offshore	Unit type	SRL level	Capacity [Mt]	Ref.
Lombardia 3	Deep Saline Aquifer	Onshore	Storage Unit	2	825	14
Abruzzi 1	Deep Saline Aquifer	Onshore	Storage Unit	3	778	14
Basilicata 1	Deep Saline Aquifer	Onshore	Storage Unit	3	766	14
Emilia 1	Deep Saline Aquifer	Onshore	Storage Unit	2	650	14
Marche 1	Deep Saline Aquifer	Onshore	Storage Unit	3	562	14
Emilia mare	Deep Saline Aquifer	Offshore	Storage Unit	2	234	14
Calabria mare 1	Deep Saline Aquifer	Offshore	Storage Unit	3	206	14
Calabria mare 2	Deep Saline Aquifer	Offshore	Storage Unit	3	187	14
Lombardia 1	Deep Saline Aquifer	Onshore	Storage Unit	2	106	14
Calabria 1	Deep Saline Aquifer	Onshore-Offshore	Storage Unit	3	80	14
Sicilia 1	Deep Saline Aquifer	Onshore	Storage Unit	2	71	14
Ravena terra	Hydrocarbon Field	Onshore	Storage Unit	3	70	14
Emilia 2	Deep Saline Aquifer	Onshore	Storage Unit	2	57	14
Abruzzi 2	Deep Saline Aquifer	Onshore	Storage Unit	3	55	14
Cugno le macine	Hydrocarbon Field	Onshore	Storage Unit	2	18	14
Lombardia 2	Deep Saline Aquifer	Onshore	Storage Unit	2	10	14
Cotignola	Hydrocarbon Field	Onshore	Storage Unit	2	7	14
S. Potito	Hydrocarbon Field	Onshore	Storage Unit	2	4	14
Leno	Hydrocarbon Field	Onshore	Storage Unit	2	3	14
Bagnolo mella	Hydrocarbon Field	Onshore	Storage Unit	2	3	14
Piadena est	Hydrocarbon Field	Onshore	Storage Unit	2	3	14
Porto cosini terra	Hydrocarbon Field	Onshore	Storage Unit	3	2	14
S. Benedetto	Hydrocarbon Field	Onshore	Storage Unit	3	2	14
Romarengo	Hydrocarbon Field	Onshore	Storage Unit	2	1	14
Rapagnano	Hydrocarbon Field	Onshore	Storage Unit	3	0.4	14
Sum CCUS ZEN storage capacity in Italy					**4 699 Mt**	

13.1.4 Greece

CO_2 emission sources and potential CO_2 storage sites in Greece is shown in Figure 13.8. The emissions per industry sector are summarised in

Table 13.8, while the potential storage sites are listed Table 13.9 Natura2000 areas are shown together with the potential storage sites in Figure 13.9

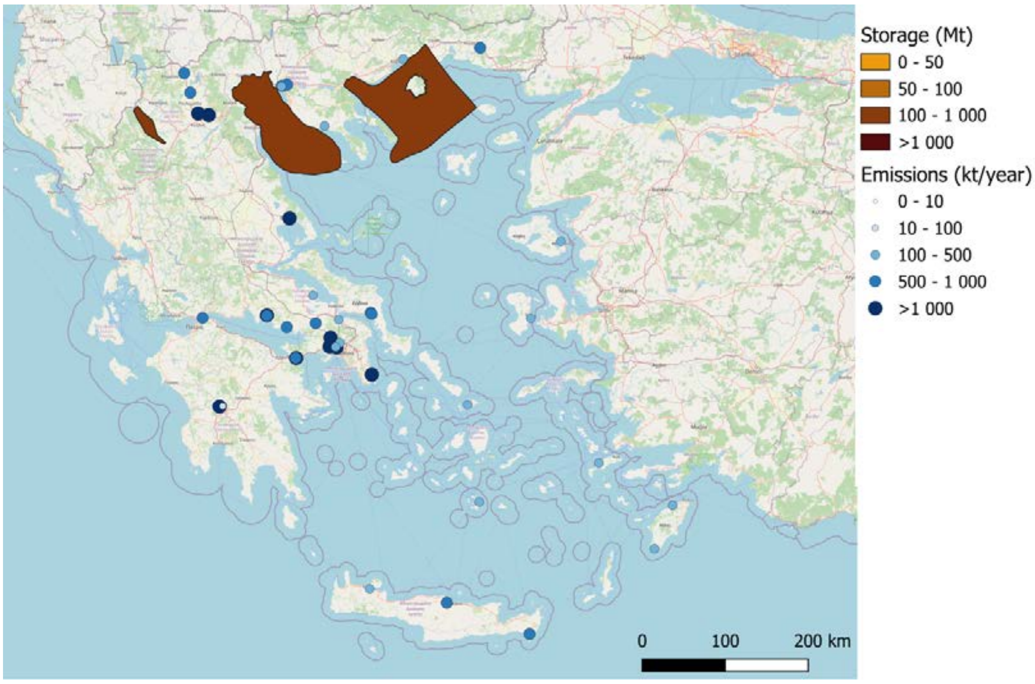

Figure 13.8 **Greece**: CO_2 emission sources and potential CO_2 storage sites.

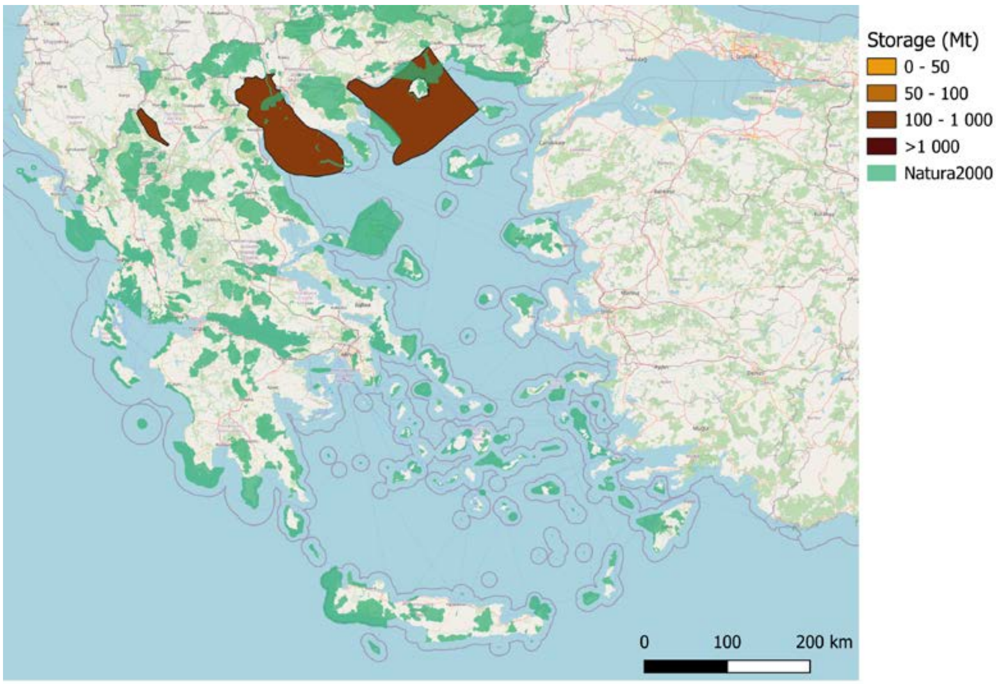

Figure 13.9 **Greece**: Potential CO_2 storage sites and Natura2000 areas.

Table 13.8. **Greece: Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kt/year		Facilities with CO_2 emissions above 100 kt/year	
	Number of facilities	CO_2 emissions [kt/year]	Number of facilities	CO_2 emissions [kt/year]
Power	1	57	22	18 793
Refineries	0	0	6	7 520
Cement	0	0	6	4 962
Other	0	0	2	440
Iron & Steel	0	0	1	242
Ammonia	0	0	1	183
Non-iron metals	0	0	1	102
Sum	**1**	**57**	**39**	**32 242**

Table 13.9. **Greece: Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 13.1 with capacity calculations.

Storage name	Storage type	Onshore / offshore	Unit type	SRL level	Capacity [Mt]	Ref.
Mesohellenic basin	Deep Saline Aquifer	Onshore	Storage Unit	2	1 150	15
Prinos basin	Deep Saline Aquifer	Offshore	Storage Unit	2	1 000	14
W Thessaloniki-korifi	Deep Saline Aquifer	Onshore-Offshore	Storage Unit	2	950	14
Prinos	Hydrocarbon Field	Offshore	Storage Unit	3	31	14
Structural of Loudias	Deep Saline Aquifer	Onshore	Storage Unit	2	28	14
Structural of Alexandria	Deep Saline Aquifer	Onshore	Storage Unit	2	11	14
South Kavala	Hydrocarbon Field	Offshore	Storage Unit	3	4	14
Sum CCUS ZEN storage capacity in Greece					**3 174 Mt**	

13.1.5 Türkiye

CO_2 emission sources and potential CO_2 storage sites in Türkiye is shown in Figure 13.10. Most of the oil and gas reservoirs which are considered as potential CO_2 storage sites are in the south-eastern part of Türkiye. Their coordinates are mostly taken from the journals of Petroleum Affairs when available (PIGM, 1997). Surface areas of the fields could not be provided since public data of exact boundaries of the fields are not available. They are therefore only shown as circles in Figure 13.10.

The emissions per industry sector are summarised in Table 13.10, while the potential storage sites are listed Table 13.11

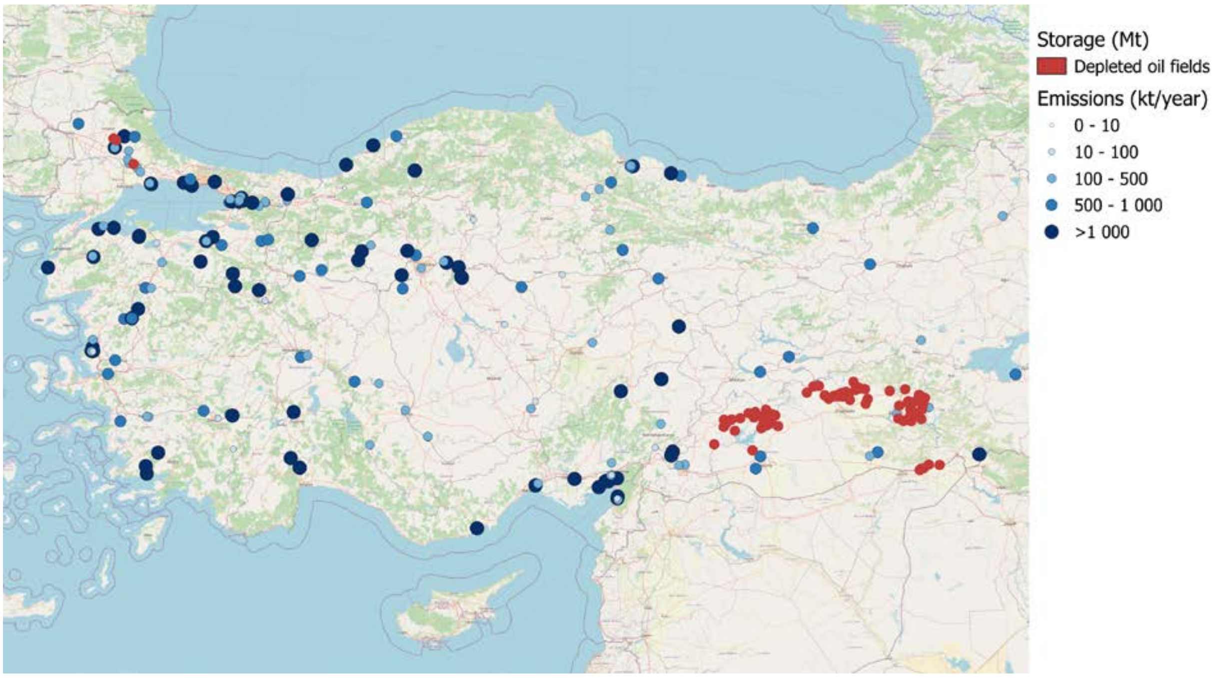

Figure 13.10 **Türkiye**: CO_2 emission sources and potential CO_2 storage sites (red circles).

Table 13.10. **Türkiye: Emission sources per industry sector** identified by CCUS ZEN. The industrial sectors are ranked from highest to lowest emissions. The mapping methodology used, including how emissions above and below 100 kton/year is calculated, is described in Section 3.1

Industry sector	Facilities with CO_2 emissions below 100 kton/year		Facilities with CO_2 emissions above 100 kton/year	
	Number of facilities	CO_2 emissions [kton/year]	Number of facilities	CO_2 emissions [kton/year]
Power	9	499	99	277 889
Cement	2	84	54	48 006
Iron & Steel	4	372	16	23 523
Refineries	0	0	5	6 031
Chemicals (other)	0	0	1	2 439
Sum	**15**	**955**	**175**	**357 888**

Table 13.11. **Türkiye**: **Possible CO_2 storage sites** identified by CCUS ZEN. The storage sites are ranked by highest to lowest storage capacity. The column named "Ref." refers to the numbered references listed in Table 13.1 with capacity calculations.

Storage name	Storage type	Onshore / offshore	Unit type	SRL level	Capacity [Mt]	Ref.
BATI RAMAN	Hydrocarbon Field	Onshore	Storage Unit	3	17.444	16
BEYKAN	Hydrocarbon Field	Onshore	Storage Unit	3	13.587	16
KURKAN	Hydrocarbon Field	Onshore	Storage Unit	3	8.252	16
RAMAN	Hydrocarbon Field	Onshore	Storage Unit	3	8.127	16
Karakuş	Hydrocarbon Field	Onshore	Storage Unit	3	7.121	16
Kuzey Karakuş	Hydrocarbon Field	Onshore	Storage Unit	3	4.965	16
Barbeş	Hydrocarbon Field	Onshore	Storage Unit	3	4.037	16
YENİKÖY (DERDERE)	Hydrocarbon Field	Onshore	Storage Unit	3	3.520	16
Güney Karakuş	Hydrocarbon Field	Onshore	Storage Unit	3	2.807	16
MALATEPE	Hydrocarbon Field	Onshore	Storage Unit	3	2.059	16
Adıyaman	Hydrocarbon Field	Onshore	Storage Unit	3	1.939	16
Cendere	Hydrocarbon Field	Onshore	Storage Unit	3	1.870	16
ÇAMURLU	Hydrocarbon Field	Onshore	Storage Unit	3	1.548	16
Çemberlitaş	Hydrocarbon Field	Onshore	Storage Unit	3	1.487	16
GARZAN-B	Hydrocarbon Field	Onshore	Storage Unit	3	1.486	16
BATI KOZLUCA	Hydrocarbon Field	Onshore	Storage Unit	3	1.430	16
Beşikli-Akgün	Hydrocarbon Field	Onshore	Storage Unit	3	1.378	16
DOĞU YATIR	Hydrocarbon Field	Onshore	Storage Unit	3	1.345	16
GÜNEY SARICAK	Hydrocarbon Field	Onshore	Storage Unit	3	1.303	16
MAĞRİP	Hydrocarbon Field	Onshore	Storage Unit	3	1.293	16
Kastel	Hydrocarbon Field	Onshore	Storage Unit	3	1.226	16
Tokaris	Hydrocarbon Field	Onshore	Storage Unit	3	1.182	16
GARZAN-C	Hydrocarbon Field	Onshore	Storage Unit	3	1.104	16
İkizce	Hydrocarbon Field	Onshore	Storage Unit	3	1.057	16
SİLİVANKA (GARZAN)	Hydrocarbon Field	Onshore	Storage Unit	3	0.916	16
GÜNEY DİNÇER	Hydrocarbon Field	Onshore	Storage Unit	3	0.830	16
Doğu Beşikli	Hydrocarbon Field	Onshore	Storage Unit	3	0.782	16
SİLİVANKA (BELOKA)	Hydrocarbon Field	Onshore	Storage Unit	3	0.732	16
GÜNEY ŞAHABAN	Hydrocarbon Field	Onshore	Storage Unit	3	0.731	16

ÇELİKLİ	Hydrocarbon Field	Onshore	Storage Unit	3	0.703	16
KATİN	Hydrocarbon Field	Onshore	Storage Unit	3	0.688	16
GERMİK	Hydrocarbon Field	Onshore	Storage Unit	3	0.676	16
GÜNEY KAYAKÖY-DERDERE	Hydrocarbon Field	Onshore	Storage Unit	3	0.571	16
Batı Fırat	Hydrocarbon Field	Onshore	Storage Unit	3	0.510	16
SARICAK	Hydrocarbon Field	Onshore	Storage Unit	3	0.494	16
BAYSU	Hydrocarbon Field	Onshore	Storage Unit	3	0.488	16
Elbeyi	Hydrocarbon Field	Onshore	Storage Unit	3	0.488	16
Şambayat	Hydrocarbon Field	Onshore	Storage Unit	3	0.483	16
Çaylarbaşı	Hydrocarbon Field	Onshore	Storage Unit	3	0.460	16
Bozhüyük	Hydrocarbon Field	Onshore	Storage Unit	3	0.412	16
GÜNEY KURKAN	Hydrocarbon Field	Onshore	Storage Unit	3	0.383	16
ÇAKILLI	Hydrocarbon Field	Onshore	Storage Unit	3	0.347	16
KARTALTEPE	Hydrocarbon Field	Onshore	Storage Unit	3	0.346	16
GÜNEY KIRTEPE	Hydrocarbon Field	Onshore	Storage Unit	3	0.330	16
Bozova	Hydrocarbon Field	Onshore	Storage Unit	3	0.278	16
KARACAN	Hydrocarbon Field	Onshore	Storage Unit	3	0.262	16
DERİN BARBEŞ	Hydrocarbon Field	Onshore	Storage Unit	3	0.243	16
İKİZTEPE	Hydrocarbon Field	Onshore	Storage Unit	3	0.232	16
Yananköy	Hydrocarbon Field	Onshore	Storage Unit	3	0.212	16
BATI MALATEPE	Hydrocarbon Field	Onshore	Storage Unit	3	0.208	16
Ozan Sungurlu	Hydrocarbon Field	Onshore	Storage Unit	3	0.208	16
OYUKTAŞ	Hydrocarbon Field	Onshore	Storage Unit	3	0.200	16
Piyanko	Hydrocarbon Field	Onshore	Storage Unit	3	0.189	16
Güney Hazro	Hydrocarbon Field	Onshore	Storage Unit	3	0.179	16
SİLİVANKA SİNAN	Hydrocarbon Field	Onshore	Storage Unit	3	0.174	16
Toytepe	Hydrocarbon Field	Onshore	Storage Unit	3	0.174	16
Kuzey Osmancık	Hydrocarbon Field	Onshore	Storage Unit	3	0.169	16
Batı Şelmo	Hydrocarbon Field	Onshore	Storage Unit	3	0.152	16
BEKTAŞ	Hydrocarbon Field	Onshore	Storage Unit	3	0.150	16
YENİKÖY (SABUNSUYU)	Hydrocarbon Field	Onshore	Storage Unit	3	0.150	16
Gölgeli	Hydrocarbon Field	Onshore	Storage Unit	3	0.149	16
DOĞU SINIRTEPE	Hydrocarbon Field	Onshore	Storage Unit	3	0.140	16
Doğu Karakuş	Hydrocarbon Field	Onshore	Storage Unit	3	0.125	16

GÜNEY KAYAKÖY-SABUNSUYU	Hydrocarbon Field	Onshore	Storage Unit	3	0.118	16
YEMİŞLİK	Hydrocarbon Field	Onshore	Storage Unit	3	0.110	16
Doğu Şambayat	Hydrocarbon Field	Onshore	Storage Unit	3	0.107	16
Batı Gökçe	Hydrocarbon Field	Onshore	Storage Unit	3	0.105	16
Deveçatak	Hydrocarbon Field	Onshore	Storage Unit	3	0.101	16
KAPIKAYA	Hydrocarbon Field	Onshore	Storage Unit	3	0.097	16
Yolaçan	Hydrocarbon Field	Onshore	Storage Unit	3	0.093	16
Yalankoz	Hydrocarbon Field	Onshore	Storage Unit	3	0.084	16
KUZEY ARIKAYA	Hydrocarbon Field	Onshore	Storage Unit	3	0.072	16
Karaali	Hydrocarbon Field	Onshore	Storage Unit	3	0.068	16
DOĞU SİLİVANKA	Hydrocarbon Field	Onshore	Storage Unit	3	0.067	16
YATIR	Hydrocarbon Field	Onshore	Storage Unit	3	0.059	16
ARIKAYA	Hydrocarbon Field	Onshore	Storage Unit	3	0.057	16
Doğu Çemberlitaş	Hydrocarbon Field	Onshore	Storage Unit	3	0.056	16
MEHMETDERE	Hydrocarbon Field	Onshore	Storage Unit	3	0.052	16
Akpınar	Hydrocarbon Field	Onshore	Storage Unit	3	0.051	16
Beyçayır	Hydrocarbon Field	Onshore	Storage Unit	3	0.049	16
Didan	Hydrocarbon Field	Onshore	Storage Unit	3	0.047	16
Bölükyayla	Hydrocarbon Field	Onshore	Storage Unit	3	0.044	16
Sebyan	Hydrocarbon Field	Onshore	Storage Unit	3	0.041	16
GÜZELDERE	Hydrocarbon Field	Onshore	Storage Unit	3	0.040	16
Batı Haznemir	Hydrocarbon Field	Onshore	Storage Unit	3	0.037	16
Beyaz Çeşme	Hydrocarbon Field	Onshore	Storage Unit	3	0.035	16
Batı Altıntop	Hydrocarbon Field	Onshore	Storage Unit	3	0.034	16
BOSTANPINAR	Hydrocarbon Field	Onshore	Storage Unit	3	0.031	16
Kayayolu	Hydrocarbon Field	Onshore	Storage Unit	3	0.031	16
Sezgin	Hydrocarbon Field	Onshore	Storage Unit	3	0.030	16
YANARSU	Hydrocarbon Field	Onshore	Storage Unit	3	0.025	16
Kedil	Hydrocarbon Field	Onshore	Storage Unit	3	0.023	16
HANÇERLİ	Hydrocarbon Field	Onshore	Storage Unit	3	0.023	16
GÜNEY RAMAN	Hydrocarbon Field	Onshore	Storage Unit	3	0.021	16
Güney Sarık	Hydrocarbon Field	Onshore	Storage Unit	3	0.019	16
Eskitaş	Hydrocarbon Field	Onshore	Storage Unit	3	0.019	16
GARZAN-A	Hydrocarbon Field	Onshore	Storage Unit	3	0.018	16

Batı Güven	Hydrocarbon Field	Onshore	Storage Unit	3	0.016	16
Kuzey Akçeli	Hydrocarbon Field	Onshore	Storage Unit	3	0.015	16
Lilan	Hydrocarbon Field	Onshore	Storage Unit	3	0.014	16
Altıntop	Hydrocarbon Field	Onshore	Storage Unit	3	0.013	16
Doğu Başpınar	Hydrocarbon Field	Onshore	Storage Unit	3	0.013	16
Çiksor	Hydrocarbon Field	Onshore	Storage Unit	3	0.012	16
Miyadin	Hydrocarbon Field	Onshore	Storage Unit	3	0.011	16
Kuzey İkizce	Hydrocarbon Field	Onshore	Storage Unit	3	0.007	16
Batı Sarısöğüt	Hydrocarbon Field	Onshore	Storage Unit	3	0.007	16
Bakacak	Hydrocarbon Field	Onshore	Storage Unit	3	0.005	16
Dikmetaş	Hydrocarbon Field	Onshore	Storage Unit	3	0.003	16
Sum CCUS ZEN storage capacity in Türkiye					**109 Mt**	

13.2 Transport options in Türkiye

This chapter describes identified infrastructures that may be relevant for CO_2 transport in Türkiye.

13.2.1 Natural gas infrastructure

A detailed description of operational pipelines in Türkiye is presented below. This overview is based on information from the Turkish Ministry of Energy and Natural Resources.

Russia-Türkiye Natural gas pipeline

In 1984, the Republic of Türkiye and the former Soviet Union signed an agreement. In 1986, a 25-year Natural Gas Purchase-Sale Agreement was signed between BOTAS and SoyuzGazExport. Natural gas imports started after 1987 and reached a maximum of 6 billion m^3/year in 1993. The Russia-Türkiye Gas Pipeline, which enters Türkiye at Malkoçlar from the Bulgarian borderline and reaches Ankara through Hamitabat, Ambarlı, İstanbul, İzmit, Bursa, Eskişehir has a length of 845 km.

Russia-Samsun-Ankara Natural Gas Transmission Line (Blue Stream)

After the 25-year Natural Gas Purchase-Sale Agreement signed between BOTAS and Gazexport in 1997, Blue Stream Gas Pipeline has been constructed as three main parts; a pipeline system on the Russian territory between the Izobilnoye-Djubga with a total length of 370 km (308 km-56" pipeline and 62 km- 48" pipeline), a pipeline system in the Black Sea pass between Djubga and Samsun (2 parallel lines of 24" diameter, each about 390 km in length) and a pipeline system in the territory of Türkiye, with a total length of 501 km (48” pipeline). The Turkish part of the pipeline, which was started to be operated in 2003, starts from Samsun and reaches Ankara via Amasya, Corum, and Kirikkale, having an additional pipe splitting from Corum Sungurlu to Duzce.

Eastern Anatolian Natural Gas Main Transmission Line (Iran – Türkiye)

The Eastern Anatolian Natural Gas Main Transmission Line was constructed after the Natural Gas Purchase-Sale Agreement signed between Iran and Türkiye in 1996 to transport natural gas imported from Iran. The pipeline has a total length of 1 491 km and a diameter of ranging between 48” and 16”. It extends from Dogubayazit to Ankara via Erzurum, Sivas and Kayseri, and to Seydisehir, Konya with a branch via Kayseri. The gas purchase from Iran was started in 2001 through the line.

Baku-Tblisi-Erzurum Natural Gas Pipeline (BTE)

The Baku-Tbilisi-Erzurum Natural Gas Pipeline was constructed in 2001 after the Türkiye-Azerbaijan Intergovernmental Agreement to transport the natural gas produced from the Shah Deniz field of Azerbaijan to Türkiye, the gas flow through the pipeline, which has a total length of 980 km and a diameter of 42" was started.

Trans-Anatolia Natural Gas Pipeline (TANAP) project

The Trans-Anatolia Natural Gas Pipeline (TANAP) Project is based on the Intergovernmental Agreement between the Government of the Republic of Türkiye and the Government of the Republic of Azerbaijan, and the annex of the Host Government Agreement signed in 2012. The aim of the project is to transport the natural gas produced in Azerbaijan to Türkiye and through Türkiye to Europe. TANAP starts in the village of Turkgozu in the Posof district of Ardahan province on the Turkish-Georgian border and passes through 20 provinces in Türkiye from Ardahan to Ipsala in Edirne. TANAP, then, connects to TAP Natural Gas Pipeline, which carries natural gas to Europe. TANAP project aimed at the construction of a pipeline having a total length of 1 850 km with a maximum capacity of 32 billion m^3 per year. In 2018, first gas delivery to BOTAS and in 2020, first gas delivery to TAP were supplied.

Türkiye-Greece Natural Gas Interconnection (ITG)

The aim of the Türkiye-Greece Natural Gas Interconnection (ITG) Project is to transport natural gas from Türkiye to Greece in the context of the European Union INOGATE (Interstate Oil and Gas Transport to Europe) Program regarding the agreement signed between Türkiye and Greece in 2003. A Natural Gas Sale Purchase Agreement regarding natural gas export for 15 years has also been signed between BOTAS and DEPA (Public Gas Corporation of Greece). In 2007, the project was extended to Italy from Greece with an intergovernmental agreement signed between Türkiye, Greece, and Italy.

TurkStream Gas Pipeline Project

With the intergovernmental agreement signed between the Government of the Republic of Türkiye and the Government of the Russian Federation in 2016, TurkStream Gas Pipeline Project was started to construct a pipeline system with a maximum capacity of 31.5 billion m^3 per year, consisting of an offshore and an onshore section. The first gas flow through the pipeline, which aims to supply natural gas from the Russian Federation to Türkiye as well as to Europe through Türkiye started in 2020.

Due to the Ukrainian crisis, the demand for natural gas in Europe other than Russia has increased and Türkiye's location makes it a potential hub for several options.

Qatar-Türkiye pipeline

This line could connect Qatar's gas reserves (24.7 trillion cubic meters, BP 2022) to Europe.

Southern Gas Corridor

The currently active pipeline transports Azerbaijani gas to Italy. The pipeline is likely to double its capacity to 20 billion cubic meters.

Trans-Caspian Gas Pipeline

The proposed pipeline aims to connect Turkmenistan's gas fields to the pipeline network in Azerbaijan and then via Georgia and Türkiye to Europe.

Israel-Türkiye-EU Pipeline

The large gas discoveries made by Israel in the Tamar and Leviathan fields, and this gas could be transported to Europe via a subsea pipeline to Türkiye first.

13.2.2 Oil infrastructure

Below is additional description of some of the pipelines that are connecting Türkiye to Iraq and Azerbaijan:

Iraq-Türkiye Crude Oil Pipeline

This pipeline was built in 1973 to transport the crude oil produced in Kirkuk and other production areas of Iraq to the Ceyhan Marine Terminal within the framework of the Crude Oil Pipeline Agreement signed between the Governments of the Republic of

Türkiye and Iraq. The first tanker loading was carried out in 1977. An amendment agreement was signed between Türkiye and Iraq for the renewal and extension of the Kirkuk-Yumurtalik Crude Oil Pipeline Agreement and its related protocols for 15 years on September 19, 2010. The Turkish part of the pipeline was owned and operated by Turkish Petroleum Pipeline Corporation (BOTAS).

Ceyhan-Kirikkale Crude Oil Pipeline

The pipeline transports the oil from Ceyhan to the Refinery located in Ankara.

Batman-Dortyol Crude Oil pipeline

The pipeline is Turkiye's first crude oil pipeline. It was first operated in 1967. The pipeline was transferred to BOTAS in 1984. Its capacity is 4.5 million tonnes per year (BOTAS, 2023).

Baku-Tblisi-Ceyhan Crude Oil Pipeline

The pipeline was built to transport oil to be produced in the Caspian Region, especially the Azerbaijan oil, to Ceyhan via Azerbaijan and Georgia and then to world markets by means of tankers. In 1999, an intergovernmental agreement was signed between Azerbaijan, Georgia and Turkiye and a host government agreement was signed in 2000 as an annex to the intergovernmental agreement, between the Republic of Turkiye and the Main Export Pipeline Associates. The pipeline that transports Turkmen and Kazakh oil depending on production, as well as Azeri oil was put into operation in 2006. Turkish section of the BTC pipeline, which is 1 076 km long, was constructed by BOTAS and it is operated by BOTAS International Limited Company (BIL).

Crude oil and natural gas pipelines and LNG facilities in Türkiye are shown in Figure 13.11. Characteristics of the crude oil pipelines are given in Table 13.12. Annual crude oil amounts transported in thousand barrels by crude oil pipelines in Turkiye are presented in Table 13.13.

Figure 13.11 Crude oil and natural gas pipelines and LNG facilities of Türkiye (BOTAS, 2023).

Table 13.12. *Türkiye: Characteristic of crude oil pipelines (BOTAS, 2023)*

Pipeline	Length (km)			Capacity (Mt / year)	Diameter (inch)	Pump Station	Storage Tanker
Iraq-Turkiye COP		Türkiye	Total	70.9		6	12
	Line I	651	986		40		
	Line II	652	890		46		
	Total	1 303	1 876				
Ceyhan-Kirikkale COP	448			7.2	24	2	3
Batman-Dortyol COP	518			4.5	18	3	23
Baku-Tblisi-Ceyhan COP	Türkiye	Total		50	34, 42, 46	4	7
	1 076	1 776					

Table 13.13. *Annual Transported Crude Oil Amounts (Thousand Barrels) by Crude Oil Pipelines (COP) in Türkiye (BOTAS, 2023). Note that 2022 = as of November 2022.*

Year	IRAQ-TÜRKİYE COP	CEYHAN-KIRIKKALE COP	BATMAN-DÖRTYOL COP	BTC COP
2022	158 954	28 713	22 933	205 548
2021	186 875	30 664	24 221	200 149
2020	191 855	32 142	24 376	208 064
2019	194 084	34 938	21 536	235 243
2018	134 662	31 300	20 470	255 770
2017	184 927	39 292	19 757	252 763
2016	189 439	35 357	20 092	253 976
2015	192426	30 982	19 724	262 188
2014	55 984	22 213	17 780	260 675
2013	91 883	23 740	18 195	249 617
2012	134 506	21 962	17 649	250 345
2011	163 276	21 786	17 092	257 143